# THE OBSERVATORY

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## MEETING OF THE ROYAL ASTRONOMICAL SOCIETY

Friday 2009 November 13 at $16^h\ 00^m$
in the Geological Society Lecture Theatre, Burlington House

A. C. FABIAN, *President*
in the Chair

*The President*. My first announcement is with regard to the death, on November 8, of Vitaly Ginzburg, member of the Russian Academy of Sciences and Head of the Institute of Theoretical Physics at the Academy's P. N. Lebedev Physical Institute in Moscow. He was elected an honorary member of the Society on 1970 February 13 and was awarded the Society's Gold Medal in 1991. Ginzburg is best known for his contribution to the theory of superconductivity for which he was awarded the 2003 Nobel Prize in physics. I remember him for his book with Syrovatskii on cosmic rays. I ask you all to stand for a moment. Thank you.

Now on to the programme of our open meeting: the first talk is on 'The dark red spot on dwarf planet Haumea', by Dr. Pedro Lacerda from Queen's University Belfast.

*Dr. P. Lacerda*. I report the discovery of a region on the surface of the large Kuiper Belt object Haumea which is darker and redder than the mean surface. This dark red spot was identified by measuring changes in Haumea's brightness as it rotates. The origin of the spot is unknown but new clues are expected from spectroscopic observations planned to study its chemical composition. Detailed results of my recent work on this object have been reported in *AJ*, **137**, 3404, 2009.

Haumea orbits the Sun beyond Neptune, in the region known as the Kuiper Belt. It is one of the largest Kuiper Belt objects (KBOs), following Eris, Pluto, and Makemake. One of the most surprising characteristics of Haumea is its very fast rotation, with a period of 3·9 hours. The rapid spin deforms Haumea into an elongated 2000 × 1600 × 1000-kilometre ellipsoid whose shape balances gravitational and rotational accelerations. It is likely that Haumea was spun up by a massive impact more than a billion years ago.

Because of its rotation and elongated shape, Haumea brightens and dims periodically as it reflects more and less sunlight. The peak-to-peak range of the light-curve tells us how elongated Haumea is, and the time between each brightening and dimming is a measure of the rotation period. The precise shape and spin period of Haumea imply that it has a bulk density roughly 2·5 times that of water. Deep spectroscopic observations show that Haumea is covered in almost pure water ice. The high bulk density stands in contrast to the icy surface and implies that Haumea must have a more rock-rich interior.

The two maxima and the two minima of Haumea's light-curve are not exactly equal, as would be expected from a uniform surface. This indicates the presence of a dark spot on the otherwise bright surface. Furthermore, the light-curve is not exactly the same shape at all wavelengths. Small but persistent differences tell us that the dark spot is slightly redder in visible light and slightly bluer at infrared wavelengths.

Possible interpretations of these measurements are that the spot is richer in minerals and organic compounds, and/or that it contains a higher fraction of crystalline ice. If the spot is the scar of a recent impact onto Haumea, then the spot material might resemble the composition of the impactor, perhaps mixed with material from the inner layers of Haumea.

New observations of this spot are planned for early 2010 using the ESO *Very Large Telescope*. The goal is to obtain detailed time-resolved spectroscopy of Haumea to identify the chemical composition of the spot region and shed light on its origin.

*The President*. Thank you very much, Pedro. Any questions? Donald.

*Professor D. Lynden-Bell.* I just wanted to make sure — this rapid rotation is so fast that it should be a Jacobi ellipsoid if it were a liquid, and not a Maclaurin spheroid.

*Dr. Lacerda*. It's fast enough. It could be both, but if it were a Maclaurin spheroid it wouldn't produce a light-curve. It is actually too fast for a Maclaurin spheroid to be the most likely case, so it's more likely a Jacobi ellipsoid.

*Professor Lynden-Bell*. It really is in that régime? That's interesting.

*The President*. You said the object could well have suffered a collision and therefore be broken — is there any way for the ice to propagate around it later? Or could the spot be the result of it having had a collision and that it has a denser interior exposed there and nowhere else?

*Dr. Lacerda*. That's certainly possible. The collision that I speculated could have produced a spot but is not the one that produced the collisional family of objects. That collision would have been too violent: it would have just ripped the whole water-ice crust off Haumea and those bits of water ice would form the moons and other objects, leaving a rockier core with a veneer of water ice, which is what we see.

In a later collision, indeed, the impactor could either splatter on the surface or it could just take off a bit of water-ice cover and expose the interior, so it's true that both are possible. If the temperature is raised, the ice essentially vaporizes and then it can recondense elsewhere.

*Mr. M. F. Osmaston*. Your density tells us that a lot more silicate got out into an area which hitherto has been regarded as the domain of water, comets, *etc*.

*Dr. Lacerda*. Yes, it's very interesting; another observation that indicates that there are a lot of silicates out there was from the *Stardust* mission, a spacecraft that went through the tail of Comet Wild 2, and used aerogel to collect dust grains from the comet and bring them back to Earth. Materials were found that must have condensed at over 1000 K, but we think that object must have formed all the way out in the Kuiper Belt; so during the formation of the planets there was much more mixing of material than we originally believed.

*The President*. It's very interesting to learn more about the structure of objects which we didn't know about ten years ago.

*Dr. Lacerda*. You can do all that with just a little dot in your image.

*The President*. Indeed; good luck with finding more structure on it.

*Dr. Lacerda*. Thank you. [Applause.]

*The President*. The next talk is on 'Natural and artificial mini-magnetospheres: what planetary magnetic anomalies can teach us about surviving a field trip to the Moon', by Dr. Ruth Bamford from RAL.

*Dr. Ruth Bamford*. Energetic ions in the solar-wind plasma are a known hazard on manned space flights to the Moon and Mars that extend over long periods of time. Attempts to protect spacecraft include active shields that are reminiscent of *Star Trek* 'deflector' shields. Here we describe a new experiment to test the shielding concept of a dipole-like magnetic field and plasma surrounding the spacecraft, forming a 'mini-magnetosphere'. Initial laboratory experiments have been conducted to determine the effectiveness of a magnetized plasma barrier in expelling an impacting, low-beta, supersonic-flowing, energetic plasma representing the solar wind. Optical and Langmuir-probe data on the plasma density, the plasma-flow velocity, and the intensity of the dipole field clearly show the creation of a narrow transport-barrier region and diamagnetic cavity virtually devoid of energetic plasma particles. This demonstrates the potential viability of being able to create a small 'hole' in a solar-wind plasma, of the order of the ion Larmor-orbit width, in which an inhabited spacecraft could travel in relative safety. The experimental results have been quantitatively compared with a 3-D particle-in-cell 'hybrid'-code simulation that uses kinetic ions and fluid electrons, showing good qualitative agreement and excellent quantitative agreement. Together the results demonstrate the pivotal rôle of particle kinetics in determining generic plasma-transport barriers.

The first question to be addressed in this talk is the nature of the radiation hazard affecting astronauts in space, particularly away from near-Earth orbit, such as on the Moon. *In-situ* measurements of the solar wind and solar proton events, show that the solar storms are made up of approximately equal numbers of energetic protons and electrons. This makes the medium a plasma, with particle energies ranging from keV to hundreds of MeV. Those solar cosmic-ray particles are not commonly found at those energies here on Earth, except in particle accelerators. However, the particles cause ionization in spacecraft instrumentation, and in human DNA that results in cell damage and even death. Conventional measures of radiation do not apply here but the hazard is very real to both instrumentation and living tissue, especially from the high flux of high-energy particles during solar storms. For astronauts going out to the Moon or Mars, the risks are extremely acute, because on such journeys the spacecraft has to travel outside the protective cover of the magnetic field of the Earth.

The *Lunar Prospector* mission surveyed the environment of the Moon at close quarters. It provided detailed data on the magnetic topology of the Moon's surface *via* an electron-reflectometer experiment. This revealed that, although the Moon has no overall dipole magnetic field, pockets of magnetic field or anomalies exist, confirming measurements made by instruments placed on the surface by the Apollo astronauts. Observations from the orbiting *Lunar Prospector* flying at an altitude of only 20 kilometres above the surface showed that these small pockets of magnetic field were able to perturb the particle distribution of the solar wind.

The magnetic anomaly located at antipodal zones of the Imbrium and Serenitatis ringed impact basins, although only 5 to 30 nT, was powerful enough to 'stand off' the solar wind. That is to say, the spacecraft passed through large, abrupt amplifications of the solar-wind magnetic-field and particle distributions as the solar wind was shocked and deflected by the crustal magnetic field. Once within the boundary, the observed depletion in the total number of energetic particles indicated that a central 'density cavity' had been formed. This was further evidenced by the observation by the *Lunar Prospector* instrument of the unusually light albedos in the local region directly below the magnetic structure, suggesting a difference in the degree of 'weathering' of the lunar surface by the solar wind. All these characteristics are indicative of the formation of a magnetosphere, but, given the size of the crustal anomaly, this would have to be classified as a naturally occurring 'mini-magnetosphere'.

Other 'mini-magnetospheres' have also been identified on two asteroids. In the early 1990s, the *Galileo* spacecraft passed in the wake of an apparent miniature magnetospheric boundary as it flew past the asteroids Ida and Gaspra. Here again, the characteristic pile-up of magnetic field and particles, consistent with the boundary of a magnetosphere with an accompanying depletion of energetic-particle density inside, was also observed by the spacecraft.

These examples of natural mini-magnetospheres around the Solar System have shown that very small magnetic structures of 10 to 20 km, and very modest magnetic field strengths, 5 nT to 30 nT, can still affect the solar wind. This was a surprise, as it has always been assumed that 'magnetospheric action' required large magnetic structures the size of a planet.

The fact that these miniature magnetospheres exist at all in nature means that the idea of creating a small, artificial mini-magnetosphere, to protect a spacecraft, may not be that far fetched. The aim now is to understand better the physics of such small-scale interactions with the solar wind and solar-proton events. Although it may indeed be true that artificial magnetospheres as spacecraft protection may still remain an impractical prospect, the evidence suggests that this will not be for the reasons that were previously thought.

The key is to appreciate the significance of scale. The physics terms that dictate the action of the large-scale interaction of solar-proton events emerging from the Sun are not precisely the same as those physics terms that dominate the very small scale of human beings. A terrestrial analogy of this would be the distinction between the important physics terms that control the ability of a Boeing 747 to fly, compared with the very different micro-physics of turbulence that dominate the very small scales important to the flight of insects. For the aircraft, the dominant physics is of fluid dynamics and ram pressure of a 60-m-long fixed-aerofoil wing, travelling at hundreds of kilometres per hour, differential pressures, *etc*. These are not the same balance of forces associated with the shedding of micro-vortices, from multiple tiny wings acting like 'paddles' executing a figure-of-eight, hovering or travelling at walking pace, from a 2-cm-long bumblebee. The scale size important to human beings in space is in the realm of micro-turbulence, like the bumblebee, compared to the colossal scale size of coronal mass ejections and solar-proton events.

Stated more explicitly, many of the physics terms used within the Vlasov–Maxwell and Poisson equations that describe the evolution of particle distributions under the effects of self-consistent electromagnetic fields in plasmas are dropped on the large-scale. This is partly out of computational necessity, and partly out of lack of relevance to the large-scale, as the contribution is swamped by the primary terms. However, on a small scale many of these neglected terms actually dominate the physics of interaction, as with the bumblebee analogy.

In order to see if this theory of the significance of the minor parameters on very small scales has any validity at all, experiments were done in the laboratory and in computer simulations. The laboratory equipment used for the investigation was borrowed from the research field of magnetically-confined fusion plasmas. The linear plasma stream of this facility acted as a proxy for a solar-wind stream of plasma. The thermal distribution of the plasma stream was about 2 eV, whereas the flow speed was closer to 100 eV. The plasma was not only flowing supersonically (as the solar-proton-event particles do in the solar wind) but it was also a collisionless plasma, *i.e.*, the mean free path between ion collisions was many times greater than the total length of the vessel. This, too, is a similar situation to the plasma of the solar wind/solar proton events, where the mean-free-path between ion collisions is greater than 1 AU.

Both simple photographs and detailed Langmuir-probe measurements showed how magnetic-field pile-up and particle pile-up were recreated in the laboratory mock-up. Most significantly, in the centre a density cavity is formed whose overall diameter was very much smaller than the ion Larmor orbit. The width of the plasma barrier created by the magnetic field at the boundary that held back the plasma stream was only of the order of a few electron Larmor-orbit radii. (The Larmor orbit is the circle executed by a charged particle as it circulates around a magnetic field.) Translating these plasma parameters into the environment of space, this would mean the equivalent barrier width would be of the order of tens to hundreds of metres across (the equivalent electron Larmor radius in space), and the overall structure does not need to be bigger than the ion Larmor radius (which in space would be tens to hundreds of km across).

Scaled up to their dimensions in space, this would enable a small pocket formed in plasma flowing around the spacecraft of only a few hundreds of metres across, in which astronauts could have some protection in addition to the other forms of shielding intended to protect the spacecraft from the very worst consequences of solar-proton events.

The idea of using magnetic fields or electrostatic fields to protect spacecraft is far from new. However, the interaction here is much more complicated than was originally conceived. It is often mistakenly assumed that the 'deflecting force' is due to particles being bent around magnetic-field lines, in a fashion similar to the deflection of GeV particles in particle accelerators. To do this at the energies experienced in space would require enormous magnetic-field strengths and hence enormous power resources, which are unlikely to be available. This is not what is happening here. Indeed, it could *not* be what is happening, given the observations of the existence of natural mini-magnetospheres identified on the Moon and on some asteroids. In these examples, the magnetic fields involved are minuscule, and the distances tiny, clearly indicating that the simple back-of-the-envelope idea cannot be how the particles are being affected. And yet the *in-situ* observations show characteristics of full-sized magnetospheres whose physics could be said to be quite well understood. It is back to the analogy of the bumblebee again!

In fact the rôle of the magnetic field, at least in the artificial mini-magnetosphere case, is to act like a cage rather than a bending magnet. This is how the magnetic field is used in magnetic-confinement fusion devices. In the case of the artificial mini-magnetosphere, the magnetic field is there to capture the thermal distribution of plasma and use the superb electrical conductivity of this 'wall of plasma', and that is being used as the 'barrier' to the impacting highly energetic particles associated with solar-proton events. Computer simulations of this scenario have shown that this does indeed happen. The question is how far can it be pushed? And can it ever be worth deploying on spacecraft? NASA's requirement for human spaceflight is that a 95% confidence level is achieved for only a 3% increase in serious health risks to the astronauts throughout a mission. There is no expectation of being able to budget for 100% shielding. However, without some drastic new technology, the current shielding is going to be woefully inadequate and is likely to be the limiting factor on the manned exploration of space.

So these results from the laboratory showed that, in principle at least, relatively tiny mini-magnetospheres could be created under a similar régime to the appropriate dimension-less plasma parameters of the Vlasov equation. Clearly we need to extend these studies to the much higher differential energies appropriate to the real-life situation in space, and to more computer simulations to extrapolate the interactions to other appropriate scenarios. But we can at least say that these first stepping-stones indicate that a previously dismissed technology is, perhaps, worthy of re-examination.

*The President*. Thank you very much; any questions?

*Dr. W. Tobin*. How might this scale to a cavity ten metres in diameter — is it practical in engineering terms?

*Dr. Bamford*. Well, that's the big question: give us some more money and we'll find out! [Laughter.] In principle, if you just look at particles scattering as if they were scattering off a giant particle — I'll use the analogy of Rutherford scattering — there is no reason why a structure of 100 metres is not sufficient to scatter it. The question is: can you get the rest of the physics to do that? I don't know at the moment, but when I've done computer simulations, it does look like it would be feasible at very modest energies because it doesn't need to be as large a bubble as was previously considered in the '60s and '70s when this technology first came to mind. They believed that you had to make an object, a magnetic structure, twenty kilometres across, because they were using the same models you'd use on a planet down to the minimum size they would work at, and that turned out to be twenty kilometres. We're going the other way: working from small to as big as possible, as it were.

*Professor A. M. Cruise*. Doesn't the physics really depend on the energy of the particle you're trying to deflect, or protect yourself from, and isn't it simpler to do a back-of-the-envelope calculation as to how much magnetic field you need to deflect a particle?

*Dr. Bamford*. It doesn't work completely like that because what is actually deflecting the particles is the electrostatic field caused by charge separation. The electrons are easy to deflect: they'll basically follow the magnetic-field lines, and although even the most energetic ions, say 100 MeV, will swing past their electrons, they notice very shortly that they've left them behind and a big charge separation forms. Now the charge separation doesn't have to be of the order of the exact energy in order to refract them — you don't have to deflect them, but refract them enough to get them away from a small pocket. In fact the analysis cannot be done on the back of the envelope because it's very non-linear — it's actually all to do with a lot of turbulence and non-linear characteristics because you're getting right down into the nitty-gritty of the behaviour.

We've done it at very modest energies but we have stopped particles that were flowing at ten times the thermal background. An experiment was done at the linear accelerator at Stanford with 28-GeV particles which they wanted to shield with some steel — it went straight through the steel. But when they put an adequate plasma in the way, they were completely reflected. Because the energy for the field is coming from the particles themselves, you're using their own momentum and charge against them, so it is self-regulating to a certain extent — not absolutely, you can blow it down. I have some movies of changing the flow speed by not a great margin — we didn't have that much scope — but you can see that the magnetosphere compresses and expands as the flow energy is changed, and we know too that that happens with the Earth's magnetosphere.

There are other techniques that might be employed to enhance the performance at high energies — that is what happens at the edge of a tokamak, and those energies are comparable to what we are getting in space; they have big shields, but they're actually trying to hold a high density only a few centimetres from a vacuum-vessel wall at room temperature, and they do it. And they do it with similar physics to what we're using here.

*The President*. Thanks very much, Ruth. [Applause.]

We have to go to Saturn next: our next talk is the 2009 Harold Jeffries lecture, by Dr. Emma Bunce of Leicester, on 'Saturn's rapidly rotating magnetosphere: new results from *Cassini*.'

*Dr. Emma Bunce*. [It is expected that a summary of this talk will appear in a forthcoming issue of *Astronomy & Geophysics*.]

*The President*. Thank you, Emma; that was an excellent talk. Let me ask a trivial question. You said that the magnetic field is an aligned rotator and Saturn has the only really pronounced ring system (I know other planets do have some sort of rings): do you think there is any connection there? Imagine that it was a misaligned rotator; do you think that would have any effect at all on the ring system?

*Dr. Bunce*. I don't think so — well, I shouldn't really say, given that I'm not an expert on the ring systems — but Uranus is the obvious extreme oblique rotator and the ring system is, well, like a big bulls-eye. I think that is a centrifugal effect.

*Professor M. Lockwood*. On the idea that the oval collapses after the shock arrives, what sort of delay is it and what does that mean for where the X-line on the night side would be? I guess my real question is: does that fit with the transit times from your modelling from aurora to aurora?

*Dr. Bunce*. That's a good question; clearly the simple answer is that we need more data and more observations like that — in fact, that event was something we simply just haven't seen again. In 2004, we just happened to get the auroral images at the right time to see that event, and of course the spacecraft was very usefully studying the solar wind, but we don't know what the *in-situ* counterpart would look like in the magnetosphere. We think we have some examples, actually, in the field-line currents that we've been studying during 2008, but you never quite have the right set of observations, so you might have the *in-situ* data but then you don't have auroral observations. In terms of the timing, it seemed to be approximately ten hours after the shock compression hit the magnetosphere to the next auroral image that we had that showed that bright auroral storm; but who knows what happened in between? So essentially, 'I don't know' is the simple answer. [Laughter.]

*Professor Lockwood*. Given that if you squeeze the X-lines, and the field lines have to get to twice that before they get reconnected, you have to double that to get the Dungey-cycle time across the open-field-line region. So I just wondered if that fits or not?

*Dr. Bunce*. Good question. Thanks, Mike!

*Dr. Lacerda*. Those extra rings you see, the concentric rings, could it be a spiral? Could it be a winding effect because of the rotation of the planet?

*Dr. Bunce*. As with the co-rotation breakdown at Jupiter? That's one of the possibilities. In fact I didn't show this, but in the infrared data there is a suggestion that there may be a secondary oval which is to do with that effect, so it is possible that there is a co-rotation breakdown effect at Saturn as well, but it's also possible that those secondary ovals are actually to do with the current system which must be present to produce the magnetic-field oscillations that we see. There has to be a current system associated with that field perturbation, and that current system is being studied by a number of people and the currents are turning out to be quite large — comparable to the solar-wind interaction — so we've got to try and find out the relative importance of those systems.

*Professor Lynden-Bell*. As you know, for Jupiter they found the hotspot where the magnetospheric line goes to Io; have they found the hotspot where the magnetospheric line goes to Enceladus?

*Dr. Bunce*. Well, I'm not sure if I'm allowed to say this, but yes. [Laughter.] It's currently being worked on and there are some data that show an Enceladus footprint, but it's not always there.

*Professor Lynden-Bell*. Yes, and associated with it do we have any equivalent of the decametric storms from Jupiter? I suspect not, because Saturn's very much dimmer than Jupiter in the radio sky.

*Dr. Bunce*. I don't think so, but it's a good question.

*The President*. Last question?

*Mr. Osmaston*. The Enceladus picture that's been published of the emission, or whatever you'd like to call it, is perfectly aligned radially, and I have a problem with why that should be. Do you have any feel that there's a problem with the perfectly radial flow line from this Enceladus eruption?

*Dr. Bunce*. I've not thought about it, to be honest.

*The President*. It must be travelling fast, I guess. Let's thank Emma again for a wonderful talk [applause].

There is now the usual drinks party after the meeting and any Fellow present who has paid the admission fee and first annual contribution but not yet been formally admitted is invited to sign the book which is on the table in the Library. The meeting is now closed, and the next open meeting will be on Friday, December 11.

## MEETING OF THE ROYAL ASTRONOMICAL SOCIETY

Friday 2009 December 11 at $16^{h}$ $00^{m}$
in the Geological Society Lecture Theatre, Burlington House

A. C. Fabian, *President*
in the Chair

*The President.* I have to announce that Dr. Hal Thirlaway died peacefully on 2009 November 30 at the age of 92. For over twenty years he led the seismology group at Blacknest, part of the Atomic Weapons Research Establishment. Under his guidance, the group made several important advances in the application of seismology to the verification of arms-control treaties. In recognition of his contribution to seismology he was awarded the Royal Astronomical Society's Gold Medal in 1972. There will be a memorial service early in 2010 to celebrate Hal's life and work. I ask you all to stand. Thank you.

The first item is going to be from Jim Emerson of Queen Mary, University of London, and he will speak briefly about *VISTA*.

*Professor J. P. Emerson*. [The speaker said that he wanted to present an update on the status of the *VISTA* telescope. That morning there was a simultaneous press release at ESO, STFC, and QMUL announcing that the telescope was now formally a part of the ESO infrastructure. The ESO website contains some stunning images of various astronomical objects taken by *VISTA* just prior to the recent science-verification exercise, including the Flame Nebula NGC 2024. The field of view (1·5 × 1 degree) is wide enough also to include NGC 2023 and the Horsehead Nebula. The images in the press release (see www.eso.org/public/eso0949) also include the Galactic Centre and the Fornax galaxy cluster, which not only demonstrate the large field of view but also the image quality and the high throughput. The speaker hoped to say more about the science coming from *VISTA* at a future meeting.] [Applause.] [Editors note: The image of the Flame Nebula referred to above is reproduced in the 2010 February issue of this *Magazine*; see **130**, Plate 2 facing page 1.]

*The President*. This is good news for ground-based astronomy. I saw *VISTA* in March when I was in Chile, and it is very impressive.

The next speaker is Tim O'Brien who will talk about 'New insights into nova explosions'.

*Dr. T. J. O'Brien*. [The speaker began by describing how novae fit into the wider group of cataclysmic variables. Novae are interacting binary systems comprising a white dwarf with, typically, a low-mass main-sequence companion. There is accretion onto the white dwarf either because the companion is filling its Roche lobe or because its wind has been intercepted by the white dwarf. Novae exhibit outbursts with amplitudes of up to ten magnitudes in the visual. The outburst is thought to be due to the explosive onset of thermonuclear reactions at the base of the hydrogen-rich material accreted onto the white dwarf. During the outburst the accreted matter is ejected at speeds of hundreds to thousands of kilometres per second. As material is ejected, the photosphere then shrinks back leading to an increase in the effective temperature. The nova fades in the visual but becomes brighter in the UV and then soft X-rays. This basic model was confirmed by observations taken with *IUE*, *EXOSAT*, and *ROSAT*. In radio observations of novae we see free-free emission from the expanding shell of ejecta, allowing us to make estimates of the ejected mass and its geometry.

We think classical novae, whilst appearing to explode only once, do in fact recur, but on timescales of thousands of years. The systems we know as recurrent novae have been seen to outburst more than once with recurrence times of, typically, tens of years. One of the best-known examples is RS Ophiuchi which most recently underwent an outburst in 2006, brightening from $V = 11$ to $V = 4$. In this case the white dwarf has a red-giant companion and interaction of the ejecta with its dense wind leads to interesting behaviour. These transient events can now be examined at many wavelengths, including intense monitoring in the X-rays with *Swift* in periods when it is not studying gamma-ray bursts. In RS Oph, we see X-rays from hot gas behind a shock in the red-giant wind then a sudden increase in brightness accompanied by rapid variations. In this case, as the ejecta expand and clear, at the soft-X-ray wavelengths we see through to the hot extended atmosphere of the white dwarf powered by on-going nuclear burning. At radio wavelengths, we were able to use *MERLIN* and *VLA* much earlier than in the previous outburst in 1985, and for the first time resolve the shock wave by using *VLBA* and *EVN* observations. Subsequent *MERLIN*/*VLBI*/*VLA* observations showed that the shell developed into a bi-lobal structure which is probably driven by the ejection of jets. Observations of jets from white dwarfs are useful in exploring a region of parameter space between neutron-star jet sources and young stellar objects.

Following the RS Oph campaign, an international *Swift* nova–CV group was set up. Coordinated from Leicester, this has so far made observations of around 40 nova outbursts. The combination of these coordinated multi-wavelength campaigns with high-cadence observations is making a significant difference to our understanding of these objects.

Summing up, the speaker said it was possible that recurrent novae such as RS Oph could be progenitors of type-Ia supernovae. It is believed that the short recurrence times and high ejection speeds indicate that the white dwarf is close to the Chandrasekhar limit. If not all the accreted material is ejected, then the white dwarf will be growing in mass and heading towards a supernova explosion. Perhaps the best candidate is the extremely fast recurrent nova U Sco in which material is ejected at up to 10 000 km s$^{-1}$ and the mass of the white dwarf in the system is estimated to be $1{\cdot}55 \pm 0{\cdot}24\ M_{\odot}$. Its last outburst was in 1999, and before that in 1987, 1979, and 1969, so we are ready and waiting with an array of telescopes to study its next explosion in great detail.] [Note added in proof: U Sco did explode on 2010 January 28.]

*The President*. Thanks, Tim. Let me ask you a question. With the *Swift* result where you showed the rapid variability, is that likely to be variable obscuration?

*Dr. O'Brien*. That's certainly what we thought initially, and I suppose that's still our best guess. So the ejecta is expanding outwards; it's clumpy, and you're getting variable obscuration. It doesn't entirely fit inside that story because you can look at the hardness ratio in the X-ray spectrum to tell whether it's due to absorption or not, and it's not a perfect fit. The other interesting thing is that there is a clear periodicity in the X-rays as well, something of order of 35 seconds, which looks like it may be an instability in the nuclear burning on the surface of the white dwarf, which has not been seen before.

*Mr. M. L. H. Hope*. Can you distinguish clearly between an increase in brilliance of the accretion disc and burning on the surface of the white dwarf?

*Dr. O'Brien*. We think so. The amplitudes are very different and the dwarf-nova outbursts that are due to accretion-disc instabilities don't really eject much material. They are an accretion event, so stuff falls through the accretion disc onto the white dwarf, whereas pretty clearly in these novae you see P Cygni profiles showing that there is ejection. So I think it's generally fairly easy to distinguish. There are just a few cases where there is a bit of debate.

*Professor D. Lynden-Bell*. Just lest it be forgotten, since he's in the audience, I would like to say that the explosion scenario in degenerate white dwarfs is due to Leon [Mestel].

*Mr. N. Calder*. Would you expect any warning sign before it went supernova?

*Dr. O'Brien*. Before it went supernova? I thought you were going to say before it went nova. I was going to say that because we've got these recurring novae, you'd think that by now we'd have learned how to predict when they were going to explode, wouldn't you? We see these things go off every ten years (in the case of U Sco). Things do change a lot in terms of our instrumentation in ten years so we are getting a lot better at being able to do that, but we can't currently predict it. There's an indication that the quiescent colours of these objects start to change just before the explosion. I don't know about the supernova case. One thing you can do is attempt to measure the mass of the white dwarf by looking at the orbital parameters of the system, so if you could possibly measure precisely the orbital period of the binary system before and after an outburst you could attempt to estimate how much mass was ejected directly. At the moment we attempt to estimate the amount of mass ejected by modelling the emission we see, and working out what the mass must be. Then you have to ask how much mass has been accreted since the previous outburst. You have to rely on knowing what the quiescent X-ray flux was, for example, to get the accretion rate. So it's all fraught with uncertainty, and that is why we've not been able to pin it down. So the answer is probably no, not quite yet.

*The President*. The next speaker is Mr. Adrian West from Newbury Astronomical Society and the subject of his talk is 'Twitter and astronomy'.

*Mr. A. West*. [The speaker began by explaining that Newbury Astronomical Society (NAS) is a group with 50 members more orientated towards outreach than observing. Twitter is a social network or 'micro-blogging' site which allows users to share information and ideas worldwide. It is extremely popular and is gaining about one million new users each month. Its main attraction is that it is simple, informative, and fun.

The speaker logged on to demonstrate how it works. First of all, an account is needed, which is free, and the aim is to 'follow' people — there are, for instance, a large number of astronomers who are users of Twitter. If you have something to say then people in turn will follow you back. The limitation is that each message, or 'tweet', is limited to 140 characters, but in that message the user can link other files or images to bring to people's attention. If you hear something interesting then you can 're-tweet', *i.e.*, broadcast the message to your circle of contacts. If it is interesting enough they in turn will do the same and the message quickly spreads throughout the community.

Last summer the NAS held a week-long public event involving solar observing, and the BBC came to talk to them. An idea was suggested in which the Moon would be observed and the image disseminated *via* Twitter. Around 11 pm one night a rather fuzzy image of the Moon was taken and posted to 'Twitpic', a facility of Twitter that stores images. One hour later it had been viewed by 1000 people which in turn attracted more followers. The idea was to do the same for the Perseid meteor shower in August, so 14 days before the date of maximum the idea was publicized and the BBC put it on their website. The event was co-ordinated from a garden shed known as the Astro-Bunker [laughter] and for 24 hours it was the most-accessed news story on Twitter. The speaker read out a few responses from followers and said that his favourite was one which read "so excited — saw a Perseid meteor last night — when I grow up I want to become an astronomer". The '#meteorwatch' topic eventually became the most accessed topic in the world, with up to 100 hits per minute, and the hit counter stopped working after 10 000 hits. Twitter itself also crashed that evening but it's not known if this was due to #meteorwatch [laughter].

Many astronomers and scientists use Twitter and there is no hierarchy — people just want to share information and can do so, often before other forms of communication. The speaker concluded by saying that NAS were not experts in astronomy but they could direct people to experts. There is a sense of community and you make friends with people of all types. There is always a new strand of each topic to read. Future plans include another #meteorwatch and '#moonwatch'. You do not need to be a scientist to do these so the advice is "get involved, share information and have fun".]

*Dr. S. Mitton.* I've used it to publicize events, and there is no question it does work. You can promote anything, book sales, a lecture ... .

*Mr. West.* That's right. If you've got the right people using the right topic, or hashtag (#), and the right number of people following you, it will spread very, very quickly, and it will spread within your group. I follow a lot of astronomers or astronomy-related organizations, and they follow me. So you'll get a lot of coverage there. We've advertised using both of those trailers for the meteor-watch and they've received almost ten-thousand hits between them.

*The President.* And professional astronomers ought to be aware that the science minister Lord Drayson is on Twitter. I went to a debate two weeks ago where questions were coming in on Twitter, which was new to me.

*Miss Alice Sheppard.* Just a Twitter anecdote that I was lucky enough to be in on: it was 'Twitterers' who influenced parliamentary question time — for the first time in history someone had managed to stop a parliamentary question being published. It was Carter Ruck and Trafigura [a case relating to the dumping of toxic waste in the Ivory Coast], of course, and it was us Twitterers who were spreading it all around and making sure it got published all over the place, except in what Chris Lintott would call the old media.

*Mr. West.* That's the thing — it is the new medium now and it works incredibly quickly. If you've got a big following you're going to get your message out very, very quickly. So it's ideal for astronomy.

*The President.* What do you do for the Geminids if tomorrow night or Sunday night is cloudy?

*Mr. West.* There will be somebody else in the world with clear skies and we'll help them. It won't be the east coast of America because they're under about a foot of snow, it's a blizzard at the moment. There might be someone else in the world and they will take images or they will talk about it, or we might get a break in the clouds. Tomorrow is looking quite good; Sunday is not looking very good. So we'll help them. We'll re-tweet their images and we won't just do images, we'll talk about the Geminids, we'll talk about the science and astronomy as well.

*Dr. C. Trayner.* If you want to promote something such as astronomy, presumably you have to be willing to lay aside a certain amount of time more or less each evening to water the plant.

*Mr. West.* You can do, it depends how big your feed is. Our feed is quite big: we've got over 2000 followers including the Jodrell Bank people, so we really only have to put a couple of tweets out to cover a wide audience. Effectively you are relying on your friends and everybody else following you. But yes, if you want Twitter to work properly and work for you and promote your organization you need to devote a bit of time to it. At least an hour a day when you're building it, and maybe ten minutes a day once it's done. So in the background when you're checking your emails, do Twitter afterwards as a bit of routine.

*The President.* We heard about the International Year of Astronomy several times in that talk and we are now going to hear more from Ian Robson. The title of his talk is 'IYA2009'.

*Professor E. I. Robson.* Let me say from the very outset that IYA2009 in the UK has been a tremendous success and I would like to take this opportunity of thanking those funding organizations for their support and all those who were involved and delivered such a brilliant, vibrant, and diverse programme of events.

Although IYA2009 had a range of goals and objectives, for me in the UK our two key goals were: to stimulate a spirit of excitement in astronomy with the public — to encourage their first look through a telescope at the Moon and other celestial bodies and experience the 'wow' factor; and to promote an enthusiasm for science and technology amongst young people. The evaluation process is now just starting but I am confident that we will have achieved both of these goals with the help of all those who participated.

The financial meltdown removed our key corporate sponsor but nevertheless almost £1M of direct IYA2009 funding was provided by the RAS (£320k), STFC (£565k), IoP (£55k), and the Scottish Government (£40k). This ranks amongst the top-funded countries and looking at the hits on the web-page, the UK also ranks in the top three and wins out easily on hits per head of population. The entire programme was overseen by an Executive Committee comprising the three main funding organizations, and a press group organized the interactions with the media. Steve Owens did the bulk of the work in coordinating and organizing events and we were able to supply resource packs as well as material for people to download from the web-page (www.astronomy2009.co.uk).

Within the UK we provided support for the following global 'cornerstone' projects: '100 hours of astronomy' (which we undertook as two separate 'Moonweeks'); the 'Galileoscope', which became the 'Schoolscope' for us; 'From Earth to the Universe'; 'Dark-sky awareness'; 'She is an astronomer'; 'UNAWE'; 'Galileo teacher ambassadors'; and 'Cosmic diaries'. Just looking at a couple of these (see the 2010 February edition of *A&G* for a more detailed discussion), the two Moonwatches were pivotal times during the year when the amateur community at large opened up their doors to the public and focussed their events, talks, and sidewalk astronomy. In total 191 events were run in Spring Moonwatch, and 348 in Autumn Moonwatch. This compares to an average of 123 events per nine days throughout the year. These events were advertised on the web and the feedback from the societies has been incredibly positive, with many increasing their membership numbers significantly. Indeed, looking at the events that were put on during the year, the amateur community certainly did us proud, doing by far the lion's share of activity. Over 100 amateur astronomical societies ran events in 2009, contributing 40% of all the IYA2009 activities within the UK. There is no doubt that the entire amateur-astronomy community deserves recognition for the work they did in making IYA2009 such a success.

Perhaps a surprise was how well the science centres, museums, and planetaria got into the act. They used the opportunity to create new shows, new displays, and to take on new activities as an experiment — something they might have been reluctant to try without the push of IYA2009. Again, the feedback has all been extremely positive and one of the key achievements has been to see how the linking between these centres of public-outreach activity has improved during the year — a great legacy for the future. One of the key highlights of this was the STFC-sponsored new digital planetarium show, 'We are astronomers'. Narrated by David Tennant, it has received rave reviews and hopefully will be exported around the world, and it is estimated that by 2011 May, when the show is two years old, one million people in the UK will have seen it.

Another major activity was the Schoolscope project. This was the provision of 1000, good-quality, 70-mm refracting telescopes, complete with tripod, finderscope, and eyepieces, to secondary schools through the length and breadth of the UK. This was funded by the STFC and the RAS and organized by the Society for Popular Astronomy. A DVD was also provided giving instructional information as well as other aspects of astronomy. The initial evaluation is again incredibly positive, with 88% ranking it as a valuable addition to the school's science department. The final evaluation will be completed by March and it has already confirmed that these telescopes are being used by students and not just stored away in a cupboard. One of the aims of the project was to provide a link between the schools and their local amateur society or university, in so doing having the potential for a real legacy value as well as obviously stimulating interest. Also, the linked astronomers were each invited to become a STEMNET Science and Engineering Ambassador as part of the project.

From Earth to the Universe is a spectacular all-weather astronomical-image display of 50 stunning images on 25 three-metre-long, metal display panels. It was funded by the RAS and toured the UK (and Ireland), and a professional evaluation has been undertaken by a student as part of her Master's thesis in education. The final example of global cornerstone projects was the Dark-sky awareness. This had two parts: 'Dark-sky discovery', which set up sites near urban areas from where people could view the night sky in relative darkness and with safety. This was one component of the theme of the increasing awareness of light pollution, something that really caught the attention of the media during the year and culminated in the second part: the award to Galloway Forest Park becoming the first officially designated Dark Sky Park in Europe.

As well as the two Moonwatch weeks, there were activities throughout the year and these were hugely varied. Examples ranged from special plays, art installations in prestigious places such as the Tate Britain, portraits of UK astronomers in the National Portrait Gallery and the Albert Hall, talks about solar astronomy at the Glastonbury festival, new orchestral works for IYA2009, 'well dressing' near Macclesfield with an IYA theme, Thomas Harriot celebration in Syon Park, sleepovers in museums, science fiction at the Royal Observatory Greenwich, the Moonbounce from Jodrell Bank, and much, much more.

One of the major breakthroughs during the year was the introduction of Twitter to disseminate information. The UK Twitter feed (http://twitter.com/astronomy2009uk) grew to be the largest national IYA2009 feed, with just over 3600 followers, which compared with fewer than 1000 for the US feed! Over the year 1200 tweets were sent to the UK followers, with information on events, astronomy news, and what to see in the sky. However, the real triumph of Twitter in the UK came from the Perseid #meteorwatch and #moonwatch. These were spontaneous programmes developed by the Newbury Astronomical Society (http://twitter.com/Newbury) and run in conjunction with IYA2009UK. By far the largest of these events was the Perseid #meteorwatch, when over the course of two nights 10 000 people took part on Twitter and observed the night sky. This resulted in huge national media coverage, and made the #meteorwatch the most discussed topic on Twitter. Truly amazing. It is widely recognized amongst the New Media global task group that Newbury AS and astronomy2009uk are setting the pace globally in this aspect of public engagement. This is something that we all need to be aware of in terms of communicating with the public and especially young people.

I trust that this short overview has demonstrated the success of IYA2009 in the UK. However, we must ensure that this is not just a one-off and that we will build on this hugely improved collaboration with the amateur societies, the science centres, and planetaria, and use this new platform of communicating with the public through the wonderment of astronomy to inspire the next generation of schoolchildren to take up science and technology in their studies and hopefully future careers. [Applause.]

*The President*. Thanks, Ian; very nice. Any questions?

*Mr. J. A. Dee*. More of an observation on the finance side from the local astronomical society's point of view: I went to do an imaging talk at Wolverhampton and they were hunting around for a Fellow to sign the finance form and they were getting quite desperate. I just happened to mention I was a Fellow of the RAS, and was asked "Can you sign this form?" A man drove from Worcester to where I live to get it signed. I was wondering whether the next time the RAS do something for the finance for astronomical societies, can we dispense with the signature of a Fellow? I think it would encourage more astronomical societies to get involved, because the further north you go, the fewer Fellows there are [laughter] — until you get to Edinburgh: there are loads of them there!

*Professor Robson*. It's an interesting point! I should say that those small awards from the RAS made a huge difference. The feedback on those has been tremendous.

*Mr. J. Stone*. I can definitely say that without the RAS award, Letchworth and District Astronomical Society could not have put on what Steve Owens described this morning as the biggest programme of events of any society in the UK. It was explicitly down to that, and I said it before in my presentation earlier today but I'll say it again — we are extremely grateful.

*The President*. Thank you!

*Professor S. Miller*. The STFC's financial outcome, and what comes out of it, has the potential to undo all the great work that you've done with the International Year of Astronomy. That message has somehow to get back to STFC. I don't know how they're going to handle that but they really do have the possibility of doing a lot of damage on a very wide public scale.

*Professor Robson*. [To Professor Edmunds:] Are you listening?

*Professor M. G. Edmunds*. The STFC council are very aware of that but I'm sure that you too are aware that the STFC council can only do so much. You've seen the figures. You know the recent economic situation. STFC will do its best to be honest, to prioritize, and to do the best it can. It's fairly obvious that these are going to be very difficult times. We'll do the best we can, but we know the damage we're doing.

*The President*. It's certainly true that the International Year of Astronomy has been a great success, thanks to Ian and Steve and many other people around the country. It is going to end, I can anticipate, with some very negative words for British astronomy, and that's very sad. Wednesday afternoon is when the media briefing is taking place. David Elliott and I are getting a briefing at 10·30. We're then getting another briefing from the Government Chief Scientist at 12·00. I don't think that's a coincidence, so things are very serious. We are thinking very hard as to how we're going to respond to it.

The last event today is a very pleasant one, and that is to present the 2008 Keith Runcorn Thesis Prize to Dr. David Jess of Belfast University for his thesis entitled 'High cadence observations of the solar atmosphere'. [Applause.] The title of his talk today is 'The Sun: rapid dynamics on small spatial scales and their implication for coronal heating'.

*Dr. D. Jess*. Thank you very much for presenting me with this award and for inviting me to speak to you today. When first asked by the RAS to provide a seminar based upon the work I undertook during my PhD, my delight soon turned to frustration when I was unable to think of a witty title. So I apologize for the slightly long-winded title, but this is the best I could do when trying to cram three years of work into a solitary sentence!

The underlying lack-of-knowledge which created my PhD project is based upon a confusing paradox, which has long been known within the astronomy community. In this instance, I am referring to the coronal-heating paradox, where the outer atmosphere of the Sun is much hotter than its surface. The surface temperature of around 6000 K is completely overshadowed by the multi-million-degree temperatures found at heights exceeding 4000 km. For over half a century, theories have been proposed for why this rapid temperature rise exists. These include solar flares, where small-scale explosive events in the outer solar atmosphere may create the necessary heat to sustain million-degree temperatures.

Another theory assumes wave motion may be the dominant method of heat transfer. In that scenario, wave motion is created at the Sun's surface, caused by the turbulent convective motions associated with granulation. This wave motion then propagates along magnetic-field lines to the outer reaches of the Sun's atmosphere, where it dissipates, releasing energy in the form of heat. Personally, I feel it is a combination of these two theories which will ultimately solve the puzzle. Both flares and wave motion depend on magnetic-field phenomena, so I believe these 'opposing' theories may have more in common than first thought.

However, detecting such small-scale flare activity on the Sun is still beyond the resolution limit of current solar telescopes. So, for the purposes of my PhD project, I focussed on the search for waves and oscillations in the solar atmosphere. My collaborative effort with NASA's Goddard Space Flight Center led to the discovery of plasma oscillations very close to the height in the Sun's atmosphere synonymous with the steep temperature gradient (Jess *et al.*, *Astrophysical Journal*, **682**, 1363, 2008). Examining co-spatial and co-temporal data sets, I have been able to conclude that the detected waves hit an 'invisible' barrier, thus preventing them from propagating outwards into the extreme edges of the Sun's atmosphere. This barrier is a result of a steep density drop, and prevents the oscillatory motion from continuing its journey outwards. It is expected that the energy contained within these waves has no choice but to dissipate and release heat into the surrounding plasma.

Waves, such as those described above, must be generated close to the surface of the Sun. In order to probe the origin of these oscillations, I utilized high-resolution observations of the lower solar atmosphere obtained with the 1-metre *Swedish Solar Telescope*. These high-resolution images provided key insight into the nature of waves at low atmospheric heights. For the first time, waves initially predicted by Hannes Alfvén in the 1940s were discovered propagating through the Sun's turbulent lower atmosphere. These Alfvén waves were found to be travelling at speeds exceeding 20 km $s^{-1}$ and, crucially, possessed enough energy to heat the Sun's localized atmosphere to its multi-million-degree temperature (Jess *et al.*, *Science*, **323**, 1582, 2009).

The results presented here have had considerable impact on current theoretical studies. Work is now going on to marry the velocities, amplitudes, and energies established here with atmospheric models to determine the possible rôle these waves may play towards global heating. Furthermore, statistical studies are being performed to evaluate the occurrence rate of such oscillations, and establish with what types of structures they are most likely to be affiliated. With steps being taken to improve current solar facilities, it is only a matter of time until the final pieces of the heating puzzle are put together.

Finally, I would like to take this opportunity to thank the RAS for the award of the 2008 Keith Runcorn Prize. I am delighted to be given this prestigious award and I look forward to contributing to the field of astronomy in the future.

*Professor N. Weiss*. I'd like to congratulate you on that very nice result. It's really gratifying to know that there is clear evidence of Alfvén waves, but if we go beyond that to the issues you were raising, there is a problem in heating the entire corona. People talk about micro-flares and nano-flares, very small structures in magnetic fields. Do you think there's a possibility of extending this description to them?

*Dr. Jess.* In terms of instrumental abilities, there is now the development of the 4-metre-class solar telescope. So hopefully this will allow us much better spatial resolution to try and determine if these small-scale flare events are occurring, and how frequently they are occurring. But as a personal belief, I do think that the end result will be a combination. I think it may be that some small-scale reconnections may trigger waves and they may carry some of the energy. I think it's going to be a combination of both.

*Professor Weiss.* And the waves will be more important the higher you go up in the atmosphere.

*Dr. Jess.* Of course, it's tough to determine because from observations these micro-flares can occur at various heights, and so perhaps flares that occur higher up can do a lot of heating themselves. The waves that are generated at the surface can perhaps heat at various heights in the solar atmosphere.

*Professor A. Hood.* I think these observations are fantastic and they really are very important, and obviously as we get more detailed observations we're going to see a lot more, that's certainly true. I just wanted to make one little comment. In Council we've been talking a bit about impact; it is interesting to note that the theory for this was developed in 1983, and it took 26 years for the observations to get there. So the impact is only being felt now.

*Dr. Jess.* Absolutely.

*The President.* Thank you again, David. The RAS apartments will be closed until 2010 January 4 and the next A & G Meeting will be on Friday January 8. I'll finish by wishing everyone a happy Christmas and a prosperous New Year.

# SPECTROSCOPIC BINARY ORBITS FROM PHOTOELECTRIC RADIAL VELOCITIES

## PAPER 212: HD 113449, HD 113762, HD 113880, AND HD 119944

*By R. F. Griffin*
*Cambridge Observatories*

Three of the stars discussed here are binaries discovered in the Yoss/Griffin survey of all the late-type *HD* stars in the North Galactic Cap ($b > 75°$). The odd one out is HD 113449, which is in the same RA but at lower declination (−5°); it is an interesting object, a late-G dwarf known to have an active chromosphere, and an astrometric orbit has already been obtained for it by *Hipparcos*.

The orbit found here, whose period is 216 days, seems to show the astrometric period to be off by about seven times its listed standard error; the *Hipparcos* value of $\omega$, 42°, is also badly off the spectroscopic determination here of 295°. Since the observed star seems a rather innocent object to be the source of significant X-ray activity, it is speculated that the unseen secondary may be a pair of M dwarfs in an orbit of very short period.

HD 113762 and HD 113880 are particularly faint for *HD* stars (fainter than $10^{m}$); they have spectral types near G1 V and K0 III, and orbits with periods of about 4 and 1½ years and eccentricities of 0·25 and 0·56, respectively. HD 119944 is a K2 giant with a 200-day period and an orbital eccentricity of 0·4.

*Introduction*

This paper originally set out to be another that provides some orbits for stars in the North Galactic Pole (NGP) field, in which many binaries were discovered in the course of the Yoss/Griffin survey[1] of all the late-type *Henry Draper Catalogue* stars at $b > 75°$. It was decided, however, to include in the paper one star which, though in the same RA as the NGP field, is at a somewhat lower declination, and which is also related to the interest recently evinced here[2,3] in active-chromosphere binaries — indeed it is surprising that it does not feature in the *CABS3* catalogue[4] of such objects. It is still more surprising, even astonishing, that the star concerned, HD 113449, has not had its spectroscopic orbit published already, since it is well-known both spectroscopically and astrometrically to be a binary — indeed, *Hipparcos* determined an astrometric orbit; the desirability of a spectroscopic orbit has been specifically pointed out, and its short period and large amplitude make it an easy subject for such an investigation. The inclusion of the star in this paper, therefore, fulfils an expressed need.

*HD 113449*

HD 113449 is an $8^{m}$ star of *HD* type K0, to be found about 7° south-following the famous visual binary system $\gamma$ Virginis and nearly 2° preceding the fourth-magnitude $\theta$ Virginis. At a declination just below −5°, it is only just accessible to the Cambridge telescope, whose coudé configuration was designed to operate only to −5° before the onset of vignetting (and, a little lower, total obscuration) by elements of the telescope structure.

Although a great deal of photometry of the star has been published, perversely its actual magnitude and colour indices seem never to have been explicitly determined, and we have to fall back on *Hipparcos*/*Tycho* for the values $V = 7^{m}{\cdot}69$, $(B-V) = 0^{m}{\cdot}85$. The colour index is close to expectation for the *HD* spectral type, but the only MK classification, which was made early in the MK era, nominally by Moore & Paddock[5] (whose paper was actually written by Mayall) but in fact by Miss E. Pisani, is G5 V. It is clearly discordant with everything else that is known about the star, and has been the subject of a number of complaints, starting with Eggen's assertion[6] that "The star is a spectroscopic binary and the secondary component is obviously affecting $R-I$." He was referring there to the $(R-I)$ colour index being far too red for the G5 spectral type, and courteously assigned the discrepancy to an effect of the secondary star rather than to an error in the spectral classification. His assertion about the star being a spectroscopic binary was a hardening of the conclusion "Var.?" in the Moore & Paddock paper[5], which gave a mean of 0·0 km $s^{-1}$ for two velocities and a 'probable error' of the mean of no less than 6·7 km $s^{-1}$, implying that the two actually observed values of the velocity were −10·0 and +10·0 km $s^{-1}$; such a discrepancy does indeed seem fairly conclusive, since the overall 'probable error' per observation for the whole large programme of which HD 113449 formed a part was 3·6 km $s^{-1}$.

The next spectroscopic reference to HD 113449 after that of Moore & Paddock in 1950 was in 1997 by Fekel[7], who was concerned with rotational velocities. The star appears to have entered his observing list by chance; most of the stars in it were chromospherically active ones, of which his paper has a long list, but HD 113449 is in a short table of 'other stars'; it is attributed a $v \sin i$ of 5·3 km $s^{-1}$, and its radial velocity was noted as 'C:', C meaning Constant.

Shortly thereafter, two developments brought HD 113449 to astronomers' attention. One was the recognition by *Hipparcos* of the star's comparative proximity (22·1 ± 0·7 pc), and the determination of an astrometric orbit (one of only 45 for which the satellite was able to determine a full set of elements without appeal to any external information). The other was the discovery by *ROSAT* that the star is an X-ray source (no. 10685 in the 'All-sky Bright Source Catalogue'[8]), with the implication of chromospheric activity. *Simbad* is completely silent on the HD 113449–*ROSAT* connection, listing no such papers in the bibliography of the star nor any such designation among its designations or in the 'external archives' section.

The first result of those twin discoveries was the compilation by Gaidos[9] of a list of 'young solar analogs', in which he included HD 113449 by mistake, since he intended to reject binaries. In fact he referred to an "exhaustive query" of *Simbad*, and other searches, that led to the rejection on grounds of multiplicity of 22 of his original list of 61 candidates, but he retained HD 113449, having evidently overlooked *Hipparcos*'s demonstration of its binary nature. He subsequently joined forces with the Henrys, who had been monitoring a number of active stars for several seasons with an automated telescope, obtaining more than 100 measurements per season. Together, they[10] found that the star showed photometric variations that almost certainly represented its rotation period, of 6·54 days; within observational uncertainty the same period was found in four out of six seasons (in the other two the amplitude of variation was close to zero). The $v \sin i$ was put at 5·8 km $s^{-1}$. They noted that it was a 'possible Pleiades cluster' star, on the grounds that its space motion was similar to that of the cluster, but since they did not know a reliable mean radial velocity such an attribution looks to be a little premature. They also noted it as a 'possible spectroscopic binary'. Their logic is hard to follow on that point, because they say that their velocity measurements have a standard error of 0·11 km $s^{-1}$, and in one place they say that any change of as much as 1 km $s^{-1}$ in a year will identify variability, but in another place they say that HD 113449 "may be a spectroscopic binary, exhibiting a change of 20 km $s^{-1}$ in 10 months." That was certainly referring to their own radial velocities, which are not listed, and not to Moore & Paddock's[5], which they go on to mention as supporting evidence. They also found a moderately high lithium abundance in the star, with $\log N(\mathrm{Li}) = 2{\cdot}08$ on the scale with $\log N(\mathrm{H}) = 12$.

At almost the same time, Strassmeier *et al.*[11] found a rotation period of 6·47 days for the star, and gave two radial-velocity measurements, of +5·8 and +8·2 km $s^{-1}$, specifying the dates, which were a week apart. The discrepancy between the two velocities is not great enough in relation to their admitted uncertainties to demonstrate real variation. It was Strassmeier *et al.*'s paper[11], rather than Gaidos & the Henrys'[10], that galvanized Kazarovets *et al.*[12] into granting HD 113449 a variable-star designation, PX Vir; they noted it as being a BY Dra variable with an amplitude of $0^{m}\cdot04$.

Bartkevičius & Gudas[13] assigned HD 113449 to membership of the 'Local Association'; they said that its radial velocity was −6·3 ± 0·6 km s$^{-1}$, giving a number of sources, all of which were secondary and the most important of which was their own private and unpublished one. Gaidos & Gonzalez[14] also considered the star to be a member of the 'Local Association'; they gave some discussion about it, seemingly directed towards excusing its discrepancies in several respects from the proper properties for such a member.

Fekel *et al.*[15] were incautious enough to use HD 113449 as the principal photometric comparison in an investigation of the chromospherically active star HD 113816; they said that it "turned out to be variable" as if that were a surprising and unfortunate reverse, notwithstanding that one of the authors of the paper[15] was among those[10] who had specifically demonstrated its variability in four different seasons previously.

Wichmann, Schmitt & Hubrig[16] obtained one spectrum of the object in a survey of nearby young stars. They gave an (un-dated) radial velocity of +11·5 km s$^{-1}$ and a $v \sin i$ (quite discordant with most other values) of 11 km s$^{-1}$.

Zuckerman, Song & Bessell[17] assigned HD 113449 to the 'AB Dor Group'; they gave its spectral type as K1, not from any sort of spectroscopy but purely on the basis of its $(V-K)$ colour index, because they did not like its *Simbad*-listed spectral type. They gave its radial velocity as +2·0 ± 0·5 km s$^{-1}$ and its $v \sin i$ as 6 km s$^{-1}$. It is hardly surprising that Zuckerman & Song[18], in a review paper in the same year, also said that HD 113449 was a 'proposed member' of the AB Dor Group; in their listing there was a column for notes, in which many stars, but not HD 113449, were noted as binaries. Fuhrmann[19], in a paper that occupies a complete issue of *Astronomische Nachrichten*, preferred to place HD 113449 in his 'Hercules–Lyra Association'; he published tracings of the spectrum in the vicinities of H$\alpha$ and the red lithium line, and gave the star's age as 40–100 million years, its [Fe/H] as −0·14, and its $v \sin i$ as 5·2 ± 1·0 km s$^{-1}$.

Paulson & Yelda[20] made a lot of observations of some 40 stars, of which HD 113449 was one, with a highly precise radial-velocity instrument. For the relevant star they obtained a total of 15 measurements spread between eight nights, and found the r.m.s. dispersion of all the measurements to be only 0·14 km s$^{-1}$.

As if the star had not been hawked around among enough different groups already, Lopez-Santiago *et al.*[21] assigned it to the 'B4 Group' of Asiain *et al.*[22]; like Zuckerman *et al.*[17], they said that its radial velocity was +2·0 ± 0·5 km s$^{-1}$. One cannot help thinking that, since the various group assignments to the Pleiades[10], Local Association[13,14], AB Dor Group[17,18], Hercules–Lyra Association[19], and B4 Group[21] must surely depend on the calculated space motion of the star, then if the real radial (gamma-) velocity were substituted for the values that have been adopted in the past there would have to be some revision — most likely cancellation — of most of the assignments. Fuhrmann[19] did at least notice that the star was known from its *Hipparcos* orbit to be a binary, and after saying that he had made use of Gaidos *et al.*'s[10] mean radial velocity for the star he went on, "but clearly, HD 113449 requires a detailed spectroscopic orbit; until then, our derived space velocity … must be considered preliminary."

The *Gemini North* telescope was used with adaptive optics to look for close companions or planets for many stars[23], including HD 113449, but

## Table I

*Radial-velocity observations of HD 113449*

*Except as noted, the observations were made with the Cambridge Coravel*

| *Date (UT)* | *MJD* | *Velocity* *km s⁻¹* | *Phase* | *(O – C)* *km s⁻¹* |
|---|---|---|---|---|
| 1999 Feb. 13·45* | 51222·45 | −7·4 | $\bar{7}$·884 | +0·7 |
| 20·50* | 229·50 | −5·0 | ·917 | −0·1 |
| 2003 Feb. 10·13 | 52680·13 | −10·6 | 0·618 | −1·2 |
| Mar. 17·07 | 715·07 | −12·0 | ·779 | +0·2 |
| Apr. 18·99 | 747·99 | −3·5 | ·931 | −0·3 |
| May 11·98 | 770·98 | +10·3 | 1·037 | −0·1 |
| 2004 Feb. 26·19 | 53061·19 | +1·8 | 2·378 | +0·4 |
| Mar. 2·18 | 066·18 | −0·1 | ·401 | −0·3 |
| 17·13 | 081·13 | −3·4 | ·470 | −0·1 |
| 30·08 | 094·08 | −5·9 | ·530 | +0·1 |
| Apr. 14·02 | 109·02 | −9·0 | ·599 | −0·3 |
| 23·92 | 118·92 | −10·2 | ·645 | 0·0 |
| May 16·96 | 141·96 | −11·5 | ·751 | +0·8 |
| June 7·91 | 163·91 | −10·7 | ·852 | −0·5 |
| 2005 Jan. 9·18 | 53379·18 | −10·5 | 3·847 | 0·0 |
| 22·24 | 392·24 | −5·8 | ·907 | +0·1 |
| Mar. 12·15 | 441·15 | +14·0 | 4·133 | +0·4 |
| 25·08 | 454·08 | +11·2 | ·193 | −0·4 |
| Apr. 19·03 | 479·03 | +5·1 | ·308 | −0·2 |
| May 7·95 | 497·95 | +0·7 | ·395 | +0·2 |
| June 6·92 | 527·92 | −5·9 | ·534 | +0·2 |
| Dec. 17·29 | 721·29 | −0·4 | 5·427 | +0·8 |
| 2006 Jan. 27·27 | 53762·27 | −9·5 | 5·616 | −0·2 |
| Feb. 16·14 | 782·14 | −11·5 | ·708 | +0·3 |
| Mar. 23·08 | 817·08 | −9·4 | ·870 | −0·2 |
| Apr. 9·01 | 834·01 | −0·5 | ·948 | +0·6 |
| 25·99 | 850·99 | +9·1 | 6·026 | −0·2 |
| May 9·95 | 864·95 | +13·3 | ·091 | −0·2 |
| 2007 Feb. 3·22 | 54134·22 | +3·3 | 7·334 | −0·5 |
| Mar. 27·06 | 186·06 | −7·4 | ·574 | +0·4 |
| Apr. 19·04 | 209·04 | −11·3 | ·680 | −0·1 |
| 29·96 | 219·96 | −12·0 | ·731 | +0·1 |
| 2008 Feb. 2·21 | 54498·21 | +8·7 | 9·016 | +0·6 |
| Mar. 5·14 | 530·14 | +13·2 | ·163 | +0·4 |
| 31·05 | 556·05 | +6·8 | ·283 | +0·1 |
| 2009 Mar. 28·05 | 54918·05 | −0·2 | 10·955 | −0·1 |
| 29·05 | 919·05 | +0·5 | ·960 | −0·1 |
| 30·05 | 920·05 | +1·4 | ·964 | +0·2 |
| Apr. 2·07 | 923·07 | +3·2 | ·978 | 0·0 |
| 9·03 | 930·03 | +7·1 | 11·011 | −0·4 |
| 21·03 | 942·03 | +12·5 | ·066 | −0·1 |
| May 26·92 | 977·92 | +9·3 | ·232 | −0·3 |

*Published observation by Strassmeier *et al.*[11]; weight 0.

in the case of interest nothing was seen. In another effort[24] that would seem doomed to failure from the outset, the spectrum of the star was observed in the λ5800-Å region and (of course, since the object is only 22 pc away) no sign was seen of the diffuse interstellar bands at λλ5780 and 5797Å.

*New radial velocities and orbit of HD 113449*

HD 113449 was placed on the Cambridge spectroscopic-binary observing programme in 2003 because the writer noticed that *Hipparcos* had found an astrometric orbit for it and it seemed a good idea to complement that with a spectroscopic one. Although the shortness of the known period of only 231 days would in many cases promise a speedy completion of the observations, the unfavourable declination, and the very limited hour-angle range of the Cambridge telescope there, means that the observing season is short, so it has taken several years to obtain satisfactory phase coverage. The 41 available measurements are set out in Table I, and readily yield the elements shown in Table II and shown in Fig. 1; for those elements where there are corresponding astrometric quantities they too are listed for comparison. The two velocities published by Strassmeier *et al.*[11] are included at the head of Table I, where they have been subject to an adjustment of +0·8 km s$^{-1}$ in an effort to put them on the same zero-point as the Cambridge observations. They have not been utilized in the solution of the orbit, but their residuals are less than the internally estimated standard errors quoted for them.

TABLE II

*Orbital elements for HD 113449*

| *Element* | *This paper* | *Hipparcos* |
|---|---|---|
| $P$ (days) | 216·48 ± 0·06 | 231·23 ± 1·96 |
| $T$ (MJD) | 53845·3 ± 1·0 | |
| $\gamma$ (km s$^{-1}$) | −0·66 ± 0·07 | |
| $K_1$ (km s$^{-1}$) | 13·03 ± 0·10 | |
| $e$ | 0·261 ± 0.007 | 0·51 ± 0·21 |
| $\omega$ (degrees) | 294·5 ± 1·9 | 42 ± 22 |
| $a_1 \sin i$ (Gm) | 37·46 ± 0·30 | |
| $f(m)$ ($M_\odot$) | 0·0448 ± 0·0011 | |
| R.m.s. residual (km s$^{-1}$) | 0·38 | |

Although the orbital period is quite close to the *Hipparcos* determination, the latter is seen to have a very optimistic standard error. The spectroscopic period has a relatively negligible uncertainty, and differs from the *Hipparcos* value by 7·5 times the latter's quoted standard error. The longitude of periastron is off by nearly five times its supposed standard error — it is nearer to the exact opposite value than to the real one. In the light of such evidence, we would be prudent to suppose that the standard errors of the other astrometric elements, too, are under-stated; in particular, the inclination, given as 126°·48 ± 10°·76, could range all the way from edge-on to face-on (90° to 180°) if we allow a factor of five increase in the quoted error. There is also an astrometric value of $T$, but its error is so compounded with that of $\omega$ that it is scarcely worth discussing.

It seems unbelievable that Paulson & Yelda[20] could have made as many as 15 radial-velocity measurements, distributed among eight different nights, of a star that exhibits such large and rapid changes of velocity as HD 113449, and nevertheless found their results to be consonant with a constant velocity with an

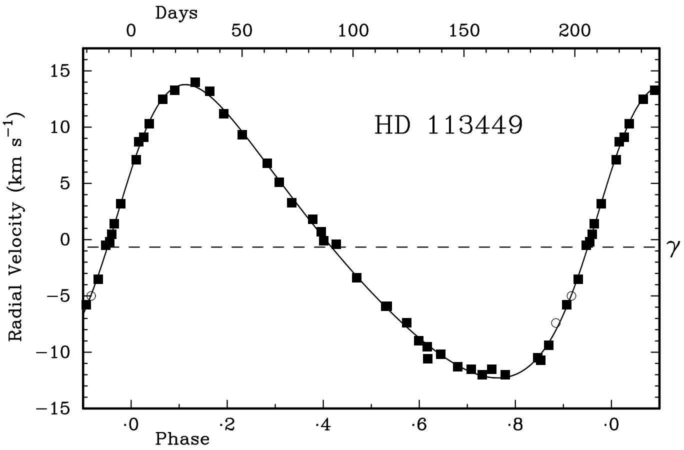


FIG. 1

The observed radial velocities of HD 113449 plotted as a function of phase, with the velocity curve corresponding to the adopted orbital elements drawn through them. Most of the observations were made with the Cambridge *Coravel* in 2003–09 and are plotted as filled squares; the two open circles represent velocities, not utilized in the solution of the orbit, that were obtained in 1999 and published by Strassmeier *et al.*[11]. They are the only dated velocities known to have been published for any of the stars treated in this paper.

r.m.s. scatter of the observations of only 0·14 km s$^{-1}$. Surely the star that they observed must not have been the one for which the orbit is reported here.

If the mass of the primary star in HD 113449 is assumed to be typical for a late-G or K0 main-sequence star, say 0·8 or 0·9 $M_{\odot}$, then the mass function requires the secondary to have a minimum mass of just over 0·4 $M_{\odot}$, corresponding to a star of early-M type. The mean $v \sin i$ derived from the 41 Cambridge traces is 4·4 ± 0·4 km s$^{-1}$. Since it seems to have been agreed that the rotation period of the star is[10,11] 6·5 days, it follows that the radius is (0·56 ± 0·06)/($\sin i$) $R_{\odot}$; if we suppose that the true radius is such as befits a star of its type, we find a value near 0·65 for $\sin i$. That implies that the true equatorial velocity of rotation is about half as much again as the measured value, but it is still quite a modest velocity and leaves scope for us to wonder whether that is all that underlies the substantial chromospheric activity that has drawn attention to the star. Of course, we know nothing about the properties of the companion star — *that* may be the real source of the X-ray activity. *If* the axial pole of the primary star is aligned with the orbital pole of the system, the $\sin i$ value that we have found for the former would require the secondary star to have a mass of about 0·75 $M_{\odot}$, appropriate to a late-K dwarf that ought not to be more than about 1$^{m}$·5 fainter than the primary. There is no sign of such a star in the radial-velocity traces, or in the tracings of the red region of the spectrum published by Fuhrmann[19] or by Destree *et al.*[24]. Duplicity of the secondary — its consisting of a pair of M dwarfs in an orbit with a period of a day or a week — would explain 'at a stroke' both its apparent absence in the visible and the activity in X-rays, but is a rather ambitious deduction to make from mainly negative evidence.

*HD 113762*

The *Simbad* bibliography knows of no papers at all that refer to HD 113762, or of any photometry or radial velocities, notwithstanding that in 1997 Yoss & Griffin published quite a useful lot of information about it in their paper[1] on the NGP field, *viz.*, its magnitudes $V = 10^{m}\cdot48$ and $(B - V) = 0^{m}\cdot61$, *DDO* photometry yielding an absolute magnitude of $+4^{m}\cdot6$ and an estimate of G1 V for the spectral type, and the information that it is a spectroscopic binary system with a γ-velocity of $-7\cdot5 \pm 0\cdot4$ km s$^{-1}$.

Miss Cannon must have been supplied with a particularly good objective-prism plate of the neighbourhood of HD 113762 (it is between ε Vir and α Com) for her *HD* classifications, because she managed to include in her catalogue stars in that vicinity that were much fainter than normal, at least in comparison with other northern-hemisphere fields. HD 113762 must be one of the faintest northern stars in the whole *Catalogue*. The area containing the faint stars is at the southern border of the NGP field as defined by the $b = 75°$ limit adopted in the Yoss–Griffin survey[1], making it the lowest in the sky as seen from Cambridge and creating real difficulty for the original radial-velocity spectrometer[25] in measuring some of the objects at all. Thus it was not until 1986, nearly 20 years after the project started, that the radial velocity of HD 113762 was first measured, and then it was with the Haute-Provence (OHP) *Coravel*, on the first occasion that the writer was privileged to have observing time on that instrument. The total number of measurements now available is 57, comprising 24, 26, and two, made with the *Coravel*s at OHP, Cambridge, and ESO, respectively, two made with the original spectrometer at Cambridge, and three with the instrument[26] at the DAO 48-inch telescope. They are set out in Table III. The OHP and ESO measures have been subject to the usual offset of +0·8 km s$^{-1}$, and are then considered to approximate to the 'Cambridge' zero-point that has been generally used in this series; the same adjustment has been made to those sources for the other two NGP stars discussed here. The Cambridge *Coravel* velocities of HD 113762 have themselves been corrected by −0·4 km s$^{-1}$ with the same intention. Velocities from the three *Coravel*s have been accorded unit weight in the solution of the orbit, whereas the 'original Cambridge' and DAO measures have been weighted ¼. With those preliminaries settled, the data yield the orbit that is plotted in Fig. 2 and has the following elements:

| | | | | | |
|---|---|---|---|---|---|
| $P$ | = | 1413·7 ± 2·5 days | $(T)_4$ | = | MJD 51150 ± 15 |
| $\gamma$ | = | −7·94 ± 0·08 km s$^{-1}$ | $a_1 \sin i$ | = | 123·4 ± 2·6 Gm |
| $K$ | = | 6·55 ± 0·13 km s$^{-1}$ | $f(m)$ | = | 0·0376 ± 0·0024 $M_\odot$ |
| $e$ | = | 0·246 ± 0·019 | | | |
| $\omega$ | = | 177 ± 4 degrees | R.m.s. residual (wt. 1) | = | 0·55 km s$^{-1}$ |

There are a few particularly bad residuals, but it usually seems best to accept the rough with the smooth rather than to try to make minor cosmetic (and probably illusory) 'improvements' to a result by special pleading for the selective deletion of offending observations.

The mass function demands for the secondary star a minimum mass of about 0·4 $M_\odot$, equivalent to that of an early-M dwarf.

HD 113762 exhibits appreciable rotation; its projected rotational velocity is found to be 4·6 ± 1·1 km s$^{-1}$ from the OHP traces and 4·9 ± 0·9 km s$^{-1}$ from the Cambridge ones. The corresponding period of rotation is about 10 sin *i* days.

TABLE III

*Radial-velocity observations of HD 113762*

*Except as noted, the sources of the observations are as follows:*
*1986–1996 — OHP Coravel ; 1997–2009 — Cambridge Coravel (both weight 1)*

| Date (UT) | MJD | Velocity km s$^{-1}$ | Phase | (O – C) km s$^{-1}$ |
|---|---|---|---|---|
| 1986 Apr. 10·96 | 46530·96 | −5·4 | 0·733 | +0·3 |
| 1987 Mar. 4·11 | 46858·11 | −16·2 | 0·964 | −0·7 |
| 1988 Jan. 31·55* | 47191·55 | −7·2 | 1·200 | +1·6 |
| Mar. 11·13 | 231·13 | −7·8 | ·228 | −0·1 |
| 17·00 | 237·00 | −7·9 | ·232 | −0·4 |
| Apr. 13·96† | 264·96 | −6·0 | ·252 | +0·9 |
| Nov. 7·21 | 472·21 | −3·3 | ·398 | +0·4 |
| 1989 Feb. 24·26‡ | 47581·26 | −3·2 | 1·475 | −0·1 |
| Apr. 28·06 | 644·06 | −3·3 | ·520 | −0·3 |
| May 27·94† | 673·94 | −2·1 | ·541 | +0·9 |
| 1990 Jan. 27·09 | 47918·09 | −5·6 | 1·714 | −0·4 |
| Feb. 12·36‡ | 934·36 | −4·8 | ·725 | +0·7 |
| 1991 Jan. 30·09 | 48286·09 | −14·8 | 1·974 | +0·9 |
| 1992 Jan. 21·25 | 48642·25 | −7·0 | 2·226 | +0·8 |
| Feb. 28·52* | 680·52 | −6·8 | ·253 | 0·0 |
| Apr. 27·09 | 739·09 | −5·3 | ·294 | +0·3 |
| June 26·96 | 799·96 | −5·5 | ·337 | −0·8 |
| 1993 Feb. 12·21 | 49030·21 | −3·1 | 2·500 | −0·1 |
| Mar. 20·18 | 066·18 | −3·3 | ·526 | −0·3 |
| July 11·91 | 179·91 | −3·2 | ·606 | +0·2 |
| Dec. 28·25 | 349·25 | −5·7 | ·726 | −0·2 |
| 1994 Feb. 16·15 | 49399·15 | −5·5 | 2·761 | +1·1 |
| May 1·05 | 473·05 | −9·3 | ·814 | −0·8 |
| Aug. 4·87 | 568·87 | −12·9 | ·881 | −1·1 |
| Dec. 13·19 | 699·19 | −15·0 | ·974 | +0·7 |
| 1995 Jan. 3·19 | 49720·19 | −16·3 | 2·988 | −0·3 |
| May 31·04 | 868·04 | −14·1 | 3·093 | −0·4 |
| June 5·99 | 873·99 | −13·9 | ·097 | −0·4 |
| 1996 Mar. 31·04 | 50173·04 | −5·5 | 3·309 | −0·2 |
| 1997 Mar. 6·15 | 50513·15 | −1·4 | 3·549 | +1·7 |
| Apr. 11·09 | 549·09 | −2·8 | ·575 | +0·4 |
| May 7·02 | 575·02 | −3·0 | ·593 | +0·3 |
| 1998 July 12·92§ | 51006·92 | −12·3 | 3·899 | +0·4 |
| 1999 Apr. 14·43* | 51282·43 | −15·2 | 4·093 | −1·5 |
| 2000 Apr. 6·02 | 51640·02 | −4·5 | 4·346 | 0·0 |
| May 7·99 | 671·99 | −3·7 | ·369 | +0·4 |
| 30·98 | 694·98 | −4·7 | ·385 | −0·8 |
| 2001 Jan. 14·20 | 51923·20 | −3·6 | 4·547 | −0·5 |
| Feb. 27·18 | 967·18 | −3·0 | ·578 | +0·2 |

TABLE III (*concluded*)

| *Date (UT)* | | *MJD* | *Velocity* km s⁻¹ | *Phase* | *(O–C)* km s⁻¹ |
|---|---|---|---|---|---|
| 2002 | Feb. 24·15 | 52329·15 | −9·7 | 4·834 | −0·3 |
| | Apr. 4·07 | 368·07 | −10·7 | ·861 | +0·1 |
| | May 5·03 | 399·03 | −11·3 | ·883 | +0·6 |
| 2003 | Jan. 11·25 | 52650·25 | −15·1 | 5·061 | −0·1 |
| | Feb. 21·12 | 691·12 | −13·9 | ·090 | 0·0 |
| | Mar. 31·99 | 729·99 | −12·6 | ·117 | 0·0 |
| | Apr. 29·07 | 758·07 | −10·8 | ·137 | +0·8 |
| | May 19·99 | 778·99 | −10·6 | ·152 | +0·3 |
| 2004 | Mar. 1·15 | 53065·15 | −3·9 | 5·354 | +0·4 |
| | Dec. 27·29 | 366·29 | −3·5 | ·568 | −0·4 |
| 2005 | May 7·96 | 53497·96 | −4·6 | 5·661 | −0·5 |
| 2006 | May 16·02 | 53871·02 | −13·5 | 5·925 | +0·4 |
| | June 11·94 | 897·94 | −15·3 | ·944 | −0·5 |
| 2007 | May 30·97 | 54250·97 | −9·6 | 6·193 | −0·6 |
| 2008 | May 19·00 | 54605·00 | −4·1 | 6·444 | −0·8 |
| 2009 | Mar. 30·08 | 54920·08 | −4·3 | 6·667 | −0·1 |
| | Apr. 22·02 | 943·02 | −4·8 | ·683 | −0·3 |
| | May 26·97 | 977·97 | −5·6 | ·708 | −0·5 |

* Observed with DAO 48-inch telescope; wt. ¼.
† Observed with original spectrometer; wt. ¼.
‡ Observed with ESO *Coravel*; weight 1.
§ Observed with OHP *Coravel*; weight 1.

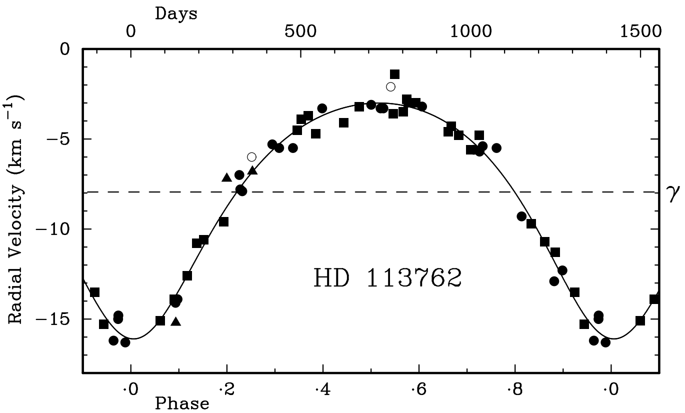


FIG. 2

As Fig. 1, but for HD 113762, except that here the open circles represent observations made by the author with the original radial-velocity spectrometer[25] at Cambridge. Additional sources of observations of this star are the OHP *Coravel* (filled circles, also used for two measurements with the ESO *Coravel*), and the spectrometer[26] at the DAO 48-inch telescope (filled triangles).

The observing records for HD 113762 include reference to a star, much fainter still, seen on occasion at a distance and position angle estimated at the eyepiece to be 25″, 120°. A more accurate, though still informal, measurement made on a picture brought up on *Vizier* puts it at 32″, 117°. Nothing else is known about the star concerned — it is too faint for its radial velocity to be measured with the available instrumentation — but the existence of another star, even at that level of brightness, *that* close to the one of interest in the sparse Galactic Pole field is a considerable coincidence.

*HD 113880*

HD 113880 is another star at the southern edge of the NGP field and is unusually faint for an *HD* star, though not as particularly so as HD 113762. The latter star is to be found about ⅖ of the way from ε Vir to α Com, the former ⅗. HD 113880 also shares with HD 113762 the distinction of having no papers whatever retrieved by the *Simbad* bibilography, but the 'measurements' section of the *Simbad* information does record a paper[27] by Oja that gives the photometry $V = 10^{m}{\cdot}11$, $(B-V) = 1^{m}{\cdot}02$, $(U-B) = 0^{m}{\cdot}92$. The information that *Simbad* overlooks by not retrieving ref. 1 includes the measurements $V = 10^{m}{\cdot}06$, $(B-V) = 1^{m}{\cdot}03$, *DDO* photometry that yields estimates of $+1^{m}{\cdot}05$ for the absolute magnitude and K0 III for the spectral type, and the fact that the star is a spectroscopic binary with a γ-velocity of $-50{\cdot}8 \pm 0{\cdot}2$ km s$^{-1}$.

Measurements of the radial velocity of HD 113880 were started much earlier than those of HD 113762; the first one was made with the 200-inch telescope in 1973. The star was less dauntingly faint for the original spectrometer, with which it was observed repeatedly, the much more favourable spectral type causing it to give good deep dips on the radial-velocity traces; in marked contrast with the situation concerning HD 113762, by the time that the first observation was made with the OHP *Coravel* in 1986 a preliminary orbit was already known. There are now 79 radial-velocity measurements in total; they are set out in Table IV. The main contributions are 20 from the original Cambridge spectrometer, 21 from the OHP *Coravel*, and 30 from the Cambridge *Coravel*; in addition there are four from the DAO spectrometer, and two each from Palomar and ESO. The *Coravel* observations have all been given unit weight in the solution of the orbit, the others ¼. The Cambridge *Coravel* measures have been adjusted by $-0{\cdot}2$ km s$^{-1}$ from the 'as reduced' values. The resulting orbit is illustrated in Fig. 3, and its elements are:

| | | | | | |
|---|---|---|---|---|---|
| $P$ | = | $575{\cdot}63 \pm 0{\cdot}23$ days | $(T)_{15}$ | = | MJD $50476{\cdot}0 \pm 2{\cdot}1$ |
| $\gamma$ | = | $-51{\cdot}01 \pm 0{\cdot}07$ km s$^{-1}$ | $a_1 \sin i$ | = | $32{\cdot}4 \pm 1{\cdot}0$ Gm |
| $K$ | = | $4{\cdot}94 \pm 0{\cdot}13$ km s$^{-1}$ | $f(m)$ | = | $0{\cdot}00410 \pm 0{\cdot}00037\ M_{\odot}$ |
| $e$ | = | $0{\cdot}561 \pm 0{\cdot}016$ | | | |
| $\omega$ | = | $346{\cdot}4 \pm 2{\cdot}4$ degrees | R.m.s. residual (wt. 1) | = | $0{\cdot}50$ km s$^{-1}$ |

The mass function does not set any interesting limit on the mass of the secondary star, and the radial-velocity traces do not indicate any measurable rotational velocity for the primary.

*HD 119944*

At eighth magnitude, this is a much brighter star than the others treated in this paper; even so, *Simbad* reports very little that has been published about it. It is at the eastern margin of the NGP field, in Boötes, nearly 3° preceding

TABLE IV

*Radial-velocity observations of HD 113880*

*Except as noted, the sources of the observations are as follows:*
*1973–1990 — original Cambridge spectrometer (weighted ¼ in orbital solution);*
*1991–1996 — OHP Coravel ; 1997–2009 — Cambridge Coravel (both weight 1)*

| Date (UT) | MJD | Velocity km s⁻¹ | Phase | (O – C) km s⁻¹ |
|---|---|---|---|---|
| 1973 June 12·19* | 41845·19 | −42·8 | 0·006 | +0·6 |
| 1978 Mar. 31·03 | 43598·03 | −43·4 | 3·051 | +2·0 |
| May 23·33* | 651·33 | −50·9 | ·144 | −1·3 |
| 1981 May 5·01 | 44729·01 | −43·0 | 5·016 | +0·5 |
| 1982 Jan. 22·27 | 44991·27 | −53·5 | 5·472 | −0·5 |
| 1983 Feb. 4·55† | 45369·55 | −50·0 | 6·129 | −0·8 |
| May 15·94 | 469·94 | −52·6 | ·303 | −0·5 |
| 1984 Jan. 9·19 | 45708·19 | −54·3 | 6·717 | −1·2 |
| Apr. 14·01 | 804·01 | −51·3 | ·884 | −0·4 |
| May 11·93 | 831·93 | −47·8 | ·932 | +0·9 |
| 1985 Jan. 24·21 | 46089·21 | −52·7 | 7·379 | 0·0 |
| Feb. 17·48† | 113·48 | −51·6 | ·421 | +1·3 |
| June 1·93 | 217·93 | −53·0 | ·603 | +0·3 |
| 1986 Jan. 25·21 | 46455·21 | −43·6 | 8·015 | −0·2 |
| Apr. 11·02‡ | 531·02 | −49·5 | ·147 | +0·2 |
| May 13·92 | 563·92 | −48·5 | ·204 | +2·4 |
| 1987 Jan. 31·20 | 46826·20 | −52·9 | 8·659 | +0·3 |
| Feb. 21·15 | 847·15 | −51·4 | ·696 | +1·7 |
| Mar. 3·12‡ | 857·12 | −54·1 | ·713 | −1·0 |
| May 7·91 | 922·91 | −51·4 | ·827 | +0·8 |
| 1988 Jan. 31·46† | 47191·46 | −52·5 | 9·294 | −0·5 |
| Mar. 11·14‡ | 231·14 | −53·6 | ·363 | −1·0 |
| Apr. 13·04 | 264·04 | −52·3 | ·420 | +0·6 |
| May 29·99 | 310·99 | −53·7 | ·502 | −0·6 |
| 1989 Feb. 11·20 | 47568·20 | −46·5 | 9·949 | +1·0 |
| 24·26§ | 581·26 | −46·0 | ·971 | −0·5 |
| Mar. 25·11‡ | 610·11 | −44·0 | 10·021 | −0·4 |
| Apr. 28·06‡ | 644·06 | −46·8 | ·080 | +0·3 |
| May 27·95 | 673·95 | −48·9 | ·132 | +0·4 |
| 1990 Jan. 31·16‡ | 47922·16 | −53·4 | 10·563 | −0·2 |
| Feb. 12·36§ | 934·36 | −53·6 | ·585 | −0·3 |
| Mar. 28·99 | 978·99 | −53·7 | ·662 | −0·5 |
| Apr. 30·01 | 48011·01 | −53·9 | ·718 | −0·8 |
| 1991 Jan. 27·13 | 48283·13 | −51·2 | 11·190 | −0·5 |
| Feb. 4·13 | 291·13 | −51·3 | ·204 | −0·4 |
| 1992 Jan. 20·17 | 48641·17 | −52·0 | 11·812 | +0·4 |
| Feb. 28·52† | 680·52 | −51·6 | ·881 | −0·6 |
| Apr. 27·09 | 739·09 | −44·9 | ·983 | −0·4 |
| June 26·96 | 799·96 | −47·6 | 12·088 | −0·1 |

TABLE IV (*concluded*)

| *Date (UT)* | | *MJD* | *Velocity km s⁻¹* | *Phase* | *(O–C) km s⁻¹* |
|---|---|---|---|---|---|
| 1993 | Feb. 12·21 | 49030·21 | −53·1 | 12·488 | 0·0 |
| | Mar. 25·05 | 071·05 | −53·0 | ·559 | +0·2 |
| | July 11·92 | 179·92 | −52·0 | ·748 | +0·9 |
| | Dec. 28·25 | 349·25 | −44·8 | 13·043 | 0·0 |
| 1994 | Feb. 16·16 | 49399·16 | −49·7 | 13·129 | −0·5 |
| | May 1·05 | 473·05 | −52·0 | ·258 | −0·3 |
| 1995 | Jan. 3·20 | 49720·20 | −52·1 | 13·687 | +1·1 |
| | June 1·96 | 869·96 | −47·4 | ·947 | +0·2 |
| 1996 | Mar. 31·05 | 50173·05 | −53·6 | 14·474 | −0·5 |
| 1997 | Mar. 6·15 | 50513·15 | −46·6 | 15·065 | −0·4 |
| | Apr. 11·09 | 549·09 | −48·7 | ·127 | +0·4 |
| | May 7·02 | 575·02 | −50·8 | ·172 | −0·5 |
| 1998 | July 24·88‡ | 51018·88 | −47·4 | 15·943 | +0·5 |
| 2000 | Apr. 6·03† | 51640·03 | −43·3 | 17·022 | +0·4 |
| 2001 | Jan. 7·25 | 51916·25 | −52·6 | 17·502 | +0·5 |
| | Feb. 27·19 | 967·19 | −53·8 | ·591 | −0·5 |
| | May 31·96 | 52060·96 | −52·2 | ·753 | +0·7 |
| 2002 | Feb. 27·10 | 52332·10 | −50·1 | 18·224 | +1·1 |
| | Apr. 4·08 | 368·08 | −51·8 | ·287 | +0·2 |
| | May 7·99 | 401·99 | −51·9 | ·346 | +0·5 |
| | June 1·01 | 426·01 | −52·9 | ·388 | −0·2 |
| 2003 | Jan. 11·25 | 52650·25 | −52·5 | 18·777 | +0·2 |
| | Mar. 19·04 | 717·04 | −51·2 | ·893 | −0·6 |
| | Apr. 18·99 | 747·99 | −47·7 | ·947 | −0·1 |
| | May 11·99 | 770·99 | −43·8 | ·987 | +0·4 |
| 2004 | Mar. 1·16 | 53065·16 | −52·8 | 19·498 | +0·3 |
| | May 22·98 | 147·98 | −53·8 | ·642 | −0·6 |
| | Dec. 27·29 | 366·29 | −44·1 | 20·021 | −0·5 |
| 2005 | Jan. 13·23 | 53383·23 | −45·2 | 20·050 | +0·1 |
| | 19·22 | 389·22 | −45·4 | ·061 | +0·6 |
| 2006 | May 11·02 | 53866·02 | −51·7 | 20·889 | −0·9 |
| | 16·01 | 871·01 | −50·8 | ·898 | −0·4 |
| | 21·98 | 876·98 | −50·5 | ·908 | −0·5 |
| | 26·98 | 881·98 | −49·6 | ·917 | 0·0 |
| | June 2·95 | 888·95 | −49·0 | ·929 | −0·1 |
| | 10·97 | 896·97 | −47·3 | ·943 | +0·6 |
| 2007 | Apr. 5·08 | 54195·08 | −52·6 | 21·461 | +0·4 |
| | May 12·99 | 232·99 | −52·9 | ·527 | +0·3 |
| 2009 | Mar. 30·09 | 54920·09 | −53·0 | 22·720 | +0·1 |
| | Apr. 22·02 | 943·02 | −53·2 | ·760 | −0·3 |

* Observed with Palomar 200-inch telescope; wt. ¼.
† Observed with DAO 48-inch telescope; wt. ¼.
‡ Observed with OHP *Coravel*; weight 1.
§ Observed with ESO *Coravel*; weight 1.

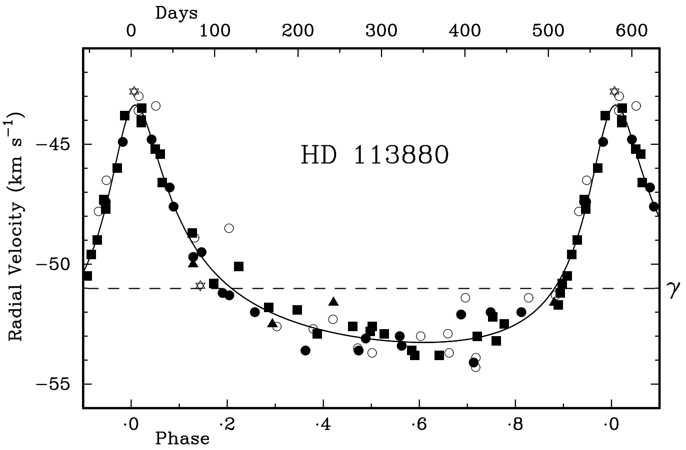


FIG. 3

As Fig. 2, but for HD 113880. In this case, there is an additional source of measurements: two made with the spectrometer at the coudé focus of the Palomar 200-inch telescope are plotted as open stars.

the fifth-magnitude star 9 Boo, which featured in the very first paper[25] on photoelectrically measured radial velocities. HD 119944 has photometry provided by Häggkvist & Oja[28]: $V = 8^{m}\cdot00$, $(B - V) = 1^{m}\cdot24$, $(U - B) = 1^{m}\cdot13$. The $V$ and $(B - V)$ given in the NGP survey[1] are $7^{m}\cdot96$ and $1^{m}\cdot24$. An MK classification of K2 III (probably made by Mrs. V. Gaizauskas) was given by Heard[29], who also reported four radial-velocity measurements, made with the 74-inch David Dunlap reflector and a prism spectrograph giving 66 Å mm$^{-1}$ at Hγ. (Because it met the selection criteria of declination, magnitude, and HD spectral type, the star featured in the large programme of radial velocities, photographic photometry, and classification that was undertaken at the David Dunlap Observatory in the years following the Second World War.) The velocities observed for HD 119944 were not sufficiently scattered in relation to the measuring error for the spectroscopic-binary nature of the star to be discovered: they were presented simply as a mean value of +13·8 km s$^{-1}$ with a 'probable error' of 2·2 km s$^{-1}$.

Velocity changes were, however, noticed in the course of a programme of radial-velocity measurement, of stars which had been discovered at the Vilnius Observatory to be metal-deficient, undertaken by Bartkevičius & Sperauskas[30] on the 1-m reflector at Mt. Maidanak Observatory in Uzbekistan with a portable *Coravel*-type instrument made by Tokovinin[31]. They reported that they had made no fewer than 23 measurements of HD 119944 in the interval 1989–1993, but they were confined to just six observing runs and so probably did not permit the derivation of an unambiguous orbit. They were not published individually; in fact the only information about them is their range, which was from +11 to +33 km s$^{-1}$.

Additional results given in the Yoss–Griffin survey[1] included *DDO*-style photometry that indicated a spectral type of K2 II–III, an absolute magnitude of $+0^{m}\cdot9$ leading to a *z* distance of 252 pc, and an [Fe/H] of −0·39. In addition, a preliminary γ-velocity of +23·2 ± 0·1 km s$^{-1}$ was listed. *Hipparcos* found a parallax of 0″·00240 ± 0″·00108 for HD 119944, putting it within a 1-σ distance range of 287 to 758 pc and giving a distance modulus of $8{\cdot}10^{+1{\cdot}4}_{-0{\cdot}8}$ magnitudes. The star is thus near zero absolute magnitude, although the determination is far from exact. Famaey *et al.*[32] included the star in their tabulation of late-type giants; they gave a mean (or it may have been intended to be a γ-) velocity of +22·23 ± 0·30 km s$^{-1}$, which was no doubt derived from such of the present writer's own observations as had been made with the OHP *Coravel* and were to be found on the corresponding data base in Geneva from which Famaey *et al.* drew their data.

The first radial-velocity observation made of HD 119944 in the NGP survey[1] was quite early, 1970, but the next was not made until 1988. The variability was discovered in that year, and the star was subsequently observed in the usual tolerably systematic fashion, until now there are the 68 velocities that are listed in Table V to serve as the basis for the orbit. There are seven observations made with the original spectrometer, 25 with the OHP *Coravel*, 32 with the Cambridge one, and two measurements each from the DAO and ESO. In the case of this star the OHP and ESO observations have been given half-weight in the solution, while the 'original Cambridge' and DAO ones have been weighted ¼ as before. On that basis the orbit illustrated in Fig. 4 is derived; its elements are:

| | | | | | |
|---|---|---|---|---|---|
| $P$ | = | 200·056 ± 0·014 days | $(T)_{53}$ | = | MJD 51180·24 ± 0·40 |
| $\gamma$ | = | +23·12 ± 0·05 km s$^{-1}$ | $a_1 \sin i$ | = | 28·42 ± 0·21 Gm |
| $K$ | = | 11·31 ± 0·08 km s$^{-1}$ | $f(m)$ | = | 0·0229 ± 0·0005 $M_{\odot}$ |
| $e$ | = | 0·407 ± 0·005 | | | |
| $\omega$ | = | 64·2 ± 1·1 degrees | R.m.s. residual (wt. 1) | = | 0·33 km s$^{-1}$ |

If the mass of the primary star is arbitrarily taken as 2 $M_{\odot}$, the mass function demands a secondary mass not less than about 0·5 $M_{\odot}$, about that of an M0 V star. It is not surprising that no evidence has been seen of it in radial-velocity traces. Those traces do, however, show very noticeable rotational broadening of the dip. The $v \sin i$ is quantified as 9·3 ± 0·4 km s$^{-1}$ from the OHP traces and as 9·2 ± 0·3 km s$^{-1}$ from the Cambridge ones. The rotation is unusually fast for a giant star, and it is tempting to suppose that the reason is related to the presence of the companion. There is no strong presumption of synchronism at the period of 200 days, but the likelihood of it is increased by the considerable eccentricity that brings the periastron separation down to less than six-tenths of the mean. At the observed eccentricity the pseudo-synchronized rotational period is shorter by a factor of about 2·1 than the orbital period and so is about 95 days. If the star really rotates in that period, then its observed $v \sin i$ shows that it has a radius of some $17/(\sin i)$ $R_{\odot}$ or $12/(\sin i)$ Gm. That is nearly three-quarters of the periastron distance calculated from $a_1 \sin i$ and $e$, but it is to be remembered that that is only the minimum distance of the primary star *from the centre of gravity*, not from the secondary star; the secondary may well be less massive (and therefore more distant from that point) by a factor of three or four, so the system is not really dramatically close and pseudo-synchronization cannot be taken for granted.

About 6′·5 south-following HD 119944 (position angle 108°), is a star equally bright but conspicuously bluer, HD 120007. It gives a wide and very shallow dip in radial-velocity traces, but it is measurable. It was observed with the original spectrometer on 1985 May 31·98, at OHP on 1991 Jan. 30·16, and with the Cambridge *Coravel* on 2006 Mar. 23·14, with results of −13·8:, −12·2, and −11·8 km s$^{-1}$, respectively. The last of those measurements showed the dip to indicate a $v \sin i$ of 17·5 km s$^{-1}$. The spectral type, estimated merely from the area of the dip, was F8 V; there does not appear to be a 'real' MK classification.

TABLE V

*Radial-velocity observations of HD 119944*

*Except as noted, the sources of the observations are as follows:*
*1988–1996 — OHP Coravel (weight ½); 1997–2008 — Cambridge Coravel (weight 1)*

| *Date (UT)* | *MJD* | *Velocity* *km s⁻¹* | *Phase* | *(O – C)* *km s⁻¹* |
|---|---|---|---|---|
| 1970 Mar. 29·17* | 40674·17 | +20·6 | 0·484 | +0·9 |
| 1988 Feb. 1·54† | 47192·54 | 19·9 | 33·067 | +0·6 |
| Mar. 13·17 | 233·17 | 14·2 | ·270 | −0·4 |
| Nov. 7·22 | 472·22 | 19·5 | 34·465 | +0·3 |
| 1989 Feb. 24·28‡ | 47581·28 | 27·9 | 35·010 | −0·4 |
| Mar. 25·14 | 610·14 | 14·4 | ·155 | +0·3 |
| Apr. 29·08 | 645·08 | 16·4 | ·329 | +0·6 |
| May 3·00 | 649·00 | 16·2 | ·349 | 0·0 |
| June 4·96* | 681·96 | 19·2 | ·514 | −1·4 |
| July 11·92* | 718·92 | 27·0 | ·698 | −0·1 |
| 1990 Jan. 31·20 | 47922·20 | 28·2 | 36·714 | +0·5 |
| Feb. 14·40‡ | 936·40 | 30·7 | ·785 | −0·3 |
| Apr. 5·04* | 986·04 | 24·6 | 37·033 | +0·4 |
| 1991 Jan. 30·16 | 48286·16 | 20·9 | 38·534 | −0·3 |
| Apr. 4·04* | 350·04 | 34·3 | ·853 | 0·0 |
| May 22·98* | 398·98 | 16·0 | 39·098 | −0·4 |
| June 13·96* | 420·96 | 13·5 | ·207 | −0·4 |
| 1992 Jan. 20·26 | 48641·26 | 15·8 | 40·309 | +0·5 |
| Feb. 27·52† | 679·52 | 20·5 | ·500 | +0·3 |
| Apr. 24·10 | 736·10 | 30·4 | ·783 | −0·5 |
| June 25·99 | 798·99 | 17·1 | 41·097 | +0·6 |
| Dec. 18·23 | 974·23 | 33·2 | ·973 | −0·7 |
| 1993 Feb. 11·20 | 49029·20 | 13·8 | 42·248 | −0·5 |
| 18·18 | 036·18 | 14·5 | ·283 | −0·3 |
| Mar. 18·15 | 064·15 | 18·1 | ·423 | +0·1 |
| July 7·98 | 175·98 | 33·4 | ·982 | +0·6 |
| 1994 Jan. 8·20 | 49360·20 | 36·5 | 43·902 | +0·3 |
| Feb. 21·16 | 404·16 | 15·0 | 44·122 | 0·0 |
| May 2·09 | 474·09 | 18·4 | ·472 | −1·0 |
| Aug. 3·89 | 567·89 | 35·2 | ·941 | −1·0 |
| 1995 Jan. 8·25 | 49725·25 | 28·1 | 45·727 | −0·2 |
| June 5·02 | 873·02 | 19·4 | 46·466 | +0·2 |
| 1996 Mar. 31·11 | 50173·11 | 34·1 | 47·966 | −0·5 |
| 1997 Mar. 1·15 | 50508·15 | 25·0 | 49·641 | +0·2 |
| 6·20 | 513·20 | 25·5 | ·666 | −0·3 |
| Apr. 16·10 | 554·10 | 34·6 | ·870 | −0·5 |
| July 19·96§ | 648·96 | 15·9 | 50·344 | −0·2 |
| 1998 May 4·09§ | 50937·09 | 31·2 | 51·785 | +0·3 |
| July 7·96§ | 51001·96 | 15·3 | 52·109 | −0·4 |
| 2000 Jan. 9·28 | 51552·28 | 34·9 | 54·860 | +0·3 |
| Feb. 11·22 | 585·22 | 25·7 | 55·024 | −0·1 |
| 14·22 | 588·22 | 23·2 | ·039 | 0·0 |
| 16·18 | 590·18 | 21·7 | ·049 | 0·0 |
| Apr. 6·08 | 640·08 | +14·9 | ·299 | −0·2 |

TABLE V (*concluded*)

| *Date (UT)* | *MJD* | *Velocity* *km s⁻¹* | *Phase* | *(O–C)* *km s⁻¹* |
|---|---|---|---|---|
| 2000 May 13·98 | 51677·98 | +19·9 | 55·488 | +0·1 |
| July 17·92 | 742·92 | 31·3 | ·813 | −1·0 |
| 2001 Mar. 12·09 | 51980·09 | 30·3 | 56·998 | −0·1 |
| 14·09 | 982·09 | 28·5 | 57·008 | −0·2 |
| Dec. 20·25 | 52263·25 | 17·5 | 58·414 | −0·3 |
| 2002 Feb. 4·26 | 52309·26 | 24·7 | 58·644 | −0·2 |
| Mar. 28·11 | 361·11 | 36·8 | ·903 | +0·6 |
| Apr. 24·05 | 388·05 | 23·9 | 59·037 | +0·3 |
| May 17·03 | 411·03 | 14·2 | ·152 | +0·1 |
| June 22·97 | 447·97 | 16·6 | ·337 | +0·7 |
| 2003 Mar. 1·19 | 52699·19 | 23·2 | 60·593 | +0·1 |
| Apr. 19·06 | 748·06 | 33·9 | ·837 | +0·4 |
| May 16·06 | 775·06 | 34·2 | ·972 | +0·2 |
| 2004 Mar. 30·12 | 53094·12 | 22·8 | 62·567 | +0·5 |
| Apr. 23·09 | 118·09 | 26·6 | ·687 | 0·0 |
| May 19·01 | 144·01 | 32·9 | ·816 | +0·4 |
| 2005 Jan. 9·25 | 53379·25 | 31·6 | 63·992 | +0·3 |
| 23·27 | 393·27 | 19·8 | 64·062 | −0·1 |
| July 16·90 | 567·90 | 36·5 | ·935 | +0·2 |
| 2006 Mar. 2·18 | 53796·18 | 18·3 | 66·076 | 0·0 |
| 23·14 | 817·14 | 13·5 | ·181 | −0·3 |
| 2007 June 2·98 | 54253·98 | 16·8 | 68·364 | +0·2 |
| 2008 Mar. 5·18 | 54530·18 | 29·2 | 69·745 | +0·1 |
| Apr. 8·10 | 564·10 | +36·4 | ·915 | 0·0 |

* Observed with original spectrometer; wt. ¼.
† Observed with DAO 48-inch telescope; wt. ¼.
‡ Observed with ESO *Coravel*; weight ½.
§ Observed with OHP *Coravel*; weight ½.

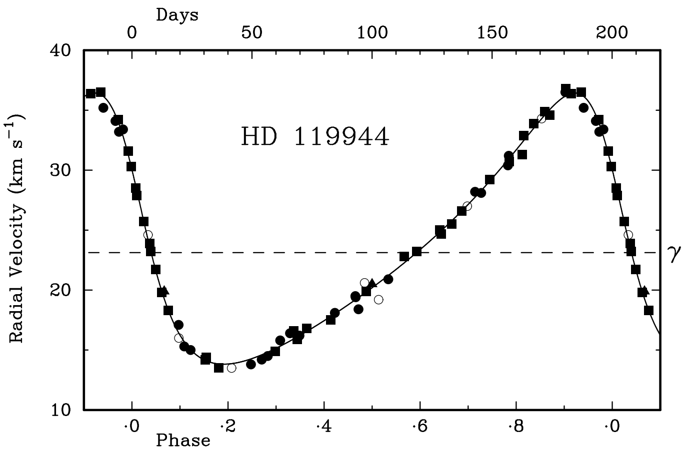


FIG. 4

As Fig.2, but for HD 119944.

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## SATELLITE-MEASURED ULTRAVIOLET COLOURS OF DWARF STARS: SENSITIVITY TO METALLICITY AND STELLAR ACTIVITY

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The *GALEX* and *TD-1* surveys have provided measurements of various ultraviolet magnitudes for a large number of F and G dwarf stars in the Milky Way. Several of these are combined with *B*-band magnitudes to form a set of colours whose sensitivity to metallicity and/or stellar activity is investigated for a sample of more than 250 F and G dwarfs. Colours involving *TD-1* magnitudes in the wavelength range 2000–2700 Å are found to be quite sensitive to metallicity once a first-order correction is made for stellar effective temperature. Levels of chromospheric activity among the dwarfs investigated here are ascertained *via* published measures of emission in the Ca II *H* and *K* lines. Among G dwarfs there is some evidence that the *GALEX* FUV bandpass could be useful as a stellar-activity indicator for stars having higher levels of chromospheric activity than the Sun. The results suggest that mid-ultraviolet photometry of dwarf stars, once calibrated for effective-temperature effects, could provide a useful stellar-populations tool if observational accuracies can be achieved at the $0^{m}\cdot05$ level.

## *Introduction*

Dwarf stars of spectral types F and G have been variously employed as tracers of the evolution of the Milky Way galaxy, often through comparative studies of attributes such as metallicity, kinematics, and age[1–6]. In studying very large numbers of stars it is often necessary to resort to metallicities derived *via* photometric means. The violet region of the spectrum of an F or G dwarf from 3000–4000 Å is crowded with metal absorption lines. At ultraviolet (UV) wavelengths shorter than 3000 Å the metallic-line blanketing becomes even stronger, and although the photospheric flux from F and G stars is greatly diminished here, this region of the spectrum holds potential for stellar-population studies[7,8,9].

The ultraviolet colours of F and G dwarfs will depend on their effective temperature, metallicity, and possibly the level of chromospheric activity. The determination of these dependencies can be investigated empirically with photometric data from space-based telescopes. In this paper several ultraviolet colours for a sample of field F and G dwarfs have been derived through use of data acquired by the *GALEX* and *TD-1* orbiting observatories.

It is well known that ground-based colours which employ bandpasses in the near-ultraviolet from 3000–4000 Å, such as $(U-B)$, are sensitive to the metallicity of late-type dwarf stars (*e.g.*, ref. 10). Extending to shorter wavelengths, magnitudes measured in the range 1700–3000 Å, where there is still significant photospheric flux from a late-type dwarf, can be combined with an optical magnitude to produce colours that would also likely be sensitive to metallicity. This region of the spectrum was sampled *via* magnitudes measured in a number of different bandpasses by the *TD-1* satellite, and by the NUV bandpass of the *GALEX* observatory.

Upon moving to wavelengths shortward of 1700 Å, the spectra of F and G dwarfs contain a number of strong emission lines that originate in hot chromospheres or transition regions, such as C IV λ1550, He II λ1640, Si IV λ1400, and C II λ1335[11]. Lines such as C IV at 1550 Å, which falls near the peak of the *GALEX* FUV bandpass, may be particularly strong, and can contribute significantly to the radiative cooling losses from the chromosphere and/or transition region. Given also the diminished photospheric component at these wavelengths, it is worth investigating whether the *GALEX* FUV fluxes of F and G dwarfs are measurably sensitive to the level of stellar activity. The *GALEX* NUV bandpass is much broader (extending from 1800 Å to 2900 Å) than the FUV band, and although it contains some strong emission lines found in late-type stars, such as Mg II λ2800 and Si II λ1815, it will sample a much larger component of stellar photospheric flux than the FUV band.

*The stellar sample chosen for investigation*

In order to investigate the UV colours of F and G dwarfs, it was decided to utilize a sample of stars for which a variety of ancillary data had been compiled by Karatas & Schuster[12] (hereafter KS06). In their programme the *UBV* photometry of 514 dwarf stars was calibrated against metallicity and absolute magnitude. In order to achieve the first of these calibrations the KS06 sample covers a wide range of [Fe/H] abundance, making it a useful one with which to study the metallicity sensitivity of shorter-wavelength UV colours. In addition to compiling *UBV* data and spectroscopic metallicities (mainly from the catalogue of Cayrel de Strobel, Soubiran & Ralite[13] supplemented with more recent high-resolution spectroscopic measurements from the literature), KS06 calculated absolute magnitudes using *Hipparcos* parallaxes, and derived values for the $E(B-V)$ reddening through the use of Strömgren photometry. The reader is referred to the KS06 paper for a list of sources for their compiled metallicities. Dwarf stars populating the metallicity interval $-1{\cdot}0 \leq$ [Fe/H] $\leq 0{\cdot}0$ are found throughout the entire $(B-V)$ colour range of the KS06 sample, with a few stars having [Fe/H] $< -1{\cdot}0$.

Information on the levels of chromospheric activity among many of the stars in the KS06 sample can be obtained from the literature in the form of the parameter log $R'_{HK}$, which specifies the flux in the Ca II $H$ and $K$ emission lines originating from the chromosphere of a star (corrected for any photospheric contribution) relative to the bolometric flux. This index is defined from measurements made on the system of the Mount Wilson $H$–$K$ survey[14,15], and has been measured in a number of high-resolution spectroscopy studies published in the literature. Values of log $R'_{HK}$ for stars in the KS06 sample were searched for, mainly among a number of principal sources[16–23]. In cases where measurements were found in two or more sources they have been averaged. As shown by Jenkins *et al.*[24], the values of Gray *et al.*[20,21] have small systematic differences from the standard Mount Wilson system. These have been compensated for by adding zero-point offsets of 0·11 and 0·06 to the Gray *et al.*[20] and Gray *et al.*[21] indices, respectively.

The resulting averaged values of log $R'_{HK}$ for the KS06 dwarfs show no obvious correlation with metallicity (Fig. 1). Therefore, the KS06 sample provides a useful one with which to assess any sensitivity of UV colours to either of these stellar characteristics. Of the most metal-poor stars in the sample with [Fe/H] $< -1{\cdot}0$, all but two have $(B-V)$ colours bluer than $0^{m}{\cdot}6$. However, among the stars with [Fe/H] $> -1{\cdot}0$ there is no obvious correlation between metallicity and $(B-V)$. Dwarfs with log $R'_{HK} < -4{\cdot}8$ are classified as chromospherically "old" by Vaughan[14], and likely have ages greater than log $t$(yr) $\approx 9{\cdot}4$ according to correlations presented by Soderblom, Duncan & Johnson[18]. For comparison, the Sun has[16] log $R'_{HK} \sim -4{\cdot}94$. The small number of KS06 stars with [Fe/H] $\leq -0{\cdot}9$ for which Ca II emission indices are available all have very low levels of activity, consistent with those stars being either old disc or halo objects.

*Ultraviolet magnitudes from the GALEX and TD-1 satellite observatories*

The *Catalogue of Stellar UV Fluxes* by Thompson *et al.*[25] provides flux data measured by the *S2/68 Ultraviolet Sky Survey Telescope* on board the ESRO *TD-1* satellite for many of the stars in the KS06 sample. This joint Belgian/UK instrument, described by Boksenberg *et al.*[26] and Humphries *et al.*[27], scanned the entire sky, producing flux measurements for 31 215 stars in four passbands. Three of these bandpasses had effective widths of 330 Å, with central wavelengths of 2365, 1965, and 1565 Å, while a fourth channel centred on

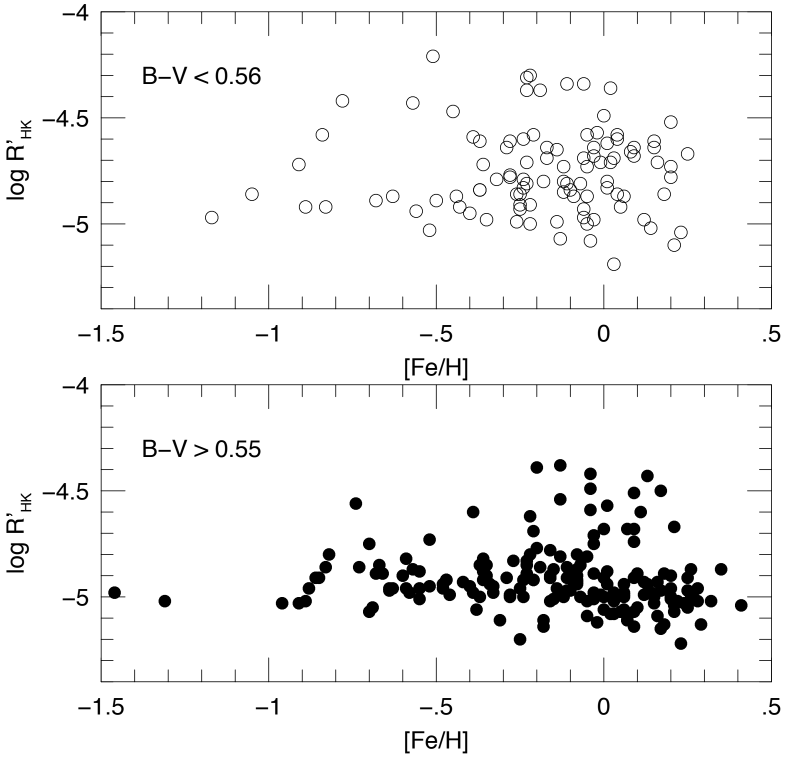


FIG. 1.

The Ca II *H* and *K* line emission index log $R'_{HK}$ *versus* metallicity [Fe/H] for dwarf stars in the KS06 sample. The upper and lower panels show stars of different effective-temperature ranges, as distinguished by two selections in $(B-V)$ colour.

2740 Å had a slightly narrower width of 310 Å. Measured fluxes $F_\lambda$, and flux errors $\sigma(F_\lambda)$, were obtained using the *VizieR* catalogue-searching service[28], and converted to the magnitude system of Haynes & Latham[29] *via* the equations

$$m_\lambda = -2{\cdot}5 \log_{10} F_\lambda - 21^{\rm m}{\cdot}175,$$

and

$$\sigma(m_\lambda) = 1{\cdot}086\ \sigma(F_\lambda)/F_\lambda,$$

where $F_\lambda$ is the flux measured in the passband of central wavelength $\lambda$, expressed in units of erg cm$^{-2}$ s$^{-1}$ Å$^{-1}$, $\sigma(F_\lambda)$ refers to the standard error in $F_\lambda$, and the second equation is derived *via* differentiation of the former. Magnitudes in one or more bandpasses were derived from the Thompson *et al.*[25] catalogue for a total of 281 stars in the KS06 sample, with the number of useful measurements being greater for the longer-wavelength bandpasses. The observational uncertainties $\sigma(m_{2740})$ and $\sigma(m_{2365})$ in the two longest-wavelength bandpasses are plotted in Fig. 2 as a function of the relevant *TD-1* apparent magnitude for stars in the KS06 sample. There are very few stars in the KS06 survey with $(B-V) > 0^{\rm m}{\cdot}7$

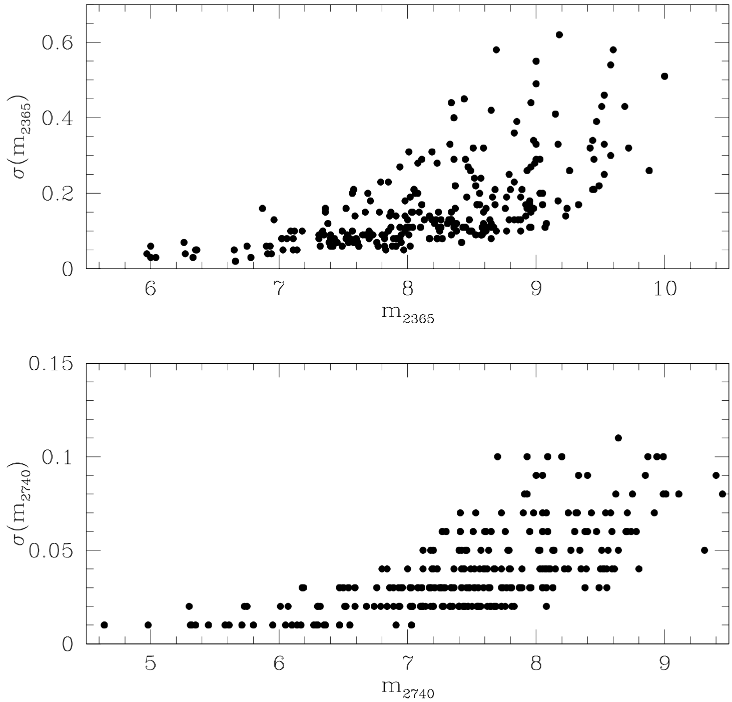


FIG. 2.

The uncertainties $\sigma(m_{2365})$ and $\sigma(m_{2740})$ in *TD-1* apparent magnitudes for stars from the compilation of KS06 are plotted in the upper and lower panels, respectively, as a function of the observed $m_{2365}$ and $m_{2740}$ magnitudes.

for which useful *TD-1* fluxes were recorded.

The *GALEX* All Sky Survey has provided FUV and NUV magnitudes for a wide variety of stars in bandpasses having effective wavelengths of 1516 and 2267Å, respectively. Measurements of *GALEX* apparent magnitudes, denoted here as $m_{\rm FUV}$ and $m_{\rm NUV}$, for stars in the KS06 list were obtained by using the *GALEX* Main Search Form (accessed *via* the web site http://galex.stsci.edu/GR4) in conjunction with the GR4/GR5 Data Release. *GALEX* magnitudes[30] are expressed in the AB system of Oke & Gunn[31]. Sources in the *GALEX* database were sought within 0·2 arcmin of each star in the KS06 compilation. No restriction was placed on sources that were imaged near the edge of a field of view. However, instances of multiple observations in which FUV or NUV magnitudes were more discrepant than $0^{\rm m}\!\cdot\!6$ were generally omitted from further consideration. Measurements of *GALEX* FUV data were obtained for 270 stars from the KS06 sample, and NUV data for 247 stars. In addition, the interstellar reddening as given by the GR4/GR5 database was also compiled.

There were 73 stars for which either two or three measurements were available for the FUV magnitude, and 65 stars with multiple NUV magnitude measurements. Following statistical precepts applicable to very small samples, the standard deviation σ among such multiple measurements was estimated from the range $R$ between the minimum and maximum values ($\sigma = R/1{\cdot}128$ and $\sigma = R/1{\cdot}693$ for two and three measurements, respectively[32]). The averages of the standard deviations calculated in this manner are $\bar{\sigma}(m_{\rm FUV}) = 0^{\rm m}{\cdot}20$ and $\bar{\sigma}(m_{\rm NUV}) = 0^{\rm m}{\cdot}26$.

The *GALEX* data base lists an estimate of the $E(B-V)$ reddening for each source based on the 100-μm dust-emission maps and calibrations derived by Schlegel, Finkbeiner & Davis[33]. These estimates are compared with values derived by KS06 in Fig. 3, where the *GALEX* catalogue values are labelled as $e(b-v)$. The formal procedure used by KS06 to determine $E(B-V)$ for the majority of stars in their sample involves comparing an observed $(b-y)$ colour with a calibration of intrinsic $(b-y)_0$ *versus* the Strömgren-system β index. Each derived reddening $E(b-y)$ was converted to an $E(B-V)$ value. This technique in some cases produces negative values for the reddening, and these are plotted accordingly in Fig. 3. Such stars are considered by KS06 to be unreddened. In cases where Strömgren photometry was not available to KS06 (129 stars), they adopted values of $E(B-V)$ based on the Schlegel, Finkbeiner & Davis[33] maps. Reddenings determined by KS06 are often substantially smaller than those

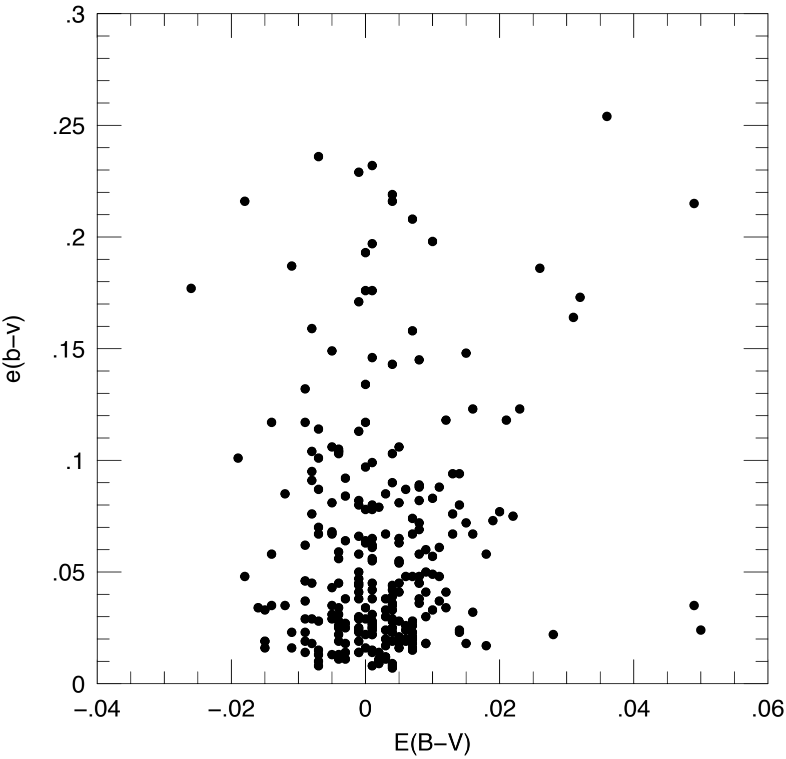


FIG. 3.

The reddening obtained from the *GALEX* website, denoted $e(b-v)$, *versus* the reddening $E(B-V)$ derived by KS06.

listed in the *GALEX* database, and there is no obvious correlation between the two sets of values in Fig. 3. This is perhaps to be expected given that the 100-$\mu$m maps reflect the integrated interstellar dust along a line of sight, whereas most of the stars in the KS06 compilation are relatively close to the Sun, which sits within a region of reduced local obscuration. According to Knude & Høg[34], the interstellar reddening is typically $E(B-V) \leq 0^{m}\cdot 1$ within the Local Bubble for distances out to 75 pc from the Sun, although sight lines of higher reddening do occur. Only about 30 stars in the KS06 compilation (6% of the sample) are more distant than this. Many of the larger values of $e(b-v)$ shown in Fig. 3 are therefore likely to be overestimates. In view of the lack of consistency between the two sets of reddening measures, no effort has been made here to correct either the *GALEX* or *TD-1* apparent magnitudes or the $(B-V)$ colour for extinction.

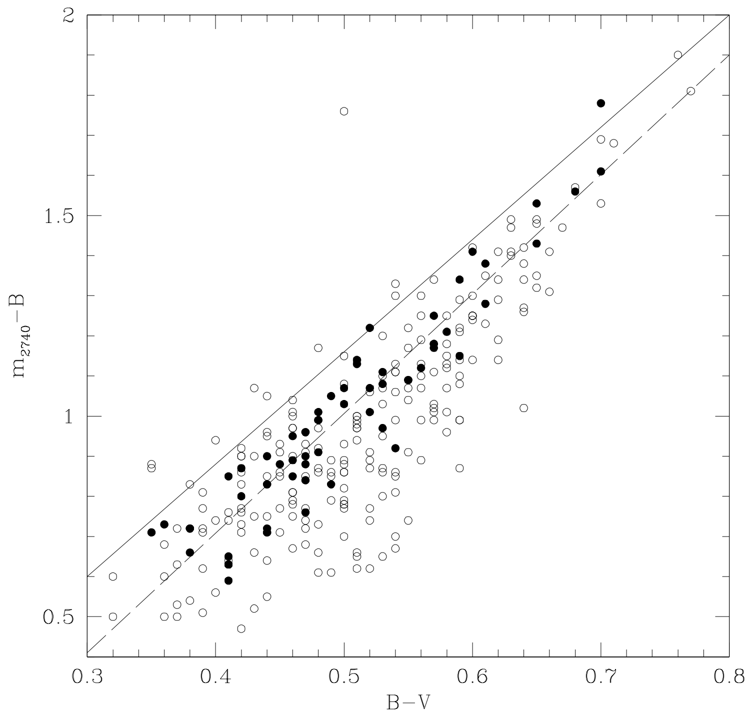


FIG. 4.

The $(m_{2740}-B)$ colour *versus* $(B-V)$ for dwarfs in the study of KS06. The solid line is an eye-estimated upper envelope to the bulk of the data points. Filled circles depict stars having [Fe/H] = 0·00 ±0·05 dex, with open circles corresponding to stars outside this metallicity range. The dashed line gives a least-squares fit to the data for the former group of stars with near-solar metallicity. The anomalous star in this figure at $(B-V) = 0^{m}\cdot 50$ with a very red $(m_{2740}-B)$ colour is HD 205420. It has a metallicity of [Fe/H] = −0·07. In Fig. 5 it sits on the locus adopted for the upper envelope to the data, and as such does not appear to be discrepant in the $(m_{2365}-B)$ colour.

*The TD-1 colours*

The four *TD-1* magnitudes obtained from the Thompson *et al.*[25] data were combined with ground-based measurements of Johnson *B*-band magnitudes to produce four colours denoted $(m_\lambda - B)$, where λ refers to the central wavelength of a particular *TD-1* bandpass.

A plot of $(m_{2740} - B)$ versus $(B - V)$ is presented in Fig. 4. Two features stand out: (*i*) there is a range of $0^m\cdot4$ to $0^m\cdot5$ in $(m_{2740} - B)$ colour at a given $(B - V)$, and (*ii*) superimposed on this scatter is a likely trend with $(B - V)$. Part of the scatter will be due to observational errors and differences in interstellar reddening. The typical error in $m_{2740}$ ranges from $0^m\cdot01$ to $0^m\cdot10$ for most of the stars in the KS06 sample (see Fig. 2). At a wavelength of 2740 Å the interstellar extinction given by Nandy *et al.*[35] is $A_{\lambda2740} = 6\cdot1\,E(B - V)$. Reddening differences of $\Delta E(B - V) = 0^m\cdot10$ between stars in the KS06 sample, at the upper limit of what might be expected based on Fig. 3, would therefore be accompanied by differences in reddening of $\approx 0^m\cdot2$ in $(m_{2740} - B)$. Thus, variations in observational error and reddening still leave a considerable margin for intrinsic scatter in the $(m_{2740} - B)$ colours of the KS06 dwarfs.

A dependence of $(m_{2740} - B)$ on effective temperature causes a mean correlation with $(B - V)$ to be evident in Fig. 4. This can be illustrated in two ways, one of which is by the eye-estimated upper envelope to the data points depicted by the solid line in Fig. 4. Stars with near-solar metallicities ([Fe/H] $= 0\cdot00 \pm 0\cdot05$) are plotted in the figure with filled circles, while stars with metallicities outside this range are depicted by open circles. A least-squares fit to the former stars has the equation $(m_{2740} - B) = -0^m\cdot486 + 2\cdot986(B - V)$, which is shown by the dashed line in Fig. 4. It is offset from, but reasonably parallel to, the eye-estimated upper envelope of the KS06 stars. The offset is presumably a consequence of the metallicity effect described below and the fact that a significant number of the KS06 dwarf stars have above-solar metallicity.

An analogous plot of $(m_{2365} - B)$ against $(B - V)$ is shown in Fig. 5. The two panels present the same data but with the plotted symbols coded differently. In the lower panel the points are chosen to denote metallicity in analogy with Fig. 4, the filled circles again depicting stars of near-solar metallicity ([Fe/H]$= 0\cdot00 \pm 0\cdot05$). In the upper panel the symbols are coded on the basis of the observational uncertainty in the *TD-1* measurements of the $m_{2365}$ magnitude; the filled squares correspond to stars with uncertainties $\sigma(m_{2365}) \leq 0^m\cdot15$, while open squares show stars for which these uncertainties exceed $0^m\cdot15$. The features seen in Fig. 5 are similar to those of Fig. 4, namely, there is a dispersion in $(m_{2365} - B)$ superimposed on a mean trend with $(B - V)$. The spread at a given $(B - V)$ can amount to $1^m\cdot6$ or more. The larger scatter in $(m_{2365} - B)$ relative to $(m_{2740} - B)$ is in part due to the greater uncertainty in the $m_{2365}$ measurements. The error in $m_{2365}$ can be up to $0^m\cdot6$ for the faintest stars in the KS06 sample (Fig. 2), around six times as large as the largest uncertainties in $m_{2740}$. However, the upper panel of Fig. 5 demonstrates that the stars for which the $m_{2365}$ magnitude uncertainties are least ($\sigma(m_{2365}) \leq 0^m\cdot15$) nonetheless exhibit a comparable scatter to the KS06 sample as a whole. Thus it would seem that the dispersion in $(m_{2365} - B)$ at a given $(B - V)$ can only partially be attributed to observational error. To test for any intrinsic component to the scatter in both Figs. 4 and 5 we look for correlations with the [Fe/H] metallicity.

In Fig. 6 plots are shown of both $(m_{2740} - B)$ and $(m_{2365} - B)$ *versus* [Fe/H] for stars in the restricted colour range $0^m\cdot48 \leq (B - V) \leq 0^m\cdot52$. There are clear correlations in both plots. These results indicate that for F dwarfs the NUV

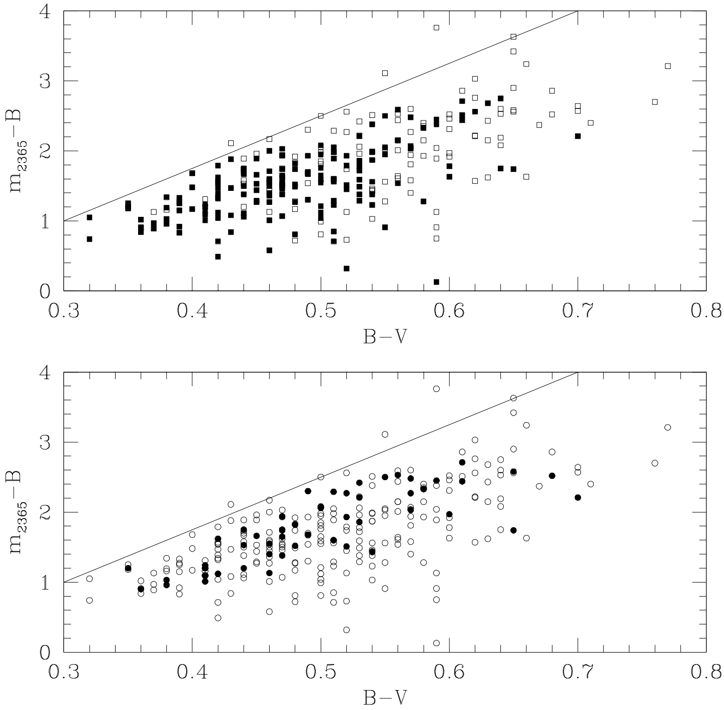


FIG. 5.

The $(m_{2365} - B)$ colour *versus* $(B - V)$ for stars in KS06. The solid line is an eye-estimated upper envelope to the data. In the lower panel the filled circles correspond to stars having near-solar metallicities of [Fe/H] = 0·00 ±0·05 dex, whereas open circles denote stars with metallicities outside this range. In the upper panel the symbols are coded according to the uncertainty in the $m_{2365}$ magnitudes, with filled and open squares corresponding to stars for which $\sigma(m_{2365})$ is ≤ $0^{m}\cdot15$ or greater than $0^{m}\cdot15$, respectively.

spectrum is very sensitive to metal-line blanketing. A least-squares regression of $(m_{2365} - B)$ against [Fe/H] for the stars in Fig. 6 with [Fe/H] > −0·90 has a slope of $d(m_{2365} - B)/d$[Fe/H] = $1^{m}\cdot55$ dex$^{-1}$ with a 1σ uncertainty of $0^{m}\cdot24$ dex$^{-1}$. This fit is shown by the solid line in the figure. By contrast the $(m_{2740} - B)$ colour is not as metallicity sensitive, with a least-squares fit for [Fe/H]> −0.90 (solid line in the lower panel of Fig. 6) giving a slope of $d(m_{2740} - B)/d$[Fe/H] = $0^{m}\cdot45$ dex$^{-1}$ (σ = $0^{m}\cdot08$ dex$^{-1}$). Turning to colours derived from shorter-wavelength *TD-1* magnitudes, neither the $(m_{1965} - B)$ or $(m_{1565} - B)$ data were found to correlate with [Fe/H] for KS06 dwarfs with $0^{m}\cdot48 \le (B - V) \le 0^{m}\cdot52$, perhaps partly on account of the larger errors in the λ1965 and λ1565 magnitude measurements.

Whether colours such as those derived from the *TD-1* data have potential for use as metallicity indicators will depend on their sensitivity to [Fe/H], the accuracy with which they can be measured, and how well their variation with effective temperature can be accounted for. In order to attain a photometric

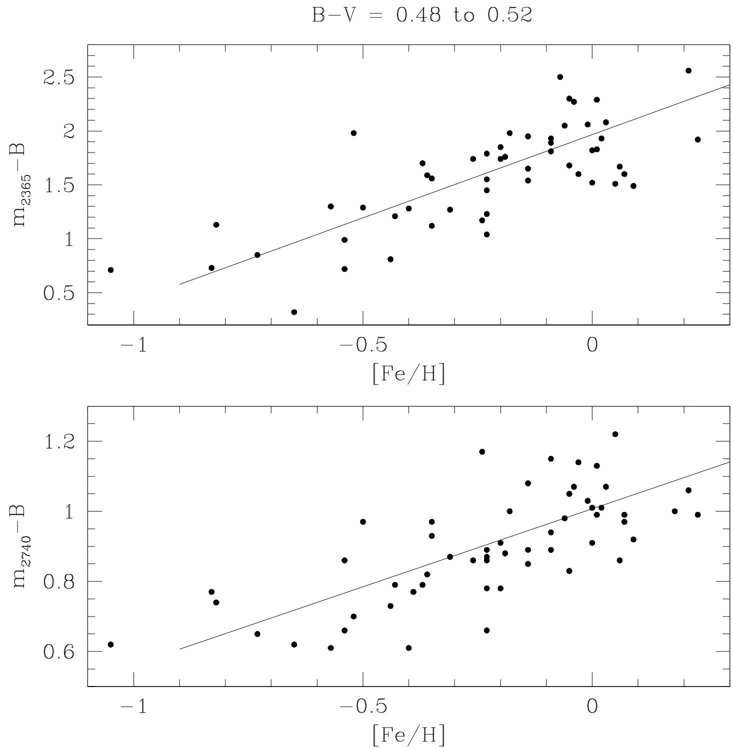


FIG. 6.

The $(m_{2365} - B)$ and $(m_{2740} - B)$ colours (top and bottom panels respectively) *versus* [Fe/H] for dwarf stars with $0^{m}{\cdot}48 \leq (B - V) \leq 0^{m}{\cdot}52$ from the sample of KS06. The solid lines show least-squares fits calculated from the plotted data points over the metallicity range $-0{\cdot}9 < [Fe/H] < 0{\cdot}3$.

metallicity accuracy of 0·1 dex for an F5 dwarf, the $(m_{2740} - B)$ and $(m_{2365} - B)$ colours would have to be measured to 3σ accuracies of $\approx 0^{m}{\cdot}05$ and $0^{m}{\cdot}15$, respectively.

An attempt to explore a first-order compensation for effective temperature was made by measuring colour residuals relative to the upper envelopes shown in Figs. 4 and 5 as solid lines. Each residual was defined as the envelope colour at a given $(B - V)$ minus the colour observed for a star of that $(B - V)$. With this definition, the bluer a star at a fixed $(B - V)$ the larger is the colour residual. The resultant $\delta(m_{2740} - B)$ and $\delta(m_{2365} - B)$ residuals are plotted against [Fe/H] in Figs. 7 and 8 for KS06 stars with $0^{m}{\cdot}45 \leq (B - V) \leq 0^{m}{\cdot}65$. The sensitivity of $\delta(m_{2740} - B)$ to metallicity is clearly apparent in Fig. 7. Filled and open symbols denote stars in the colour ranges $0^{m}{\cdot}45 \leq (B - V) \leq 0^{m}{\cdot}55$ and $0^{m}{\cdot}55 < (B - V) \leq 0^{m}{\cdot}65$, respectively. Both groupings appear to follow much the same relation between $\delta(m_{2740} - B)$ and [Fe/H]. The relationship in Fig. 7 may be non-linear over the 2·0 dex metallicity range covered by the KS06 stars. The range in $\delta(m_{2740} - B)$ at [Fe/H] = 0 is $\sim 0^{m}{\cdot}3$, or about three times the observational

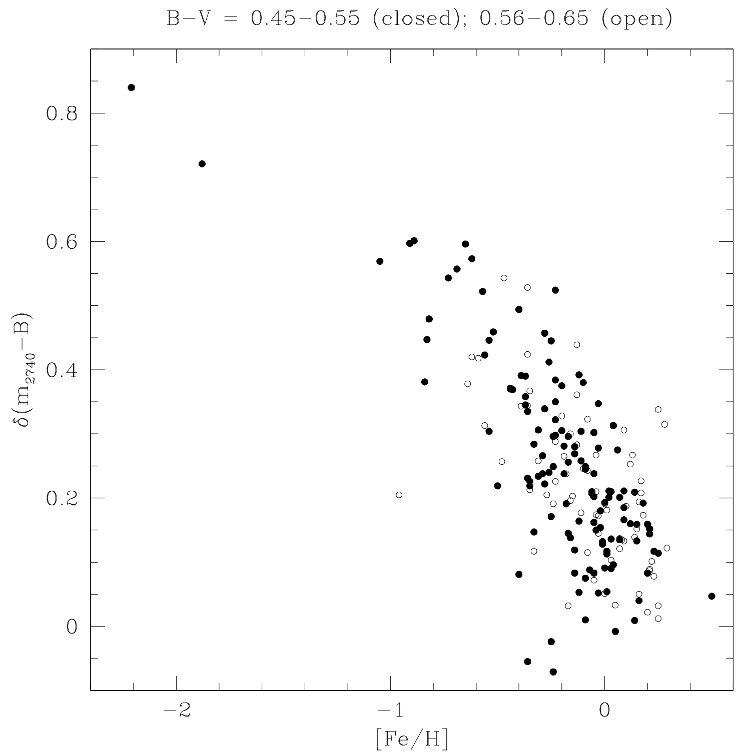


FIG. 7.

The $\delta(m_{2740} - B)$ residual, measured relative to the solid line in Fig. 4, *versus* [Fe/H] for dwarf stars with colours in the range $0^{m}{\cdot}45 \leq (B-V) \leq 0^{m}{\cdot}65$ from the sample of KS06. Filled circles denote stars with $0^{m}{\cdot}45 \leq (B-V) \leq 0^{m}{\cdot}55$, while open circles correspond to $0^{m}{\cdot}56 \leq (B-V) \leq 0^{m}{\cdot}65$. The discordant star with [Fe/H] = −0·96 and $\delta(m_{2740} - B) = 0^{m}{\cdot}205$ is HD 201889, which is listed as a double star in the *Simbad* database. It falls just off the top of the upper panel of Fig. 8, in a place that is not unusual.

error in $(m_{2740} - B)$ for the faintest stars in the KS06 sample. It is possible that the scatter about the correlation in Fig. 7 could be dominated by observational error and variations in interstellar reddening.

Fig. 8 shows $\delta(m_{2365} - B)$ *versus* [Fe/H], with the stars again separated into two $(B-V)$ colour ranges: $0^{m}{\cdot}45$–$0^{m}{\cdot}55$ (bottom panel, filled circles) and $0^{m}{\cdot}56$–$0^{m}{\cdot}65$ (top panel, open circles). The hotter dwarfs in the bottom panel do show a correlation between $\delta(m_{2365} - B)$ and metallicity, with the λ2365 residual differing by $\approx 1^{m}{\cdot}5$ on average between [Fe/H] = −1·0 and 0·0. The cooler dwarfs in the upper panel of Fig. 8 show a greater scatter, which together with the more limited range in [Fe/H] among these stars tends to obscure any potential colour–metallicity relationship.

*The GALEX colours*

Two colours were formed from the *GALEX* photometry by comparing the NUV and FUV magnitudes with those in the *B* band: $(m_{\rm NUV} - B)$ and

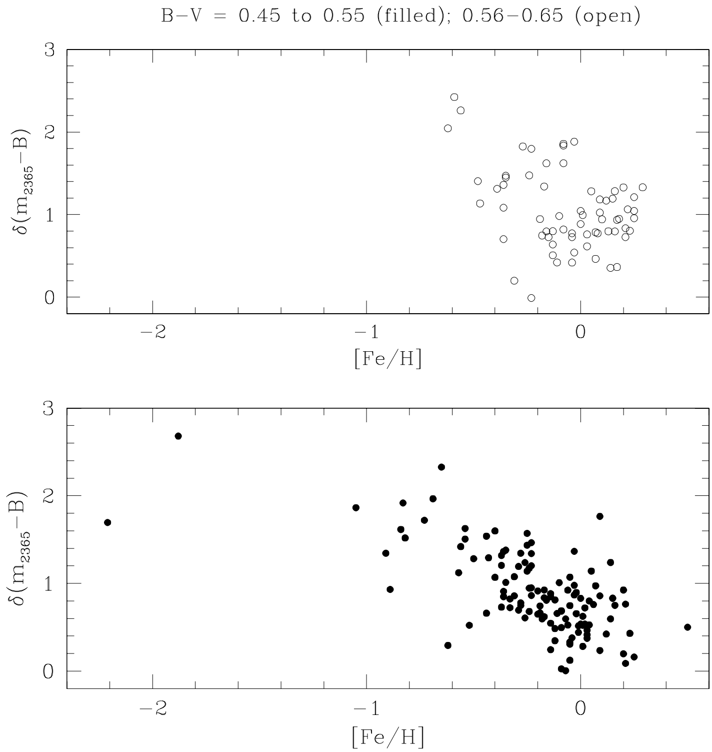


FIG. 8.

The $\delta(m_{2365} - B)$ residual *versus* [Fe/H] for dwarf stars from KS06. The top and bottom panels show stars in different effective temperature ranges corresponding to $0^{m}{\cdot}56 \le (B - V) \le 0^{m}{\cdot}65$ and $0^{m}{\cdot}45 \le (B - V) \le 0^{m}{\cdot}55$, respectively.

$(m_{FUV} - B)$. A problem with interpreting the former colour for stars in the KS06 sample is that for most of them the $m_{NUV}$ magnitude is bright enough to be in the range where the performance of the *GALEX* NUV detector is non-linear[30]. Fig. 9 shows $(m_{NUV} - B)$ *versus* [Fe/H] for stars in the KS06/*GALEX* overlap sample having apparent magnitudes of $m_{NUV} \ge 14^{m}{\cdot}0$. At these magnitudes the non-linearity effects in the NUV detector are small according to Morrissey *et al.*[30] (see their Fig. 8). This group of KS06 dwarfs has an intrinsic colour range of $0^{m}{\cdot}60 < (B - V) < 0^{m}{\cdot}85$, and a check was made to verify that there is no correlation between $(B - V)$ and [Fe/H] among them. Thus the trend seen in Fig. 9 implies that the *GALEX*-based $(m_{NUV} - B)$ colour of G dwarfs is sensitive to metallicity. However, the KS06 sample of stars is not appropriate for calibrating this effect. A sample of fainter dwarfs with spectroscopic metallicities is needed for that purpose.

There are only a few stars in the KS06 sample for which the $m_{FUV}$ magnitude is bright enough that non-linearity in the FUV detector is a concern.

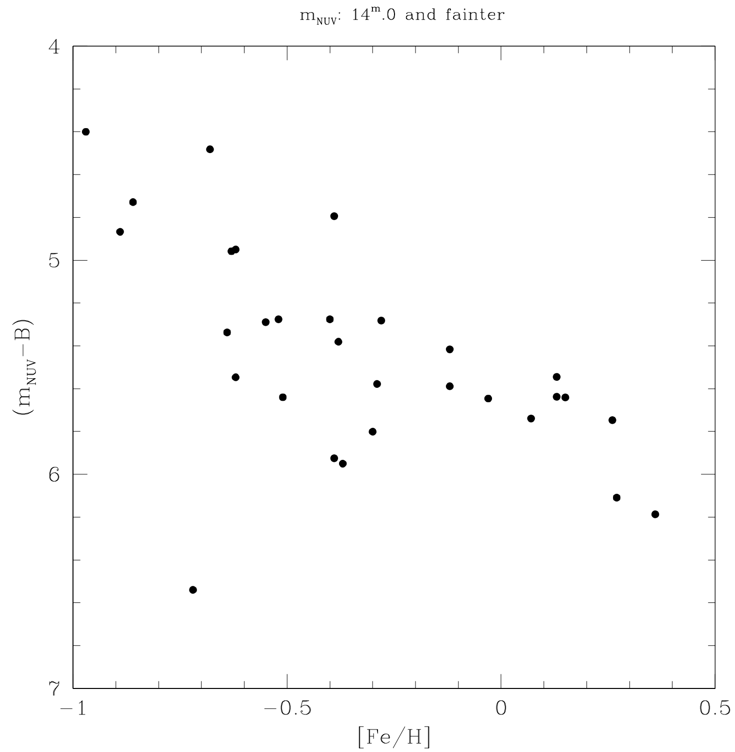


Fig. 9.

The $(m_{\rm NUV} - B)$ colour *versus* [Fe/H] for dwarfs from KS06. Only stars with *GALEX* apparent magnitudes of $m_{\rm NUV} \geq 14^{\rm m}{\cdot}0$ are shown in this plot in order to minimize the effects of detector non-linearity. The low point at [Fe/H] $= -0{\cdot}72$ depicts HD 18235.

The $(m_{\rm FUV} - B)$ colour for these stars is plotted against $(B - V)$ in Fig. 10. A linear least-squares fit for stars with $(B - V) \leq 0^{\rm m}{\cdot}60$ has the equation $(m_{\rm FUV} - B)_{\rm lsq} = 1^{\rm m}{\cdot}701 + 16{\cdot}473\ (B - V)$, which is shown as a solid line in the figure. Among redder dwarfs in the KS06 sample the scatter is somewhat larger, such that a fit-by-eye is shown which was chosen to pass through the points $(B - V, m_{\rm FUV} - B) = (0^{\rm m}{\cdot}6, 11^{\rm m}{\cdot}585)$ and $(0^{\rm m}{\cdot}90, 13^{\rm m}{\cdot}5)$. Residuals $\delta(m_{\rm FUV} - B)$ were calculated about these straight lines, and are shown plotted against metallicity in Fig. 11 and against the chromospheric activity index log $R'_{HK}$ in Fig. 12. This residual is defined such that a negative value indicates a star that has a bluer-than-average $(m_{\rm FUV} - B)$ colour compared to other stars of the same $(B - V)$. In the former figure the samples are split into groups bluer than $(B - V) = 0^{\rm m}{\cdot}56$ (top panel) and redder than $(B - V) = 0^{\rm m}{\cdot}55$ (bottom panel). There is no obvious trend with [Fe/H] in either group.

Dwarfs in the KS06 sample with $(B - V) < 0^{\rm m}{\cdot}56$ appear to show no correlation between $\delta(m_{\rm FUV} - B)$ and the chromospheric indicator log $R'_{HK}$. Among the dwarfs with $(B - V) > 0^{\rm m}{\cdot}55$, however, the $\delta(m_{\rm FUV} - B)$ residual

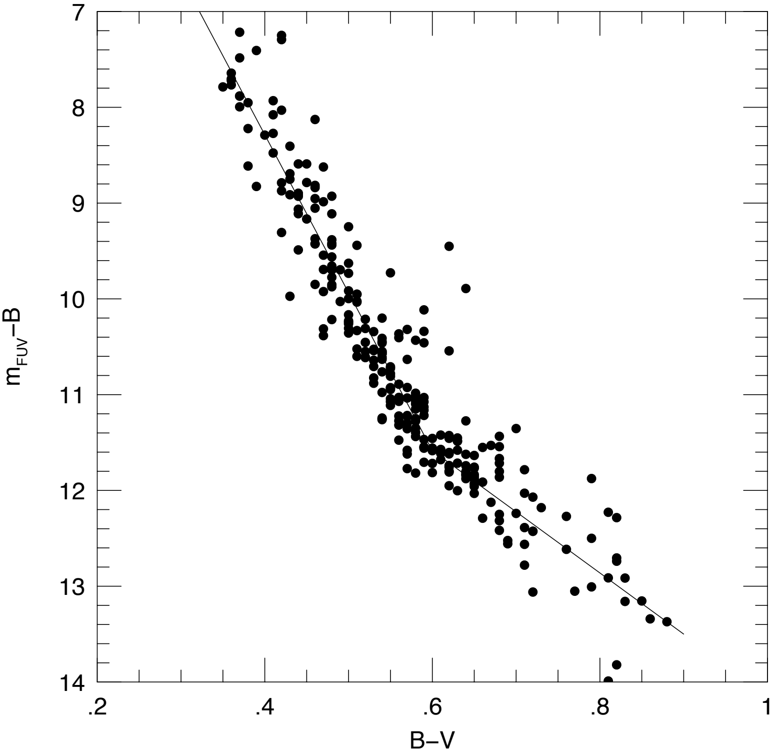


FIG. 10.

The $(m_{\rm FUV} - B)$ *versus* $(B - V)$ two-colour diagram for dwarfs from the sample of KS06. The straight line for $(B - V) < 0^{\rm m}{\cdot}60$ is a least-squares fit, whereas the solid line passing through the data points for redder dwarfs was chosen to connect $(B - V, m_{\rm FUV} - B) = (0^{\rm m}{\cdot}90, 13^{\rm m}{\cdot}5)$ with the bluer fit at $(B - V) = 0^{\rm m}{\cdot}60$. The two high points at $(B - V) \sim 0^{\rm m}{\cdot}63$ are for stars HD 22263 and HD 42438.

shows a systematic decline to more negative values among higher levels of stellar activity signalled by $\log R'_{HK} > -4{\cdot}8$. This trend is in the correct sense to be produced by stronger chromospheric and transition-region emission lines increasing the flux in the *GALEX* FUV bandpass. Among stars less active than $\log R'_{HK} = -4{\cdot}8$ (the chromospherically 'old' stars of Vaughan[14]) there is no discernible trend in Fig. 12. The $\delta(m_{\rm FUV} - B)$ residual may be more sensitive to stellar activity among the redder dwarfs by virtue of the fainter photospheric FUV flux of these stars as compared to the bluer sub-sample.

There may be a contribution from stellar variability to the stellar activity data in Fig. 12. According to Radick *et al.*[36] and Lockwood *et al.*[37], the cyclic variation in chromospheric activity of a solar-like main-sequence star is found to be empirically related to the mean level of long-term chromospheric activity by $\log({\rm rms}\ R'_{HK}) \approx \log R'_{HK} - 1{\cdot}2$, which gives $({\rm rms}\ R'_{HK}) \approx 0{\cdot}063\ R'_{HK}$. Converting this to an rms variation in the index $\log R'_{HK}$ *via* the relation ${\rm rms}(\log R'_{HK}) = 0{\cdot}4343\ ({\rm rms}\ R'_{HK})/R'_{HK}$, leads to ${\rm rms}(\log R'_{HK}) \sim \pm 0{\cdot}03$. Such variations could contribute some scatter to Fig. 12, but would not be expected

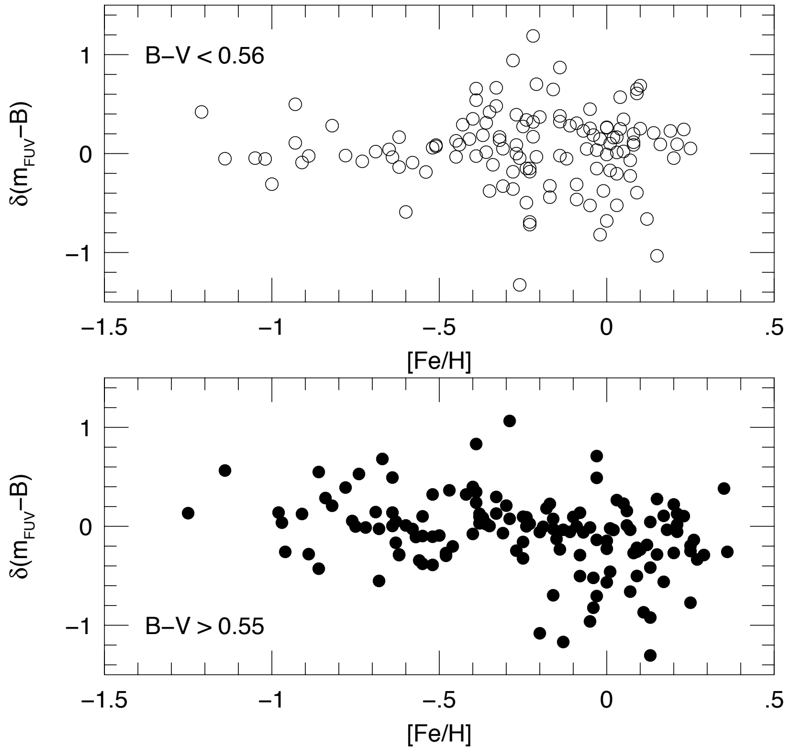


FIG. 11.

The FUV colour residual $\delta(m_{FUV} - B)$, measured relative to the solid lines in Fig. 11, *versus* [Fe/H] for dwarfs in the KS06 sample. The upper and lower panels show stars in different $(B - V)$ colour ranges.

to erase the correlation seen between $(m_{FUV} - B)$ and activity among dwarfs with $(B - V) > 0^{m}{\cdot}55$. The stars which define this correlation have log $R'_{HK} > -4{\cdot}8$, and as such are chromospherically 'younger' than other stars in KS06 of similar colour and [Fe/H]. Since most of them have [Fe/H] within $\pm 0{\cdot}3$ dex of solar metallicity (see Fig. 1), there is nothing unusual in terms of their combination of chromospheric activity and metallicity.

*Conclusions*

Colours formed by comparing the λ2740 and λ2365 magnitudes measured by the *S2/68* instrument on board the *TD-1* satellite with ground-based *B* magnitudes show a significant variation with metallicity among F and G dwarf stars. The mean sensitivity of these ultraviolet colours can be compared with that of the index $\delta_{0{\cdot}6}$ based on the $(U - B, B - V)$ two-colour diagram[38]. Over the [Fe/H] metallicity range from $-1{\cdot}0$ to $0{\cdot}0$, a change of $1{\cdot}0$ dex is attended by a systematic (but not linear) change of $\approx 0^{m}{\cdot}17$ in $\delta_{0{\cdot}6}$, using the data of KS06. This is notably smaller than the counterpart ranges in the $\delta(m_{2740} - B)$ and $\delta(m_{2365} - B)$ residuals plotted in Figs. 7 and 8. If magnitudes in the 2000–3000-Å region of the

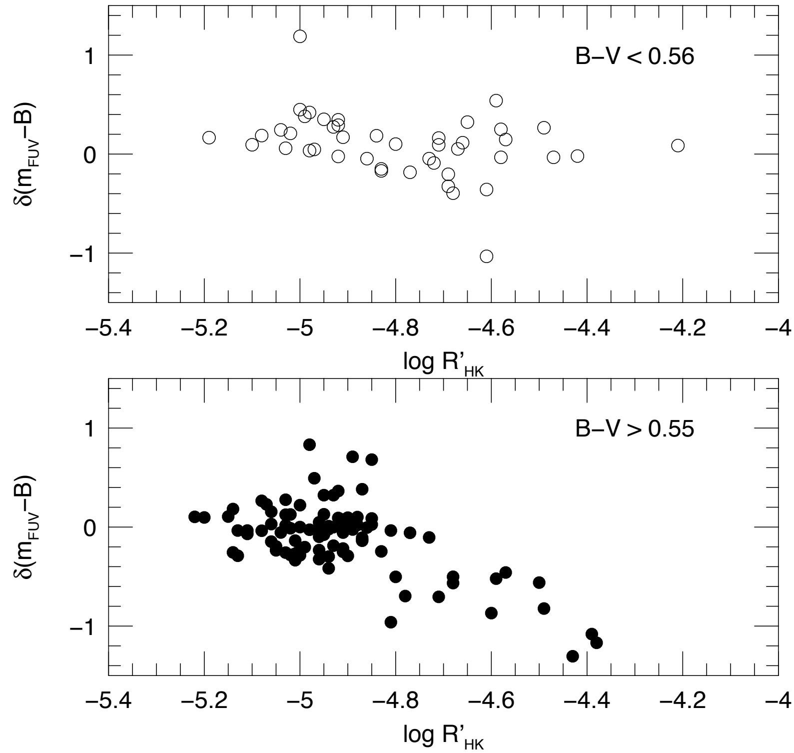


FIG. 12.

The colour residual $\delta(m_{\rm FUV} - B)$ *versus* the chromospheric activity index log $R'_{HK}$ for dwarf stars from KS06. The upper and lower panels show stars in two different $(B - V)$ domains.

spectrum could be measured to an accuracy of better than $0^{m}\cdot05$, then the potential exists for developing ultraviolet-colour systems for F and G dwarf stars that would have greater sensitivity to metallicity than colours based on line blanketing in the 3000–4000-Å region.

Given the heterogeneous nature of the metallicity catalogue of Cayrel de Strobel, Soubiran & Ralite[13], some of the scatter in the colour–metallicity relations found in this paper could be due to errors in the values of [Fe/H] compiled by KS06. The correlation between the *UBV*-based $\delta_{0\cdot6}$ parameter and [Fe/H] was fitted by KS06 with a quadratic function, as in Fig. 4 of their paper. The residuals in [Fe/H] about their best-fit range from 0·0 to ~ 0·4 dex with a quoted dispersion of ±0·17 dex. Assuming that this places an upper limit on the uncertainty in the [Fe/H] abundances leaves open the possibility that a significant part of the scatter in Figs. 6, 7, and 8 of this paper could be due to errors in [Fe/H].

Opacity sources in the UV are numerous[39–42], and include not only many narrow absorption lines, but also some broad absorption lines such as λ2800 Mg II, plus bound-free absorption due to elements such as Al (*e.g.*, a continuum edge at 2076 Å), Si (extending to shorter wavelengths from edges at 1524 Å and 1682 Å), Mg (*e.g.*, edges at 1620 Å and 2515 Å), and Fe. The depths of formation of some of these features are illustrated for the solar chromosphere by Fig. 1 of Vernazza, Avrett & Loeser[43], while the effects of the bound-free opacity in the UV spectrum of the quiet Sun at disc centre are shown in Fig. 3 of Vernazza, Avrett & Loeser[39]. The bound-free absorption could contribute to the greater metallicity sensitivity seen in the *TD-1* λ2365 bandpass by comparison with the λ2740 band.

There is some indication that the FUV bandpass of the *GALEX* photometric system is sensitive to stellar activity among dwarfs with $(B-V) > 0^{m}\cdot55$. Verification of this effect with a larger sample of stars is needed. The $(m_{\rm FUV}-B)$ colour could have significant utility were it to prove sensitive to chromospheric activity level but relatively insensitive to metallicity. In this context, flare activity among dwarf stars in the Hyades and Pleiades clusters has been detected using *GALEX* imaging[44]. Such effects might open the door to mid-ultraviolet colours serving as age diagnostics among F and G dwarfs, since chromospheric activity among such stars declines with age[18].

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# PERIODIC BEHAVIOUR OF STARS IN THE GEOS RR LYRAE DATABASE

## PAPER 2: LONG-TERM STABILITY OF THE BLAZHKO PERIOD IN AR HER

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The GEOS database of O – C values for RR Lyrae stars has been used to investigate 104 years' of data for the RRab-type variable star AR Her. The pulsation period of the star has changed at least three times during that time. The star is known to have a Blazhko period of about 31·6 days, but it has been found to have changed from 31·544 ± 0·037 days to 31·918 ± 0·058 days between the early and later data. There are other long-term variations in the O – C diagram which represent slow changes in the pulsation period of the star on a time scale of tens of years. The shape of the Blazhko O – C phase diagrams has remained the same over the whole 104 years despite the changes in the pulsation period of the star and the other long-term changes in the pulsation period.

### *Introduction*

The star AR Her was chosen for study from the GEOS[1] (Groupe Europeen d'Observation Stellaire) database of O – C values because of the large amount of data covering a time interval during which the pulsation period has changed several times. There are 450 times of maximum light covering 104 years. The pulsation period listed in the GEOS database is 0·470028 days, but a minor change to a value of 0·470055 days produces the O – C diagram in Fig. 1.

This O – C diagram is not a unique interpretation of these data. For example, Firmanyuk[2], using data obtained between JD 2415000 and JD 2445000, gave the early data — before JD 2420000 — an O – C value one pulsation cycle more positive than in Fig. 1. Twenty years later, Husar[3] (see his Fig. 7), who used a larger data set which extended from JD 2415000 to JD 2453000, also placed the JD 2420000 to JD 2425000 data one pulsation cycle more positive than in Fig. 1 in this paper, which implies that there has been a period change after JD 2445000 and before JD 2484700. The same problem arises with the lone datum at HJD 2444512 in Fig. 1. That point, and the whole of the later data, could have been plotted with an O – C value one pulsation period (0·47 day) more positive, as was done by Husar. In Fig. 1 we have assumed the minimum number of period changes, and without additional data being discovered there is no way in which a definitive O – C diagram can be produced. Fig. 1 implies that there have been three period changes in the last 104 years while the equivalent O – C diagram (Fig. 7) of Husar implies that there have been five, or more, period changes. In the analyses which follow, the correct number of period changes will not influence the results. The points to note from Fig. 1 are: (*i*) from HJD 2400000 (hereinafter omitted) +17060 (1905) until HJD +34946 (1954) the O – C values are becoming more positive — a pulsation period of 0·470065 days would be a better fit to these data; (*ii*) some time after HJD +34946 (1954) the period has decreased and from HJD +36356 (1958) until HJD +39692 (1967) there is a steady negative trend in the O – C values; (*iii*) between HJD +40479 (1969) and HJD +44512 (1980) the period has reverted to approximately the same value as it had from 1905 until 1954; and (*iv*) between 1980 and HJD +47666 (1989) the period changed again, and from 1989 until the end of the data in 2008 the period was approximately constant. A pulsation period of 0·470046 days is a better fit to these data.

Care has to be taken when considering the changes in period evident from the O – C values. The gradient between 1958 and 1967 is approximately the same as that between 1989 and 2008, and the gradient from 1969 until 1980 is approximately the same as that from 1905 until 1954. However, inspection of the rest of the data shows that there is a typical range of about 0·06 day in the O – C values in any one year due to the Blazhko effect (see below). The observations between 1958 and 1980 occur less often than once per year. It is clear, therefore, that any attempt to define the exact periods over this time interval is likely to be influenced by the sampling interval interacting with the Blazhko variations. Therefore, the only certainty with regard to the pulsation period is that the data are consistent with, but do not prove, that there are two preferred pulsation periods for AR Her. These periods are 0·470065 and 0·470046 days. They differ by 0.000019 days, that is, about $4 \times 10^{-5}$ of the average period. The short-term data runs will be discussed again below.

The exact nature of AR Her has been problematic for several decades. For example, Balazs & Detre[4] discovered the Blazhko effect in this star and determined its period. In 1961 Almar[5] discussed the Blazhko period of this star and tried to explain the variations by means of a harmonic analysis in which the pulsation period and the Blazhko period were related by a series of interacting pulsations. In 1980 Borkowski[6] revisited this approach. He made an exhaustive analysis of the variations and tried to represent the light-curve changes as a beat between the accepted pulsation period and a second period in order to produce

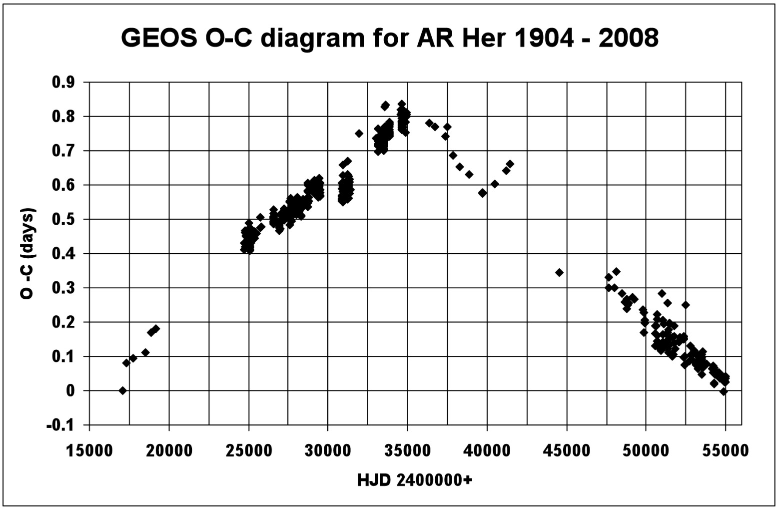



FIG. 1

The modified GEOS O – C values for AR Her from 1904 to 2008 plotted with an ephemeris of 2417060·4 + 0·470055 *E* days.

the 31·6-day Blazhko period. Later, in 1992, Kinman & Carretta[7] carried out a spectroscopic investigation. They suggested that the metallic-line changes in the spectrum of the star throughout the pulsation period required there to be two stars and were indicative of there being a chance juxtaposition on the sky of those two stars. In 1999 Smith *et al.*[8] revisited this suggestion and concluded that the variation in AR Her could not be due to the combined variation of both an RRab star and an RRc star. More recently Husar[3] made new observations and compared those with archival data. He found O – C departures of up to $1^{h}\cdot 5$ (0·06 days) from a constant pulsation period over a few days. These departures were interpreted as being due to the previously known Blazhko effect and differences were found between his light curves and the archival ones. As recently as 2008, Pagel[9] made new observations in which he found a small additional maximum in the pulsational light curve near to the time of minimum light. He also made an analysis of the long-term variations in the O – C diagram of this star and discussed the problems of gaps in the data causing difficulties with the exact form of the O – C diagram. In the present paper no attention has been paid to the form of the light variations. Only the times of maxima are being used.

*The Blazhko-period variations*

The data represented graphically in Fig. 1 were analysed in several ways. The first method used was the same as that used for RR Lyrae in Paper 1[10]. The data were divided into two-, three-, or more-, year data bins and the best-fit period found to these subsets. It became clear that the period for all subsets was just over 31 days and that there was much less variation in the Blazhko period in this star than was found in RR Lyrae itself. Table I lists the best-fit periods to two-year data bins throughout the 104 years. These results are shown graphically in

TABLE I

*The best-fit Blazhko periods to two-year data bins. The dates refer to the start of the second year of each data bin.*

| *Year* | *P* *days* | *Year* | *P* *days* | *Year* | *P* *days* |
|---|---|---|---|---|---|
| 1927 | 31·4228 | 1939 | 30·9598 | 2001 | 33·7601 |
| 1928 | 31·3362 | 1944 | 31·5338 | 2002 | 32·0924 |
| 1929 | 31·2774 | 1950 | 32·2497 | 2003 | 32·0924 |
| 1932 | 31·7138 | 1951 | 31·7058 | 2004 | 31·8960 |
| 1932 | 30·9905 | 1954 | 31·7420 | 2005 | 31·5756 |
| 1935 | 31·5776 | 1996 | 31·6756 | 2006 | 31·6556 |
| 1936 | 31·5497 | 1998 | 32·3939 | 2007 | 31·6056 |
| 1937 | 31·7178 | 1999 | 31·7561 | 2008 | 31·4961 |
| 1938 | 31·4426 | 2000 | 33·3000 | | |

Fig. 2. It can be seen that there is a slow trend to a slightly longer period and two points are offset from the rest of the points by about 0·1 day; they occur where the subsets include one or more of the three points which are offset from the rest of the data in the original O – C diagram in Fig. 1. The data have been analysed over these years both with and without the discrepant points and with data bins of up to four years. The longer Blazhko periods of about 32 to 33 days are a result of the inclusion of the original discrepant O – C values. Removal of these three points reduces the Blazhko period over this interval to about 31·9 days, a value consistent with that when all the later data are analysed together. Without some good reason to reject the original discrepant O – C values it cannot be determined definitively just what happened to the Blazhko period over the years 1989 to 2002 but the three discrepant points have been omitted

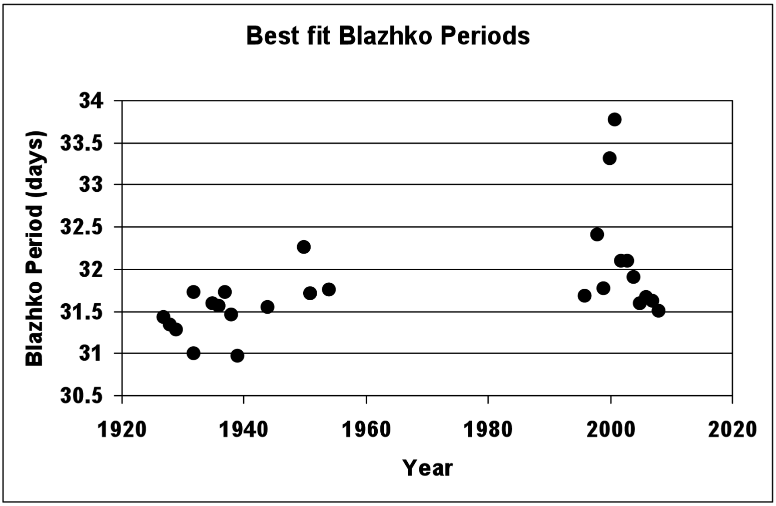



FIG. 2

The best-fit Blazhko periods to two-year subsets of the data.

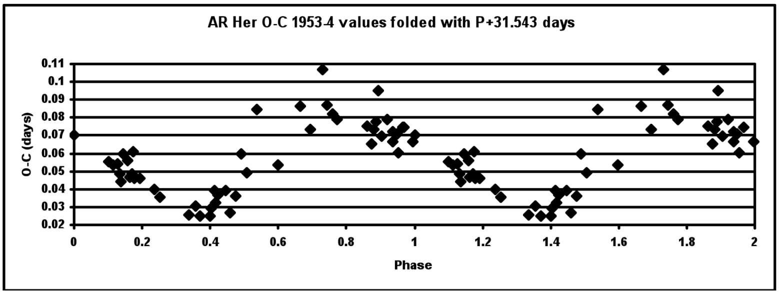
from the phase diagrams discussed below. The best-fit Blazhko periods are too few and too spaced out in time to allow any determination of whether these variations are periodic.

The slight gradient in Fig. 2 has been confirmed by taking the whole of the data from 1926 to 1954 and, separately, the whole of the data from 1989 to 2008 and determining the best-fit Blazhko period to the two data sets. The values are 31·544 ± 0·037 days for the earlier data and 31·903 ± 0·046 days for the later data, suggesting a difference at about the 6σ level. If the formal standard errors are indicative of the real accuracy then it seems that the apparent trend in Fig. 2 is real and the Blazhko period has increased by about 1% over about 50 years. If only the data from 1926 to 1929 inclusive are used then the best-fit period is 31·4614 ± 0·1188 days. The shorter data run has increased the standard error but the mean value is consistent with the suggestion that there has been a steady increase in the Blazhko period over the interval covered by the observations. If this is correct, then this variation, when considered with the changes in the pulsation period plus the other long-term changes discussed below, suggests that the behaviour of the Blazhko variations is independent of the other changes.

The shape of the Blazhko-period variations is shown in the phase diagrams in Fig. 3. In the upper panel, only data from the two years 1953 and 1954 have been used as they have a similar mean level in the O – C data shown in Fig. 1 and can therefore be superimposed without any other modifications. The lower panel shows the data for the years 2004 to 2008 inclusive, folded with the best-fit period to those data. Note that the shape of the curve has persisted despite the changes in both the pulsation period and the Blazhko period between these two data sets. Even after de-trending the long data runs with their best-fit periods there are still variations which are much larger than the range of O – C values shown in Fig. 3. These longer-term variations will be discussed below but from Fig. 3 it can be seen that the Blazhko-period O – C variations have a range of about 0·06 day. The linear retardation of the time of maximum light in the pulsation period, which is what is being measured here, takes about 70% (22 days) of the Blazhko period and the recovery to the original phase occurs over the remaining 30% of the period.

### *Inclusion of the 1958 – 1980 data and other O – C variations*

The above analyses were all made without including the data between 1958 and 1980, during which interval the pulsation period changed twice. It is clear from Fig. 1 that the gradients in these data closely match those in both the earlier and later data, suggesting that perhaps the pulsation period has flipped between two preferred values over the last 104 years. In order to try to test this, a second analysis has been performed on modified data. The assumption was made that the gradient in the 1958 to 1967 data was the same as the 1989 to 2008 data and that the 1972 to 1980 gradient was the same as that for the 1905 to 1954 data. A mean-level correction was made to the two short data runs and then an ephemeris based upon the two best-fit periods to the two larger data sets was removed. The new modified data set is shown graphically in Fig. 4. It is immediately obvious that in addition to the changes in the pulsation period which were evident in the original data shown in Fig. 1 there have been many other small changes in the pulsation period which have led to the detail in Fig. 4. It should be noted that had both the early and later data been placed one pulsational cycle, 0·47 day, more positive on the original O – C diagram, as was done by Firmanyuk[2] and Husar[3], then Fig. 4 would have looked very different. Our interpretation of the



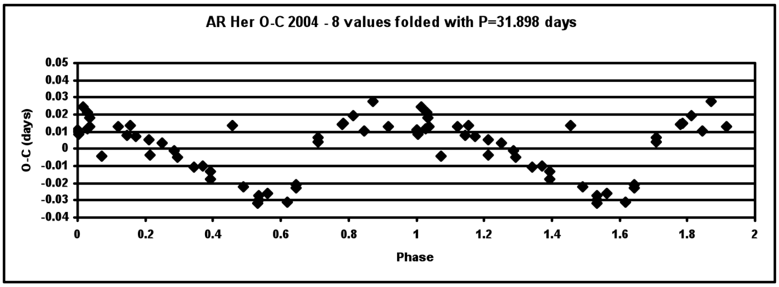




FIG. 3

The upper panel shows the 1953 and 1954 O – C values folded with the best-fit Blazhko period of 31·543 days. The lower panel shows the 2004 to 2008 O – C values folded with the best-fit period to those years' data of 31·898 days. Despite the change in both pulsation period and Blazhko period, the two phase-diagrams have very similar shapes.

O – C values makes a minimum number of assumptions with regards to long-term variations, but this does not necessarily make it correct.

Without a unique set of long-term O – C values following removal of the more obvious changes in the pulsation period, there cannot be a definitive interpretation of the long-term variations in this star. The data in Fig. 4 have been analysed both with and without the 1958 – 1980 data and with and without the earliest five observations. If the variations in Fig. 4 are periodic, and the data do not allow a definitive answer to that question, then a period of about 43 years seems possible, but a period of about 40 years cannot be defined with accuracy from about 100 years of data. The range of the O – C variations in Fig. 4 is about 0·1 day and is most clearly seen in the data range from HJD +24 000 to HJD +32 000. These two combinations of period and amplitude are compatible with the effect being due to light-travel times in a binary system, as was suggested by Kinman & Carreta[7] from their analysis of metallic lines in the spectrum of the star throughout its pulsational cycle. However, this result cannot be used to prove that hypothesis.

The scatter in the phase diagram indicates that while the modified 1958 to 1980 points do not depart significantly from the other points in the phase diagram, neither can the hypothesis that there are two preferred identical pulsation periods be demonstrated. The best that can be said is that the

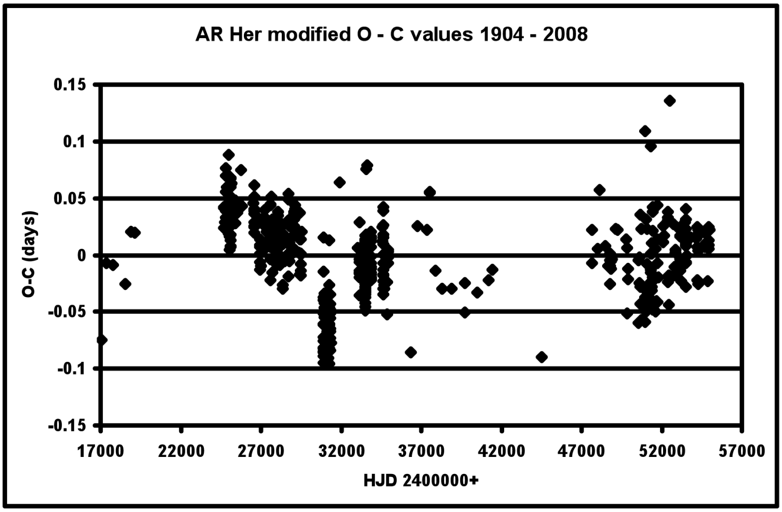



FIG. 4
AR Her O – C values from 1904–2008 after being pre-whitened with the two pulsation periods.

hypothesis is not disproved.

If the long-term variations are removed from the data first, the best-fit period found for the earlier data is 31·542 ± 0·035 days, while it is 31·923 ± 0·010 days for the later data. Both values are essentially the same as the values obtained from the original data, confirming the reality of a small change in the Blazhko period over the last 104 years. The vertical scatter on the phase diagram when the pre-whitened data are folded with these periods is reduced to about half of that before the removal, with a total scatter of about ± 0·02 days. This is still larger than one would expect from purely observational error, suggesting that there are other sources of pulsation-period variation. It will require a large amount of new data to determine the real nature of these long-term variations.

*Summary and discussion*

In this discussion a comparison will be made between the results obtained in this paper with those on RR Lyrae itself in Paper 1. Results which seem to be certain for AR Her are: (*i*) the pulsation period has changed at least three and possibly five, or more, times in the last 104 years; (*ii*) the data are compatible with, but do not prove, the hypothesis that the pulsation period has had two preferred values during that period; (*iii*) in addition to the visually obvious changes in the pulsation period (Fig. 1), there have been other changes in that period which can be modelled by one, or more, longer periods which are in the tens-of-years range. Whether these are truly periodic variations or only random effects in the data cannot be decided from these data alone; (*iv*) the Blazhko period has lengthened by about 1% over the last 60 years and possibly by about 1·4% over the whole of the 104 years; (*v*) the data suggest that the Blazhko-period variations occur independently of changes in the pulsation period of the star; and (*vi*) the shape of the Blazhko-period phase diagram has similarities to that of three years of RR Lyrae data but is different in that the linear phase lag of the time of maximum takes about 70% of the Blazhko period and the recovery about 30%.

Perhaps the most obvious similarity between RR Lyr and AR Her is that the pulsation periods have changed over the approximately 100 years of observations. In RR Lyr the period change was about $2 \times 10^{-5}$ while in AR Her the change was larger at about $4 \times 10^{-5}$. In both RR Lyr and in AR Her there have been changes in the pulsation period which have periods or time scales of tens of years. The Blazhko period in RR Lyr changed between 34 and 42 days (20%) and the changes seemed to be periodic. In AR Her the Blazhko period has only changed by about 1% over the 104 years of observations. In RR Lyr it was difficult to find yearly data runs where all of the O – C values showed a 'clean' phase diagram; only 3 years out of 109 years showed this 'clean' phase diagram. By contrast, every year of O – C values for AR Her shows a 'clean' phase diagram and whatever causes the scatter about these Blazhko phase diagrams is present in RR Lyr and not detectable in AR Her. There are similarities in the form of these 'clean' Blazhko phase diagrams but in RR Lyr the retardation in the time of pulsation maximum takes about 90% of the Blazhko period while in AR Her that value is about 70%. If the amplitude of the Blazhko phase diagram (days) is considered as a fraction of the pulsation period of the star (days) then the values are about 14% for RR Lyr and about 13% for AR Her. These values are not significantly different. If the gradient of the retardation of the phase of maximum is calculated by dividing the total retardation (days) by the number of days over which the retardation occurs then the gradients are about 0·2% for RR Lyr and 0·27% for AR Her. It will require the analysis of more stars before it can be judged whether there is any significance to these values. Attempts to model causes for the Blazhko effect will have to take into account such differences in behaviour.

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## CORRESPONDENCE

*To the Editors of 'The Observatory'*

### *Public Reaction to a $V = -12{\cdot}5$ Supernova*

Imagine reading this page at night. By starlight. It could happen. What would be the effect today, on humankind, of a supernova having an apparent magnitude equal to –12·5, roughly equivalent to that of the Full Moon? No one has recorded such a spectacle in historic times (meaning the last few thousand years in the northern hemisphere and the last few hundred in the southern). Looking to the future, the event is unlikely in any one human lifetime but inevitable on longer time scales.

Before tackling this question, though, it is necessary to address another: can a Galactic supernova be spectacular without producing such extreme physical effects that no person will care about the psychological and cultural effects? Both ionizing radiation and relativistic particles are unhealthy in large quantities.

As Ruderman pointed out[1] in 1974, the most probable life-threatening effect of a supernova would be depletion of the Earth's ozone layer by high-energy electromagnetic radiation. This scenario would subject the Earth to a huge increase in solar UV flux. Refinement of Ruderman's model by Ellis & Schramm[2] and by Gehrels *et al.*[3] established a 'kill radius', at which nominal atmospheric ozone is halved, equal to 8 pc. (Fields *et al.* further showed that a supernova at 10–20 pc may collapse the heliosphere to less than 1 AU in radius, thus subjecting the Earth to particle radiation as well.[4]) On the other hand, Thomas and colleagues demonstrated that ozone depletion is only equal to ten percent at a supernova distance of 30 pc, and that this depletion is short lasting[5]. Clearly, the social and psychological effects of a supernova — the topic of this letter — are made more-or-less irrelevant by physical effects at some supernova distance between 10 and 20 pc. Let us assume, for the purpose of this discussion, that our hypothetical supernova is far enough away so as *not* to toast the Earth (> 30 pc).

On the other hand, supernovae reach absolute visual magnitudes of approximately –18 (depending upon the type). Thus, $V = -12^{\mathrm{m}}{\cdot}5$ corresponds to distances from 100 pc to 160 pc. Millions of cubic parsecs occupy a volume between a radius of 30 pc and these outer limits (in which ordinary interstellar absorption, at one magnitude per kiloparsec, normally will be unimportant). This volume is mostly within the Galactic disc, where massive stars — relevant in the case of core-collapse supernovae, the more common sort — are concentrated. (Nuclear-detonation supernovae probably belong to a less disc-concentrated population.)

Are there candidates in hand? Yes: Antares and Betelgeuse are both M supergiants at about 120 pc and 150 pc, respectively. Their position on the H–R diagram strongly suggests that they have completed core hydrogen fusion and so have future life expectancies considerably less than their $10^7$ year total life spans. Indeed, Beatrice Tinsley long ago suggested that both have begun carbon fusion and so might not have more than about $10^4$ years to go. Beyond that, one cannot say, for after carbon ignition, stellar atmospheres do not have time to respond to changes in central conditions. Implied is that there is a one percent probability of core collapse in the next one hundred years.

Other recently advertised SN progenitors include T Pyx (for a Ia type event) and η Carinae. Both, though, are at kiloparsec distances, leading to an expected light maximum of perhaps $V = -9^{m}$ (more like a quarter Moon).

Reiterating, casual observers will see only visual phenomena, just as for all the naked-eye (Galactic) supernovae in recorded history. Nonetheless the event may alter our behaviour. How will we react to a bright supernova? How will this reaction differ from that to the last occurrence, a naked-eye supernova much fainter than our imagined one, which took place in 1604? While we may feel unqualified to do so, scientists surely will be asked to opine on such matters, should the rare event take place.

Our hypothetical supernova would be the sudden brightening of a star in the sky. Its light would remain concentrated in a point, with long diffraction spikes produced by the eye's cornea. Shadows cast by it would consist only of umbra; the shadow edges would be sharp. The supernova would, for a time, be visible day and night. Let us further imagine that the supernova is located on the celestial sphere (and first occurs on a day of the year) so as to maximize its visibility as a function of world population — perhaps in the plane of the Milky Way. We place our hypothetical supernova with apologies to the people of Norway, who might welcome the light from a high-declination supernova during a long, cold winter's night.

The reader may feel that much of this scenario is moot. Today, many of us live enclosed, urban lives. Our experience of the sky is muted by light pollution. Yet the brightness of the supernova is not the entire story. We argue that it is the temporary nature of an unexpected celestial event that engenders widespread, popular response, in addition to simply its brightness.

Psychologically, the majority of people still live in a pre-Copernican universe: most of us, most of the time, dislike change, whether it is the replacement of our favorite soft drink by "new, improved (high-fructose corn-syrup) Ceptsi", or even just a name replacement. Nunavut applied to part of northern Canada apparently disturbed only a few Canadians; Mumbai and Myanmar troubled writers on foreign affairs and those who thought they knew their geography. But the removal of Pluto from the canonical nine planets (done first by the Rose Planetarium in New York and then later, but more officially, by the International Astronomical Union) upset many. A good deal of the latter fuss and bother arose because the media gave the impression that something about Pluto actually had *changed*.

In particular, changes in the sky offend many of the folk who notice them. Every observatory, planetarium, and university astronomer is used to telephone calls about flying saucers when Venus reaches greatest western elongation. Yet that configuration has happened many times before in the callers' lives. Apparently duration is important. Spectacular *Iridium* (satellite) flares occur frequently, but they last for seconds at most, and hardly anybody notices them. But our hypothetical supernova will be bright at least as long as a typical bright appearance of Venus. A theorist's supernova fades with a half-life of 77 days (the half-life of cobalt 56 decaying to iron 56), giving us more than two years from a peak at $V = -12^{m}\cdot5$ to a Venus-like $V = -4^{m}\cdot5$. Changes in the sky on the order of days, weeks, or months provoke an emotional response, especially novel changes. And after more than four-hundred years, the supernova will be effectively novel.

What does history teach us to expect? Stephenson & Green[6] have compiled just about everything there is to be said about the events of 1006, 1054, 1181, 1572, and 1604. SN 1006 was the brightest of these, at perhaps $V = -7^{m}\!\cdot\!5$ to $V = -9^{m}\!\cdot\!5$ — still far below our $-12^{m}\!\cdot\!5$. Moreover, the world one thousand years ago was much different from the one in which we live. Still, the 1006 supernova was well documented; what do these documents tell us?

Those that have survived come from Latin, Syriac, Arab, Chinese, and Japanese sources. (The 1006 supernova occurred at low declination in the constellation Lupus and culminated in the daytime.) Those records originally were catalogued by Goldstein[7] and by Goldstein & Ho[8]. Latin reports are confused by the fact that the supernova sometimes was referred to[9] as a "comet".

'Alī ibn Ridwān (*circa* 988–1061) tells us that the supernova explains why civil wars had recently broken out among Muslims in Arabia, as well as famine and pestilence. According to this Egyptian astrologer, the supernova "claimed" thousands of victims. In Switzerland, the supernova was merely connected to a three-month drought. That it was reflected upon at all in Europe was not a given, considering that European cosmology of the time rejected the notion of celestial change altogether.

The story from China is more interesting. In 1006, Chou K'o-ming (954–1017), of the Imperial Astronomical Bureau, was travelling outside of the capital when the supernova appeared. On their own, people could not decide what kind of omen the supernova presented and were anxious. At first, it was considered a *Kuo Huang* star, which foretold war, flood, starvation, epidemic, and ill-fortune for the ruler. This was understandable because most 'guest stars' in the ancient Chinese sky were considered to be prodigies. However, upon his return, Chou K'o-ming declared the 1006 supernova a *Chou-po* star, a portent only seen during the reign of a virtuous and wise Emperor. The Emperor was, needless to say, pleased, and instructed civil and military officers throughout the country to celebrate the supernova, thereby calming the people and rating Chou K'o-ming a promotion. This is a fascinating appeal to authority as *Chou-po* were, by definition, yellow in color. The 1006 supernova most likely was bluish white. Thus, the population was asked to believe what they were told, not what their eyes showed them.

In Japan, the debate was about whether the 'guest star' was new or the brightening of an existing star. Regardless, it presaged an important event. Offerings were made, and a prominent general asked for amnesty in regard to unstated crimes.

The world of 2010 is much different from that of ten centuries ago. We now know what a supernova is, as a physical phenomenon. As opposed to before the so-called Scientific Revolution, supernovae today have (to use the modern term) scientific meaning. This does not prevent the supernova from *also* still having metaphysical meaning — usually predictive — to certain people. Might our future supernova augur favourably (as it did to Chou K'o-ming) or unfavourably (as it did to 'Alī ibn Ridwān)? Solar eclipses typically are said to foreshadow unfortunate outcomes. A supernova is a sort of 'anti-eclipse' — a noon at midnight as opposed to the darkness at noon of an eclipse. Thus, the supernova plausibly could be interpreted as a positive sign — except that it probably will not be, insofar as change in the sky is, by default, 'bad'. So, just as in 1604, our hypothetical supernova might be considered an apocalyptic omen by some. (Somebody surely will trot out Nostradamus.) Alternatively, it might be said to herald political change or punishment at hand for wrong-doers. These are all historically standard interpretations.

Extreme reactions are more likely to occur today on the metaphysical fringe, as opposed to within 'mainstream' established religions. Here, there may be a spectrum of responses. For instance, we might anticipate little outward reaction among the Buddhists, Hindus, Taoists, and Confucian adherents of the world. Our expectation is that the event would seem most important to the 'synoptic' religions — whose theology is closely coupled to events in human history. (We invite readers with greater expertise than the authors to provide us with their opinions.)

There are superficial similarities between the supernova and the Christian gospel's Star of Bethlehem; this religion just might interpret the supernova as, at least, a symbol of hope. (The arrival of a second Christ child is a less likely interpretation than is the Second Coming, though.) Moreover, if the supernova appears near the plane of the Moon's orbit, it might for several months produce a spectacular star-and-crescent every 27·3 days, an important Islamic symbol, and the learned might think of the 86th *surah* of the *Qu'ran*, 'The Night Visitant'.

Within traditional Judaism, the end of the Sabbath is signalled by the visibility of three stars. The idea is to make the Sabbath linger as long as possible, since tradition expects that the Messiah will come on that day. Planets are included along with stars for this purpose, so presumably a supernova would count. Perhaps the Sabbath will end a little earlier during the supernova apparition.

Notice that, heretofore, we have described a reaction to a supernova not that different from those expected (and experienced) during the 16th and 17th Centuries. Historical analogies may only take us so far, though. In the 21st Century, many human beings' fear of change in the sky has been altered forever by history. Today our fright is based upon the potential for terrestrial collisions, whereas in Aristotelian times the heavens and Earth were thought separate. (It used to be taken for granted that 'heavenly objects' could not physically encounter 'Earthly objects'.) The supernova, immobile on the celestial sphere, likely would not trigger the distinctly modern fear of impact. On the other hand, historian of science JoAnn Eisberg ran a test: She Googled 'supernova' and got "destruction of the Earth" and "Armageddon . . .". These were (out-of-context) excerpts from reputable sites! That a bright supernova need not be a 'kill-radius' supernova will be lost on many, and indeed such confusion might spread angst in the 'blogosphere'. Even though our particular supernova may be harmless, it will be a reminder that life on the Earth is contingent.

Another major difference between today and 1604 is technological. All past bright supernovae occurred during the pre-telescopic age. Our supernova might be discovered as brightening while still only very slightly brighter than the $V = -0{\cdot}5^{m}$ to $V = 1^{m}$ we see for Betelgeuse and Antares now. Neutrino astronomy of the 21st Century might well allow the detection of carbon-fusion onset (when the star's neutrino luminosity begins to exceed the photon luminosity) in those or other supernovae progenitors. If the supernova is not — literally — a 'new' star, is its psychological impact lessened?

The public response to our supernova will very much depend upon the rapidity with which media address the matter, and the tack they decide to take: sensationalizing imagined danger or merely presenting a *YouTube* curiosity. If it is the latter, the subject quickly will drop out of the news cycle. One of our colleagues is cynical about the corporate response: "When the month of brightness [is] over the event would be obliterated from memory by a scandal involving the Obamas' pupp[y]."

So far, we have addressed a broad, sociological response. At the strictly personal level, would there be people who, due to the supernova, pay attention to the sky for the first time in their lives? The appearance of Comet C/1995 Hale–Bopp may be used as a comparison. (We choose this comet as opposed to, say, 1P/Halley, which benefitted from inherited fame and a propaganda machine prior to its arrival.) Indeed, there undoubtedly would be public confusion as to the difference between a supernova and a comet (again), depending upon when the last bright comet had appeared in the sky and the extent of its tail. There is an important distinction, however: a supernova will not change its appearance, as comets do, during its apparition; it only will fade. Will this constancy cause human interest to diminish as well?

More prosaically, there will be few practical consequences of our supernova, beyond some possible low-amplitude flutter in the financial markets. Of course, certain individuals (astrologers?) will attempt to profit personally from the event. Furthermore, there are probably no strategic or political implications of the supernova. (In the excitement of the moment, we hope people do not mistake the supernova for the futuristic 'Star Wars' laser weapons that we have heard so much about.) However, tactical warfare — of which there are, sadly, perpetual examples worldwide — always has been affected by nocturnal illumination (*e.g.*, moonlight). A month or six weeks in which there is little 'cover of darkness' might alter fighting tactics. We suppose this applies to hunting and fishing, too. More generally, we are curious as to how many gadgets now include some sort of Sun sensor — which could be made to malfunction by an unexpected bright light. Letting our minds roam, we wonder whether *animals* will react to a supernova.

What fun it is to speculate on our supernova's effect upon the arts. Might a supernova lead to a neo-romanticism in regard to the sky? Steve Renshaw, in Japan, predicts easy entry of such a phenomenon into pop culture: he imagines new *anime* characters 'Novaboy' and 'Novagirl'! (Picture the action figures.) How will Conan O'Brien, David Letterman, and John Stewart deal with it? And we refer just to that sliver of world popular culture that is called Western.

Closer to our professional 'home turf', and more within our speculative comfort zone, a $V = -12^{\mathrm{m}}\cdot5$ supernova would cause the illumination from the Milky Way to disappear and astronomers to lose their coveted dark time. Meanwhile, all of us who read *The Observatory* would 'gear up' for the increased number of visitors at public and educational observatories. (What will they see besides a blinding light? Well, at 150 pc, the light echo will be resolved after 1–2 days and the ejecta after 1–2 months.) That the supernova would lead to increased funding in science and science education is, to us, a bit of a pipe dream, albeit a pleasant one.

Will any of this happen? What unforeseeable influence will our supernova have? Our hypotheses are largely untestable. We are tempted to perform an experiment suggested to us by John Westfall: hang a shiny Christmas ornament somewhere high, such that its specular reflection of the Sun is visible. (It will have to be at just the right distance from the observer so that its 'magnitude' equals $-12^{\mathrm{m}}\cdot5$.) Then watch to see if passers-by notice it *at all*.

We thank the scientists, historians, and anthropologists with whom we have conversed about the subject of this essay, including Clark Whelton, John Westfall, Leo Houziaux, Christoffel Waelkens, Yuri Efremov, Steve Shore, Ronald Hicks, Giulio Magli, Brian Waddington, Tony Beavers, Ennio Badolati, Richard Baum, JoAnn Eisberg, Peter Broughton, Axel Harvey, Alistair Kwan,

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Yours faithfully,
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## *The First SETI Scans*

This letter is not meant to be a search for 'sources' of the long-standing debate that led up to the first SETI scan to find artificial signals from possible technological alien civilizations. It aims rather at meriting praise to all involved in Project Ozma, the 50th anniversary of which fell on April 8 this year.

The technology used for the scan, focussed on the 21-cm hydrogen line, had been developed by Frank Drake, along with his associates John Findlay, David Heeschen, and Ross Meadows, at the National Radio Astronomy Observatory (NRAO) in Green Bank, West Virgina. The reasoning for the Project was the assumption of solar-type stars to have planets in possible signal-source zones. Lloyd Berkner, the acting director of the Observatory, authorized the Project to start in 1959 April, prior to the full-time directorship of the Observatory and the Project by Otto Struve, advocate of planetary systems around slow-moving stars.

At about 4 a.m. (EST) on 1960 April 8, Drake and one of his telescope operators, together with other team members, aimed Green Bank's antenna at τ Ceti, tuned to a channel covering the frequency of 1420·405 MHz. When τ Ceti set that day, Drake switched to ε Eridani. Minutes later Green Bank's receiver recorded strong signals consisting of around eight beats of radio noise per second[1]. The same signals recurred about two weeks later; Drake resolved these to be stationary and coming from planet Earth.

Several months before, in 1959 November, Otto Struve, who earlier in that year had become the director of the NRAO Green Bank, announced Ozma in his Compton Lectures at the MIT. His announcement of the Project came several weeks after the publication of *Occurrence of Life in the Universe*, a paper by Su-Shu Huang[2], which appeared about the same time as *Searching for Interstellar Communications*, by Giuseppe Cocconi & Philip Morrison[3]. Huang, a former student of Struve and with whom he had discussed his paper, speculated that there is a good chance of detecting habitable zones in the vicinities of ε Eridani and τ Ceti. Both stars, less than four parsecs away, also figure in Cocconi's & Morrison's scenario of possible signal-detection sites. According to Huang[2], on different occasions Struve mentioned τ Ceti as first choice for detecting a planet of astrobiological interest.

In 1955 Struve had used the term 'Astro-Biology' in his paper *Life on Other Worlds*[4]. Relying upon logical hypothesis, he assumed there are countless numbers of planets with some forms of life in the Galaxy.

Struve, known as an initiator of many researches, passed away on 1963 April 6 — all but three years after the first SETI scan, to which he had given approval, supervised, and regarded as the beginning stages of a shake-up in scientific and philosophical thought.

Appropriately, in the 50th year of SETI, credit for pioneering should not only go to Drake, his associates, and the team members of Project Ozma, but also to Berkner, Cocconi & Morrison, Huang, and Struve.

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## REVIEWS

**The Eerie Silence: Are We Alone in the Universe?**, by Paul Davies (Allen Lane, London), 2010. Pp. 242, 24 × 16 cm. Price £20 (hardbound; ISBN 978 1 846 14142 3).

This carefully crafted discussion of the issues confronting searches for extraterrestrial life, and more explicitly for extraterrestrial intelligence, marks the 50th anniversary of SETI. Although Davies is an enthusiastic supporter of the concept that we are not alone in the Universe, his treatment of the issues — and all are touched upon in this book — is objective, frank, and admirably free from personal bias. He guides 'the layman' methodically through concepts ranging from definitions of life, habitability zones, the recognizability of alien intelligence, and reactions to a positive SETI detection in a style that is neither didactic nor condescending but refreshingly conversational, yet at the same time one which succeeds in conveying a surprising amount of quite complex scientific information. Topics as diverse as 'weird' microbes, space travel, teleporting, and quantum computers are handled engagingly, with a clear perspective of the impact and implications of each upon the subject. Nowhere are personal preferences allowed to colour the assessments of the odds.

The common pitfalls of projecting humanoid characteristics onto alien life are studiously examined, and concepts like a shadow biosphere, or a complete diaspora of non-terrestrial life within the Galaxy, are handled in a scholarly fashion with appropriate references. Davies sums up the present state of knowledge fairly and dispassionately, answering the question posed in his own title by concluding, "We just *don't know*". In essence the book is designed and planned like a scientific paper, presenting relevant facts, ideas, associated physics, a few fanciful alternatives, and some dead-end concepts with well-judged weight; it is just much more engaging to read (and of course a good deal longer).

The dust-jacket blurb includes epithets about the author such as "lucid and readable", "explains with fluent simplicity", "sublime stuff", "provocative and controversial, but ... maintaining the rigorous scientific approach of the physicist". All are accurate, and well-deserved. You do not need to be passionately either pro- or anti-SETI in order to get something out of this book. It is an excellent read, with just the right amount of wry humour, and is unhesitatingly recommended. Do be careful, though, *where* you read it. The person trying to read it over your shoulder could have originated on Mars. — ELIZABETH GRIFFIN.

**The Elements: A Visual Exploration of Every Known Atom in the Universe**, by T. Gray (Black Dog & Leventhal, New York), 2009. Pp. 240, 26·5 × 26 cm. Price £22·95/$29·95 (hardbound; ISBN 978 1 57912 614 2).

I once set a question for my students to imagine a simple world possessing just the first 26 chemical elements, from hydrogen to iron, and to describe how it would differ from ours in terms of scientific and cultural development. After all, every element essential for life (H, C, N, O, Mg, P, K, Ca, Fe….) would be represented, even if the debris of exploding stars had not supplied the rest. It would be a metal-poor world, unwarmed by radioactive decay from within. Its civilization would have had no Bronze Age, and there would be no brass for telescope tubes, no cobalt for stained-glass windows, no gold, no mercury for dental fillings, no silver-halide film, no stray alpha particles to probe inside the atom, and (at least some advantages) no arsenic or thallium for would-be poisoners, and no nuclear weapons. (I could go on!)

Such mental exercises bring us back to the arrangement of the Periodic Table, and an appreciation for the amazing variety, versatility, and beauty of the chemical elements. This book, written by a self-confessed element collector (a trickier exercise than merely collecting minerals), delights the eye and exercises the imagination, with each element receiving one or more double-page spreads, an arrangement which nicely suits the coffee-table format. There are many fascinating facts, ranging from details of specialized metallic alloys through gemstones to quack medicines (such as germanium bath salts). The photography and reproduction are excellent, and the text informative, engaging, and somewhat off-beat. Essential data for each element are presented graphically by means of a sidebar. These comprise relative atomic mass, atomic radius, electron arrangement (using *spdf* notation), crystal structure, density, atomic emission spectrum (in the visible waveband, alas without any wavelength scale), and of course melting and boiling points. Those wanting more esoteric or precise data must go back to their copy of Kaye & Laby, the *Chemical Rubber Company Handbook*, or to other standard sources.

*The Elements* will have wide appeal, and I'm sure many astronomers (and indeed chemists like me) will be attracted by the superb appearance and very modest price of this romp through Mendeleev's table of the chemical elements. Highly recommended. — RICHARD MCKIM.

**The Periodic Table: Its Story and Its Significance**, by Eric R. Scerri (Oxford University Press), 2006. Pp. 346, 23·5 × 15·5 cm. Price £22·50/$35·00 (hardbound; ISBN 978 0 19 530573 9).

Dimitri Ivanovich Mendeleev (1834–1907) was born when a few proponents of phlogiston still walked the Earth and died in the era of X-rays and electrons. He worked on a variety of problems (from gas laws in 1856 at least until 1895, when he faced the problem of argon), but the average scientist will, of course, say "periodic table", perhaps even "the periodic table", though there were at least five folks who proposed such tables before Mendeleev in 1869 and more than 700 versions after, according to author Scerri (who turns out to be a near-neighbour of mine up at UC Los Angeles). The book, which is the first comprehensive history of periodic tables published since 1969, begins, of course, with the ancient Greeks, and ends with some modern problems in, mostly, inorganic chemistry and philosophy of science, the latter having to do with just what is meant by "an element".

The last chapter is entitled 'Astrophysics, nucleosynthesis, and more chemistry'. I think you will (assuming you are an astronomer, cosmologist, *etc.*) get more out of the preceding nine chapters, for the tenth has a large number of items about which you are likely to say either, "I already knew this", or "but that isn't really true". And yes, a good many of them are the same items, like J. A. Wheeler supposedly coining the phrase "black hole" (a couple of years after it had appeared in print), Fred Hoyle and the excited state of carbon-12 (already in a pre-war data table), and the Big Bang supposedly occurring at $t = 0$ and $T = 10^{32}$ K. Öpik gets no credit at all, and Salpeter I think too little, for recognizing that a three-body process would be needed to get from helium to carbon.

Of course, as in any good book by a serious historian, there are disillusionments aplenty for us dabblers. Henry Moseley, for instance, is generally given too much credit by the folklore (hagiography, says Scerri), illustrating the principle that early death can be a good career move. Most curiously, it is suggested that terrestrial technetium (Tc) may actually have been isolated by the Noddacks and Walter Berg in 1925. We, who still feel triumph at the discovery of Tc in M stars, are pretty sure the longest-lived isotope has a half-life of about a million years, and having followed the yellow-brick path of the *s*-process upward from the iron peak, are naturally puzzled. Among the more charming pictures are $B^2FH$ with the model steam engine given to F on his 60th birthday (1971) and one of Mendeleev strongly resembling Rasputin. Bethe is given credit for participating in the alpha-beta-gamma paper in the text, but it is sorted out in an end-note.

Just how important has the periodic table been in the "making of scientists"? The issue came up about a decade ago in connection with science-education standards for California high schools, which originally said it should be introduced no earlier than late in high school and only within the context of pre-college courses in chemistry and physics. A group of objectors rallied under (perhaps just the name of) Glenn T. Seaborg in a way that prompted me to ask the 60-member council of the American Physical Society when they had first encountered the concept, and whether perhaps it had encouraged them to become scientists (as opposed to some precognitive teacher or mentor showing them the table on the grounds that they were going to become scientists). The average was late grammar school, about age 10, rather than 16–17, and the majority view was that meeting the periodic table had indeed been an important item in their early education. Glenn (who was a UCLA undergraduate and classmate of my father) would have been pleased, both by that outcome and by this book. — VIRGINIA TRIMBLE.

**Preserving Astronomy's Photographic Legacy: Current State and the Future of North American Astronomical Plates** (ASP Conference Series, Vol. 410), edited by W. Osborn & L. Robbins (Astronomical Society of the Pacific, San Francisco), 2009. Pp. 202, 23·5 × 15·5 cm. Price $77 (about £50) (hardbound; ISBN 978 1 58381 700 1).

In recent years during the course of my work I have been called upon to dispose of thousands of astronomical plates. Admittedly, some of those were glass copies of sky surveys, and fortunately all have gone to good homes, although finding locations which can safely store and keep large numbers of glass plates weighing several tons is difficult indeed. All of the survey plates had been scanned by machine, such as the now defunct *APM* at Cambridge, so it was no longer necessary to have the physical manifestation in order to examine the contents.

There are, however, several-million glass plates which have not been scanned and which also represent unique snapshots of the sky at a range of epochs stretching back more than 100 years in both the spectroscopic and visual régimes. Just putting together a census of this collection is proving a major undertaking because photography was so prevalent in the last century; many observatories built up collections and now, with pressure on space and manpower, very few want to keep their plate archives, and a central repository is sorely needed. I am strongly of the opinion that this is the way forward and that those institutions who wish to dispose of their plate collections should be able to do so in the full knowledge that they will go somewhere where the plates will be cared for and the data made available to visiting investigators *via* a resident plate scanner. However, whilst a plate archive in the USA seems to be going ahead, a projected similar institution at the Royal Observatory at Uccle in Belgium seems to have stalled.

When this book arrived for review my heart sank. Firstly, it is about one-third of the usual thickness of books in this series, and secondly, on examination I found that it dealt largely with plate archives in the USA, with a little about Europe and merely a passing mention as far as the UK goes, even though our photographic tradition is one of the strongest. In fact the large collection of plates which used to reside at the Royal Greenwich Observatory in Herstmonceux, and then in Cambridge, now languishes in a warehouse in London with little immediate prospect of being placed in a position of access. However, in both the US and Europe, there does seem to be an active interest in scanning plates, with many institutions using commercially available machines, although it is pointed out that the logbooks are just as important as the plates themselves.

The heart of this volume is the report of a workshop organized at the Pisgah Astronomical Research Institute (PARI) in Rosman, North Carolina, from 2007 November 1–3. It was attended by 32 people, only three of whom had come from Europe, the rest being residents of the USA or Canada (including Elizabeth Griffin who is currently attached to DAO). Amongst other things, PARI, a public, non-profit organization, is the home for APDA, the Astronomical Photographic Data Archive which now houses 100 000 plates and films from such institutions as Palomar, Kitt Peak, Edinburgh, CTIO, and Harvard. Whilst it is currently accumulating unwanted collections and 'orphan' plates, there is no official recognition (and more importantly funding) for this aspect of its work. Discussions at the meeting ranged from defining the current situation regarding plate archives, what can be learnt from other plate archives, defining standards and protocols for archiving, to where to find sources of funding. Another important part of the proceedings were the papers by Simcoe and Shelton which evaluate two commercially available scanners, one of which appears to offer astrometric repeatability of about 1 micron for a modest price.

The appendix contains the result of a questionnaire which was sent out to American universities and observatories asking for details of plate collections and their current attitude to the maintenance or disposal of their collections. This elicited more than 200 responses from Canada, Mexico, and the USA. Whilst nearly all the keepers of major plate collections replied, there was, disappointingly, no response from Tonantzintla and Tacubaya which have a large collection of Schmidt plates and, nominally at least, a complete zone of the Astrographic Catalogue.

In these days of the Virtual Observatory, where multi-wavelength, multi-epoch data can be called up at the press of a button, it is sobering to read that the Workshop noted that the photographic database had been mined to perhaps the 0·01% level. It's time for more to be done about this huge resource. — ROBERT ARGYLE.

**Verre d'Optique et Lunettes Astronomiques**, by Philippe Véron (Ed. Fondazione Giorgio Ronchi, Florence), 2009. Pp. 456, 23·0 × 16·5 cm. Price: €67·50 (Europe, about £60) or €70 (North America) (paperback; ISBN 978 88 88649 22 1).

Glass always fascinated me as a kid, be it only through its ability to enclose totally a volume while allowing one to peer from outside into it or from the inside out. As a teenager, I retained for many years a glossy booklet illustrating the story of glass over the centuries. Liège, the city of my university studies and first professional years, hosts a renowned glass museum. Crystal pieces cut by artists from Val-Saint-Lambert (in Liège's suburbs) followed my various international moves and are still decorating my living room.

These few lines are just to emphasize the fact that Philippe Véron's book on optical glass and astronomical refractors could only awaken a genuine interest when it landed on my desk for review. And here it is: a solid work of 450+ pages, including 29 pages of bibliographic references and 2300+ footnotes! A treasure. The chapter headings say it all in a few words: glass manufacturing; glass origin; cristallo and Bohemian crystal; introduction of coal heating; discovery of the astronomical refractor; optical glass; burning glass; discovery of flint glass; achromatic refractors; manufacturing of flint in France; manufacturing of achromatic refractors in France; manufacturing of flint by Guinan's process; birth of glass chemistry; modern industry of optical glass.

The fresco is broad, from quartz lenses in the ancient civilizations to our modern optical fibres, *via* astronomical refractors and processes allowing the production of large objectives. The book has definitely a French touch, but more importantly it has Véron's touch for abundant and precise documentation of details. (Incidentally, Véron has a rich unpublished biographical dictionary of French astronomers that would one day deserve meeting an enlightened publisher.)

The book offers a number of illustrations, some of them in colour. An index should, however, be included in a possible second edition or in a translation into English. In spite of this minor reservation, I warmly recommend this book even if your mastery of French is limited. The wealth of information provided, together with pointers for further reading, is so big that the most demanding readers should find enough to satisfy their hunger.

The book is available in Europe from the Museum Boerhaave, P.O. Box 11280, NL-2301 EG Leiden, The Netherlands. Interested readers from North America should approach Mrs. Joyce Hay, Library Acquisitions, Canada Science & Technology Museum Corp., 2421 Lancaster Road, Ottawa ON, K1B 4L5, Canada. — A. HECK.

**An Introduction to Radio Astronomy, 3rd Edition**, by B. F. Burke & F. Graham-Smith (Cambridge University Press), 2009. Pp. 444, 25 × 18 cm. Price £40/$75 (hardbound: ISBN 978 0 521 87808 1).

This is the third edition of a book that many graduate students and others will find a valuable reference work. It covers the practicalities of making radio observations, from the basics to advanced concepts, in about the first third of the book, and then ten chapters cover the application of these techniques to various branches of astrophysics. This edition is about 30 pages longer than the last one. Much of the extra space goes into discussions of cosmology and in particular the advances brought about by the microwave-background observations in the last few years, and the remainder on descriptions of a number of current developments in radio-telescope design and construction. Some of the earlier parts of the text have been rearranged and tidied up, for example, the figures have been improved by re-setting the text for the labels and annotations in a more consistent style. The list of references looks comprehensive, and there is a good index (though without the luxury of an index of astronomical objects; a few make it into the main list). I still maintain the view that we should push the subject towards consistent use of SI units (those of us who teach undergraduates try not to think of anything else), but here we have the usual hybrid mix of units and equations. This edition is only available as a hardback. There are a few typos, but I found nothing worthy of this *Magazine*'s *Here and There* column. — GUY POOLEY.

**Cosmic Noise: A History of Early Radio Astronomy**, by W. T. Sullivan III (Cambridge University Press), 2009. Pp. 542, 25·5 × 18 cm. Price £85/$140 (hardbound; ISBN 978 0 521 76524 4).

This remarkable book is a complete and encyclopaedic history of radio astronomy up to 1953. Early attempts at receiving radio waves from the Sun dating back to 1900, the successful detection and mapping of cosmic radio noise by Jansky and Reber, and the development of the main research groups after World War II, are described in meticulous detail. The foundations of meteor radar, the hydrogen line and its revelation of Galactic structure, surveys of radio sources, cosmology, the physics of radio emission, and the techniques of aperture synthesis, are all rooted in the years 1946–53; their logical development is lucidly presented in separate chapters.

Sullivan has assembled an impressive archive of all available material from this early period, including correspondence and interviews with almost all the main participants, and a fascinating collection of photographs. I was involved from 1946 onwards, but nevertheless found something new to me on almost every page.

Such a complete account of the early days of a new science affords a rare opportunity for sociological studies. Sullivan is well equipped for this, and skilfully handles the complex relationships between the parvenu radio astronomers and their traditional optical counterparts, and between the competitive radio groups. The various problems of funding, and the effect of differing wartime radar experience in the USA, UK, and Australia, are particularly well presented.

This book is the product of a lifetime study: it was 38 years in writing, and the contract with Cambridge University Press was dated 1984. The author, and the Press, are to be congratulated for their persistence. The result is beautifully presented. It is a work of outstanding and excellent scholarship. — F. Graham-Smith.

**The Low-Frequency Radio Universe** (ASP Conference Series, Vol. 407), edited by D. J. Saikia, D. A. Green, Y. Gupta & T. Venturi (Astronomical Society of the Pacific, San Francisco), 2009. Pp. 457, 23·5 × 15·5 cm. Price $77 (about £50) (hardbound; ISBN 978 1 58381 694 3).

Many early observations in radio astronomy were made at metre wavelengths (frequencies from tens to hundreds of MHz). The technology was more manageable, but the long wavelengths meant that high resolution could only be achieved by using large arrays and, in particular, aperture synthesis. Observing frequencies have been moving up through the band, with ever-improving resolutions and sensitivities, but there has been renewed interest in recent years in going back to metre wavelengths. In no small part is this a result of the *Giant Metrewave Radio Telescope* (*GMRT*), which is run by the TIFR and situated in Pune. The telescope, which observes at frequencies from 50 MHz to 1·4 GHz, has been in operation for about a decade and is still being developed. This meeting was a tribute to the founder of the Tata Institute of Fundamental Research (Homi Bhabha) on the centenary of his birth, and to a significant extent also to the telescope and its team. There are also contributions relating to other instruments operating in the same part of the radio band (*WSRT*, *LOFAR*, the *VLA* at 74 MHz, and a number of embryonic systems around the world). This volume shows the strength of the research in a wide range of astrophysical and technical areas. Telescopes such as *GMRT* are only possible because of the continuous improvements in computing and data reduction, in part because one of the big limitations is imposed by the ionosphere's variable and sometimes dramatic phase screen.

Like many conference reports, there is something for everyone in this volume. It is well produced, with my only criticism being that some of the diagrams are really hard to resolve. Maybe some of the snapshots of the participants, used throughout as page-fillers, could have been shrunk to allow the science to become clearer. — GUY POOLEY.

**.astronomy: Networked Astronomy and the New Media — Cardiff 2008**, edited by R. J. Simpson & D. Ward-Thompson (Canopus Academic Publishing, Bristol), 2009. Pp. 197, 21 × 15 cm. Price £19·99 (ISBN 0 9549846 9 2. Proceedings are only available on-line; for more details go to http://dotastronomy.com/).

The pronunciation for the title of this book is 'dotastronomy' and it is intended to draw attention to the use of new electronic media in astronomy. The book contains the papers which were presented at a conference held in Cardiff in 2008 September. In keeping with the ethos of this conference, not all participants or presenters of papers were physically present in Cardiff. Some of the contributions were transmitted to the meeting over the World Wide Web and indeed the conference was both 'blogged' and 'twittered' while it was proceeding. 'New media' are the buzz words much in evidence here, and internet-based means of both content delivery and communication such as 'blogs', 'podcasts', and 'micro-blogging' (*e.g.*, 'twitter' or 'tweeting') are enthusiastically being adopted by many of those who were involved in this conference.

The book is in three sections, the first of which deals with 'Tools and technology'. Andy Lawrence gives an overview which will be useful to those new to this field. Carol Christian and Alberto Conti, presented their paper in a live video link from the USA. They describe the creation of *Google Sky* and how they hope to see it develop. The contribution by Robert J. Simpson contains more information than can be contained in only part of a review. He describes many applications which he, and others, have created to allow many data sets to be incorporated into *Google Sky*. Iain A. Steele argues that "the invisible hand of the market" will allow robotic telescopes to be employed efficiently and uses the *Liverpool Robotic Telescope* as an example. Mark Holliman describes the use of 'PaperScope' to view graphically the relationship between various publications, and gives examples.

The next section of the book is termed 'Citizen astronomy'. Chris Lintott describes Galaxy Zoo (see also **128**, 342). E. S. Lakdawalla shows how amateurs can make visually appealing images and also how, by using archival data, new discoveries can be made. *The Faulkes Telecope* project team outline the use of those telescopes by schools and others not only to obtain visually pleasing images but also to make scientific discoveries. Ian Robson describes the International Year of Astronomy (IYA) from a UK perspective and R. Doran relates how the IYA can be used to train teachers in astronomical matters in order to educate their pupils better, as part of the Galileo Teacher Training Programme.

In the final section of the book, 'New media', S. R. Lowe shows how using 'AstroTwitter' allows both amateur and professional observers to know what is being observed by the world's telescopes in real time. This not only applies to Earth-based telescopes but also, for example, to *Mars Phoenix* and other off-world telescopes. N. J. Rattenbury describes the twice monthly 'Jodcasts' which allow the public to interact with the Jodrell Bank team. Gomez, Gomez &

Yardley show how the use of Facebook, Bebo, or MySpace, allow investigation of the statistics behind interactions and the development of new programs; their own particular example is 'The Impact Calculator'. Finally Pamela L. Gay describes a world in which all persons with access to a PC or a mobile phone can ask questions, receive answers, and generally interact with the rest of the astronomical world

The enthusiasm and skill of the contributors to this book is evident. So is their lack of understanding on just how far behind them many people are in their understanding of the terminology used. One contributor uses at least twenty-four acronyms which are not explained. If you do not know what a 'mash-up' is or a 'cron job' then you will be left wondering. There is no discussion of the accuracy of the data. It seems to be generally assumed that modern data will have few systematic errors. There are no suggestions as to how it will be possible to carry out continuous observations on those objects for which it is required.

The book has many useful references to web sites which allow the reader to 'log on' and personally investigate the potential of this technology. It can be recommended as an introduction to the subject, although those who are already familiar with the workings of some of the technology described will get more from the book than those to whom this is all new. — E. NORMAN WALKER.

**Future Spacecraft Propulsion Systems: Enabling Technologies for Space Exploration, 2nd Edition**, by P. A. Czysz & C. Bruno (Springer, Heidelberg), 2009. Pp. 584, 24·5 × 17·5 cm. Price £135/$209/€149·95 (hardbound; ISBN 978 3 540 88813 0).

For the past 50 years, humankind's exploration of space has been limited by the chemical-propulsion systems which are used by every nation's launch vehicles and spacecraft. Although other power sources, such as nuclear fission and fusion, have been envisaged for many decades, most of them remain only dreams.

In this updated and revised edition, the authors discuss the main characteristics, advantages, and disadvantages of different spacecraft-propulsion systems, ranging from launchers designed to reach Earth orbit to deep-space probes and interstellar explorers. Their book describes in detail the shortcomings of current systems and the requirement to develop new, low-cost launch vehicles and space tugs that are capable of conducting sustained operations in low Earth orbit. Meanwhile, in order to establish a permanent human 'presence' in the Solar System and to explore out to the boundary of interstellar space, they call for renewed development of advanced nuclear or high-energy space-propulsion systems. The book concludes with a discussion about the possibilities and issues associated with interstellar travel and future exploration of the Galaxy.

Aimed at a technically literate readership, the book is particularly thorough in dealing with the potential and drawbacks associated with various types of nuclear propulsion. The authors are on less familiar ground when discussing planetary science and astronomy, often using references to various popular publications, rather than scientific literature. However, the main drawback of the book is the limited editorial overview. The text suffers from a fair amount of repetition, plus numerous minor spelling and grammatical errors, and a failure to revise the main index. In my review copy, an entire section of more than 30 pages was missing, while another section of 25 pages, including colour plates, was duplicated. This is most unfortunate in a volume that has such a high retail price. — PETER BOND.

**Cosmic Collisions: The Hubble Atlas of Merging Galaxies**, by L. Lindberg Christensen, D. de Martin & R. Yumi Shida (Springer, Heidelberg), 2009. Pp. 144, 30·5 × 25·5 cm. Price £29·99/$39·95/€39·95 (hardbound; ISBN 978 0 387 93853 0).

Astronomers now recognize that mergers between galaxies are central to the evolution of the large-scale structure of the Universe. These encounters determine not only the morphology of galaxies but to a large extent their stellar contents. And perhaps most surprising of all, these gigantic collisions appear to fix the growth rate of each galaxy's central supermassive black hole. For all these reasons this field is now highly active, attracting observers and theorists alike. In terms of public interest, it also benefits hugely because of its striking visual appeal.

This book is well positioned to profit from all this. As we all know, the *Hubble Space Telescope* in its various instrumental incarnations has provided a matchless wealth of astronomical images at various wavelengths. But even by these high standards the selection presented here is spectacular. The authors have chosen well in both scientific and visual terms. They give a clear account of current thinking about galaxy evolution, and have selected superb images to illustrate this. The production of the images on the page is exemplary.

With only 144 pages this is not a cheap book. However, ensuring that your library has a copy can hardly fail to pay dividends in terms of student interest. — ANDREW KING.

**MHD Flows in Compact Astrophysical Objects: Accretion, Winds and Jets**, by V. S. Beskin (translated from the Russian by N. A. Ivanova) (Springer, Heidelberg), 2010. Pp. 443, 23·5 × 15·5 cm. Price £77·50/$129/€89·95 (hardbound; ISBN 918 3 542 01289 1).

Author Beskin was the last student of Sergey I. Syrovatskii, to whom he dedicates the book and to whom he attributes his preference for exact solutions to approximate equations over approximate solutions to exact equations (as advocated, for instance, by Yakov B. Zel'dovich). The volume primarily addresses the Grad-Shafranov approach to describe axisymmetric stationary flows around astrophysical objects, including ones where General Relativity is important. Thus accretion discs, stellar winds, jets, active galactic nuclei, and magnetospheres are all part of the universe of discourse (but cosmology is not!). Each chapter has an abstract and an introduction to the kinds of sources to which its equations apply. The equations number more than 1000 and the problems more than 100, most of the form "Show that ..." or, occasionally, "Explain ...." or "Check ...", extending the solutions derived in the text to more complex situations. The 22 pages of references (from Abramowitz to Znajek) cover the Russian literature far more thoroughly than is usual in books written originally in English. There has been some updating of references and text since the Russian original was published in 2005. Grad and Shafranov themselves are each represented by only one short paper among the references, but Syrovatskii gets none at all, and author Beskin is first author of a whole page of 30 references. I am currently debating whether this volume stays upstairs in my office to look up formulae in or goes down into the astrophysics-group reading room because others may be able to make more use of it than I can. — VIRGINIA TRIMBLE.

**Heliophysics: Plasma Physics of the Local Cosmos**, edited by C. J. Schrijver & G. L. Siscoe (Cambridge University Press), 2009. Pp. 435, 25·5 × 18 cm. Price £40/$60 (hardbound; ISBN 978 0 521 11061 7).

I was immediately attracted by this book. It encapsulates a key theme in modern Solar System science — namely the gradual drawing together of all those sub-disciplines that study Solar System plasma environments, *i.e.*, solar physics, solar-terrestrial physics, the magnetospheres and aeronomy of other planets, moons, and comets, plus the study of the solar wind and its interaction with the interstellar medium. This drawing together has gathered pace throughout the first decade of the 21st Century; it has now become a global community project under the title of "heliophysics" and has a clear focus on understanding the fundamental processes that determine the behaviour of cosmic plasmas.

This book is a deliberate step in that project. It is the first of a series of three volumes that aim to provide material for training post-graduates and advanced under-graduates in the concepts that underpin and unify heliophysics. This first volume seeks to provide an overview of the whole area with a strong emphasis on plasma physics as the unifying theme. Subsequent volumes will focus on storm-like events and how long-term variations in solar activity affect the Solar System (not least the Earth).

The book comprises some thirteen chapters focussing on a range of topics within heliophysics and each written by different experts. They provide a stimulating set of material that is well worth reading. The first two chapters provide an excellent introduction to the subject and its language, including an unashamed focus on the use of mathematics to describe plasma physics. The introduction emphasizes that the key challenge in the study of cosmic plasmas is complexity — how do the existing laws of physics determine the behaviour of these complex systems and create the structures that we observe in cosmic plasmas? It brings out the rôle of magnetic fields as the unifying force in such plasmas and draws interesting comparisons between the rôles of gravity and magnetic fields as organizing factors for cosmic structures.

The emphasis on magnetic fields continues with the next four chapters looking at different aspects, including the creation and destruction of magnetic fields plus magnetic-field topologies, reconnection, and structures. These form a mixed bag of chapters. The magnetic-structures chapter is excellent and introduces some of the generic structures that appear across different plasma environments, *e.g.*, current sheets, flux ropes, and magnetic cells (the latter is a generalization of the concept of magnetospheres). The other chapters are too focussed on the rôle of magnetic fields in solar physics — a fascinating topic to be sure, but, contrary to the aims of the book, the authors fail to show how their topics apply in other Solar System environments. There is also, I feel, a lack of consistency in the way that these chapters handle the creation and destruction of magnetic fields, *i.e.*, the respective rôle of dynamos and reconnection. The chapter on creation and destruction is overwhelmingly about creation (*i.e.*, dynamos), while the reconnection chapter fails to bring out the fundamental rôle of reconnection as the destroyer of magnetic fields. This needs to be done better if the goal is to emphasize universal plasma processes.

This is followed by a chapter on the all-important topic of turbulence, which has emerged in recent years as a key issue in the dynamical behaviour of cosmic plasmas. In this book, the main focus is on turbulence in the solar wind, where a wealth of *in-situ* measurements has advanced the subject. The author cites a good example of the importance of the topic — showing that turbulent heating is a mechanism that may explain the anomalously high solar-wind temperatures observed beyond Earth's orbit (which deviate hugely from adiabatic behaviour). The chapter also touches on turbulence in the solar atmosphere and the interstellar medium, but this discussion is limited by the sparse data currently available.

There are then four chapters that give a more conventional presentation of the heliosphere, starting with a chapter on the solar atmosphere, followed by chapters on stellar winds, planetary magnetospheres, and finally solar-wind–magnetosphere coupling. Like the four chapters on magnetic fields, these chapters vary in their efforts to provide a generic view of cosmic plasma processes. The chapter on planetary magnetospheres does a good job here — pulling out general aspects of magnetospheric physics and showing how these operate in a variety of environments. In contrast, the solar-atmosphere chapter is narrowly focussed on the Sun and, to my mind, throws away the opportunity to discuss what we know of Sun-like stars. This would have enlivened the chapter and been true to the heliophysics aim of putting cosmic plasma processes in a universal context. There are similar problems with the chapters on the stellar winds (focusses on the solar wind) and solar-wind–magnetosphere coupling (focusses on Earth's magnetosphere). Both chapters would have benefitted from a short discussion on other examples of these phenomena. The chapter on stellar winds is particularly deficient here, because it fails to warn students that most of the stellar winds studied by astronomers exhibit profound differences to the solar wind. Astronomical studies have so far focussed on the slow, cool winds flowing out of stars more massive than the Sun. These are rich in species with bound electrons and therefore can absorb and emit electromagnetic radiation; thus these winds are driven by radiation pressure and can be observed spectroscopically. The winds of Sun-like stars are hard to observe because they are dominated by protons and therefore emit little electromagnetic radiation.

The final two chapters are more clearly aligned with the aim of seeking out universal processes in cosmic plasmas. They both seek to compare aspects of heliophysics. The first of these chapters looks at systems where inter-particle collisions are an important part of the physics, focussing mainly on Earth's ionosphere, but also drawing comparisons with the solar chromosphere. This is a very welcome step. The terrestrial ionosphere is by far the most accessible example of a cosmic plasma in which collisions play a major rôle. Studies of similar plasma régimes in the solar atmosphere and more distant objects (*e.g.*, accretion discs) can only benefit from comparative studies with the ionosphere. The final chapter presents a review of planetary environments across the Solar System. It first discusses general properties such as magnetic fields, magnetospheres, plasma sources, and dynamics (including the suprathermal particles almost always present in Solar System plasmas). It then reviews the environments of major magnetized objects other than Earth, *i.e.*, Jupiter, Saturn, Uranus, Neptune, Mercury, and Ganymede, and finishes with a short discussion of environments around non-magnetized objects, in particular Venus, Mars, and Io.

I found this to be a fascinating book and well worth dipping into to learn about many aspects of heliophysics. However, the book as whole does not live up to its goal of unifying the subject and discussing universal plasma processes. Some chapters do this brilliantly but others are overly focussed on the sub-disciplines within heliophysics and lack the wider vision needed. Another problem with the book is that some chapters use SI units, but others use cgs units. This inconsistency is particularly irritating given that the formulation of many plasma-physics equations is dependent upon the choice of units. The educational aims of the book would have been better served by consistent use of the modern SI system. This would make it more accessible to new graduates and to scientists in related disciplines such as laboratory plasmas, as well as those in areas of heliophysics where SI is already standard.

Having noted these problems, I still consider it to be a valuable addition to the literature and an excellent step towards developing heliophysics as a primary discipline. I am happy to recommend it as background reading for students coming into the discipline (and I note that the price is quite reasonable for a book of this kind and that you can already find good deals on the web). I would also recommend it to any astronomers who wish to learn what heliophysics has to contribute to our understanding of universal astrophysical processes. — MIKE HAPGOOD.

**An Introduction to the Theory of Stellar Structure and Evolution, 2nd Edition**, by D. Prialnik (Cambridge University Press), 2009. Pp. 314, 25·5 × 18 cm. Price £37/$70 (hardbound; ISBN 978 0 521 86604 0).

At least ten textbooks on stellar structure and evolution have appeared since 1990. The authors invariably describe the intended readership as advanced undergraduates and beginning graduate students. Of the ten, Prialnik's is probably the best designed, in length and level, for the undergraduate. I used the first (2000) edition that way once, before switching over to the 2004 second edition of *Stellar Interiors: Physical Principles, Structure, and Evolution*, by C. J. Hansen, S.D. Kawaler & V. Trimble (HKT)(conflict of interest statement!)

Prialnik's second edition differs from the first in the addition of chapters on mass loss and interacting binaries (her own territory) and a tidying up of the solar-neutrino problem. The discussions of basic principles and applications have mostly and deliberately been left unchanged, along with the use of historic results, to emphasize that stellar structure and evolution is a well-established physical theory, despite its complexity. Some topics, for instance the contribution of brown dwarfs to galactic dark matter, would have been better updated.

I particularly like the figures the author uses to illustrate the various standard sets of nuclear reactions, For instance, p–p I, II, and III are somewhere between a balloon man losing his wares and an Arthur Murray diagram of the rumba. Her description of why stars become red giants is an honest one — equationless words simply cannot do justice to the issue.

But some things that were wrong the first time around still are. One does not see extra helium in AGB stars — they are too cool. But the *s*-process excesses (including the very existence of Tc) that really are a signature of thermal pulses and mixing, go unmentioned (see p. 69 of HKT). Neon burning is missing from the advanced nuclear stages (p. 312 of HKT). And, curiously, given that it is the author's bailiwick, the new chapter on interacting binaries has no dwarf novae (HKT, pp. 91–93).

A number of historical notes do as good a job as such things usually do. Credit to Strömgren as well as Eddington and Russell for appreciable hydrogen in stars is a plus, though Payne is wrongly associated with the composition of the Sun, rather than of K giants. But the discussion could easily leave the reader thinking that 50% by mass is the modern number. The transition from geocentrism to heliocentrism was, of course, more complex than could reasonably be crammed into half of p. 191, and I am not quite sure that the supernovae of 1572 and 1604 were as central as stated there.

I write in the margins of textbooks in the process of preparing lectures. The 2000 edition of Prialnik averages about two corrections and amplifications per page. But so does my most-used copy of HKT. Some readers/writers/reviewers you just cannot please! So, if indeed you need to teach (or need to learn) undergraduate stellar astrophysics, give Prialnik's second edition a try. — VIRGINIA TRIMBLE.

**Cosmology Across Cultures** (ASP Conference Series, Vol. 409), edited by J. A. Rubiño-Martín, J. A. Belmonte, F. Prada & A. Alberdi (Astronomical Society of the Pacific, San Francisco), 2009. Pp. 500, 23·5 × 15·5 cm. Price $77 (about £50) (hardbound; ISBN 978 1 58381 698 1).

This volume of the ASP Conference Series reproduces 72 papers delivered at a workshop with the same title, held in Spain in 2008 September. As its Foreword advises, the contributions range from archaeoastronomy *via* the "science" of the middle-ages to modern cosmology. They have been grouped into epochs, and each sub-section actually stands alone but is the better appreciated when viewed as part of humanity's combined efforts to relate life to the cosmos. One thing they all share is the need for more and better observational data.

The book commences with a number of aspects of 21st-Century cosmology, and although it is doubtless up to date and as accurate as it can be I felt it was unfortunate to place that sub-section first. By focussing first on matters highly analytical, it left me hoping that the more archaeoastronomical studies would likewise concentrate on relationships between data (of whatever kind) and the cultural thinking of the time. In that sense I was disappointed. The many studies of stones, structures, remains, and sightings are as thorough as the data permit, but many of the hard facts cannot unfortunately be much more than conjecture. So, since it would have been premature to present astronomical, astrological, or spiritual relationships between former civilizations and their celestial universe as other than the designs of primitive calendars, what I really took to task was the title of the book. Modern cosmology is mathematical, rigid, global, and intentionally devoid of cultural biasses, whereas what the archaeoastronomy papers try to express is the extent to which actual astronomy (chiefly in some form of calendar, *e.g.*, by encapsulating the azimuth of some celestial event in the alignment of a structure) has or has not been significant for each locality and people. These two interpretations of 'cosmology' are different animals, and I felt it a bit ambitious to glue together the whole mixture between the same pair of covers. But it's an interesting collation of many different studies searching for some commonality.

The Foreword states that the workshop's programme had arranged its papers in a grand mixture and that they were re-ordered into epochs for the printed version. Having seen the on-line programme I'm not convinced that the shuffle was such a good thing; certainly, some papers can be logically grouped, but there are always ones that straddle several boundaries at once and muddy the organization.

My major concern is the writing. Many of the authors are not native English speakers, and neither are the editors. Many of the papers contain errors of grammar, spelling, and word choice and include invented 'scientific' terms, and while a reviewer whose native tongue *is* English should not carp at the disadvantages which other authors face — and usually overcome supremely well — I did find it much easier to read, and thus to appreciate better, the papers whose writing was fluent and correct. Since there were four editors (no less), surely they could have served the contributors better.

Having said all that, I must emphasize that this book represents a vast amount of scholarship, information, and variety. It should be in the library of every history-of-science (or history-of-astronomy) department, and should be recognized as a valuable reference source on all these issues down the ages — whether or not they do in fact offer much insight into any cultural connections. — ELIZABETH GRIFFIN.

**Universe or Multiverse**, edited by B. Carr (Cambridge University Press), 2009. Pp. 517, 24·5 × 17·5 cm. Price £29·99/$49·99 (paperback; ISBN 978 0 521 14069 0).

Suppose you are a regular player of the National Lottery: you know the chances of winning are rather small, but it's just a bit of fun. Then the TV cameras turn up and you realize that it could indeed be you. The interviewer asks if you feel surprised, and you say "Well, millions of people enter. Someone's going to win; whoever they are, they'll feel special — but they aren't". Then the interviewer says "Fair enough, but the strange thing is that yesterday you were the only person who bought a ticket, and yet you still chose the right numbers". You would conclude that the interviewer was lying: the only realistic way to generate a winner of such a process is if there are also a lot of losers.

This analogy captures where we stand in cosmology and fundamental physics. Our lottery numbers are the parameters of physical theories (28 masses and coupling constants in the Standard Model alone, plus the gravitational constant and the cosmological constant). It is easy to imagine changing these from their observed values, and the consequences for life are usually deeply unpleasant. For example, the cosmological constant $\Lambda$ is between $10^{60}$ and $10^{120}$ times smaller than the zero-point energy from field modes up to a cutoff at 1 TeV or at the Planck scale. And yet raising $\Lambda$ by only a factor 10 to 100 would almost entirely suppress the formation of galaxies, stars, and planets. Similar arguments can be made for other parameters. In short, the Universe has won the mother of all lotteries; how did this happen? You can argue that the laws of physics are designed for life (a view proposed by Hoyle and by Dyson) — and this is certainly an interpretation that appeals to the religious mind — but an alternative is to reason as with the lottery example: there must exist an ensemble of Universes (the Multiverse), most of which are indeed unspeakably hostile to life.

This Multiverse hypothesis is increasingly discussed in cosmology, and often generates strong feelings — usually because it comes coupled with 'the A word'. The Anthropic Principle is a term coined by Brandon Carter in 1974 to describe the inevitable selection effect in which observers will only see Universes that permit life. This sounds like common sense, but has aroused great hostility over the years, with anthropic reasoning being dismissed as a tautology that is unscientific and tantamount to a form of religion. Into this heated debate has boldly stepped Bernard Carr, producing a volume with 28 articles, which largely summarize the issues discussed at conferences in Cambridge (2001) and Stanford (2003). Let it be said at the outset that this is a very fine volume, which covers all the essential arguments in some detail, giving space to the leading researchers who have explored the implications of the Multiverse, as well as to critical voices. In both respects, it moves the argument on to a new level from the still-valuable 1986 book by Barrow & Tipler.

This subject generates a set of 'Big Questions', particularly the physical reality of members of the ensemble, how different laws of physics might arise in them, and how all this might be tested. Regarding testing, Carr makes a nice analogy with the Earth. It seems unlikely that the Earth was placed by hand at just the right distance from the Sun to permit liquid water, so we can be pretty confident that Earth-like planets will in due course be detected at all sorts of distances from their primaries. But the circularity of the orbit is also relevant, and a highly elliptical orbit would disfavour life; thus it is also no surprise that the eccentricity of Earth's orbit is small (roughly 2%). But from the point of view of conditions in an ensemble that favour life, there is no need for it to be 0·000 001. Thus one could have predicted an eccentricity of order 0·1 before it was ever measured. This same argument was used by Steven Weinberg in 1989 to predict a non-zero cosmological constant at the observed level, an argument that he recapitulates in the book. Critics (Lee Smolin here) complain that Weinberg assumed that only $\Lambda$ varied between members of the ensemble. To know if this is a valid criticism, we need to understand what generates the ensemble. The book discusses various alternatives — the 'many worlds' of quantum mechanics (Carter); the fashionable 'string landscape' (Susskind; Kallosh). There is even a theist take on this (Robin Collins), in which the generation of the Multiverse is seen as the ultimate hand of the Creator. The exciting frontier of this reasoning is to search for evidence, not only that the ensemble exists, but also what aspects of physics might vary within it. In this book, perhaps the most thought-provoking argument of this kind is the one concerning the energy scale of 246 GeV found in the Higgs potential. This number is seen as 'un-natural' in the sense that it is not protected from quantum corrections raising it to much higher levels. But, as summarized by Linde, it appears that changing its value by as little as 1% would result in a universe devoid of carbon or oxygen. Arguments such as this, together with Weinberg's prediction of $\Lambda$, are persuading increasing numbers of physicists and cosmologists that the idea of observational selection in the Multiverse must be considered seriously — even though the controversy will doubtless continue. This book will be essential background reading for anyone who wants to engage seriously on either side of the debate. — JOHN PEACOCK.

**Exact Space-Times in Einstein's General Relativity**, by J. B. Griffiths & J. Podolský (Cambridge University Press), 2009. Pp. 525, 25·5 × 18 cm. Price £75/$125 (hardbound; ISBN 978 0 521 88927 8).

This book discusses a wide range of exact solutions to Einstein's field equations, and explores their structural properties. It will be of interest to anyone who wishes to gain a deeper understanding of spacetimes and their attributes, such as singularities and horizons. It is fairly specialized and a high degree of mathematical competence is assumed, so I think the target readership will principally be researchers in relativity, but it also acts as a valuable resource for a wider group who may consult it to understand better some of the more common metrics. The layout is logical, with an introduction which introduces concepts such as the algebraic classifications of spacetimes, and then considers a number of solutions, generally increasing in complexity, from transformations of the Minkowski metric, through the Schwarzschild metric and its generalizations, to some which are complicated but physically interesting; if you want to know the metric of an accelerating, rotating, charged black hole, you will find it here, with a cosmological constant thrown in for good measure. Some metrics, which may be of no physical interest, are also discussed where they help to illustrate some points. It is not completely comprehensive, deliberately so, in order that at least some of the metrics can be discussed in some detail, but references are included so the book also acts as a good literature review. The formal structures of the spacetimes are explored quite comprehensively. On the other hand, explanations of the physical and geometrical character of the solutions vary in how extensive they are, but there was only one occasion, in the discussion of wormholes, where I felt a fuller discussion might have been beneficial. The situations described are not confined to the most obvious: there is, for example, quite an extensive discussion of the non-linear interaction of plane wave-like phenomena, which is illuminating.

In all, this is a formidable achievement, bringing together a wide range of exact solutions to Einstein's equations, and exploring their formal structure and physical properties. It very much does 'what it says on the tin', confining itself largely to those issues, with a little context discussed briefly where relevant. It is well illustrated, with extensive use of conformal diagrams, and will act as a valuable library resource. — ALAN HEAVENS.

**Bang! The Complete History of the Universe**, by B. May, P. Moore & C. Lintott (Carlton Books, London), 2009. Pp. 200, 28 × 23 cm. Price £16·99 (paperback; ISBN 978 1 84732 336 1).

This is the third, updated edition of this publication, previous editions having been translated into 13 languages and sold over 150 000 copies worldwide. In its 200 pages it takes the reader on a journey through time — from the Big Bang to the present day. The main titles of the seven core chapters are clear indications of how the story is treated — 'Genesis: in the beginning', 'And then there was light', 'The evolving Universe', 'Stars and planets', 'The emergence of life', 'Into the future', and 'The end of the Universe'. Overall it succeeds in telling a clear, intelligible story. The text is light and chatty and the graphics very clear and well executed. The balance of text to images is good, whilst the images and their reproduction are superb. The core of the book spans 133 pages. This is followed by a section (18 pages) of 'Practical astronomy'. The final chapter contains a 16-page section on biographies of famous astronomers. Whilst this chapter provides extremely useful and relevant information to complement the story, the practical-astronomy section seems rather out of place and is of poor quality. In addition, the star maps are not the best I have seen. There are so many good books for the amateur observer that these pages might have been better filled with more of the core material of the book, with perhaps a reference to some of Patrick's other excellent publications. Finally, it is a great pity that there are a few inaccuracies. For example, on page 114 it says that "The Moon stabilises the tilt of the Earth's axis, which is currently 23 degrees…". However, the whole package is of high quality and will make a valuable addition to the library of anyone interested in the evolution of the cosmos. — JOHN GRIFFITHS†.

**The Cosmic Keyhole: How Astronomy is Unlocking the Secrets of the Universe**, by W. Gater (Springer, Heidelberg), 2009. Pp. 247, 24 × 16 cm. Price £26·99/$29·95/€29·95 (hardbound; ISBN 978 1 4419 0512 3).

This is a series of short essays of topics of interest in modern astronomy. The author previously worked in the public-outreach departments of both the European Southern Observatory and *Hubble Space Telescope*, so not only does he possess a flair for this work, but he has also been in close proximity to two of the most advanced astronomical research institutions on the planet. This experience manifests itself in the ability to take cutting-edge research topics and present them at a level which is both clearly explained and informative without being too simplistic, which is quite a task but one the author manages with skill.

† The Editors sadly have to report the untimely death of Dr. Griffiths on 2010 April 9.

The contents are divided into four topics: 'Water and the search for life in our Solar System', 'Our active Solar System', 'Worlds around other stars', and 'The Universe at large'; eleven essays in all, averaging about 20 pages each. No attempt is made to include the latest news and the epoch of writing appears to be around mid-2008, but in any case being up to date is clearly not the intention. Rather, each essay gives the impression of being thoughtfully constructed from the available material, which, given the journalistic origins of the author, means that many of the references at the end of each chapter are press releases instead of the inevitable, but later, scientific papers which result from the important observations being made and described within. There are some colour plates in the centre of the book which more or less correspond to the topics in the text but are not referred to specifically, and some, especially those at half-page size, are rather on too small a scale to be really useful.

A few slips or infelicities were noted — for instance, we are told that as it was buffetted in the upper atmospheric hazes of Titan during the descent stage, *Huygen*s was tilted by as much as 20°C [*sic*], and that for many years spectrographs were capable of detecting "wobbles" of several metres per second where surely kilometres per second is meant here. Actually the units come out as 'meters' since American English seems to be the main standard which Springer apply to their general-interest astronomy books at least.

On the whole, this is a considered, well-written, and informative book which can be dipped into as the fancy takes one. — ROBERT ARGYLE.

**Heaven's Touch**, by J. B. Kaler (Princeton University Press, Woodstock), 2009. Pp. 264, 24·5 × 16·5 cm. Price £16·95/$24·95 (hardbound; ISBN 978 0 691 12946 4).

This book covers the whole of modern astronomy at a popular level. The theme of the book is that, however vast and complex the Universe may be, it is always subtly connected with humanity.

It was light that originally communicated the contents of a very limited universe to humanity, but nowadays knowledge of a much greater universe reaches us from radiation at all wavelengths, as well as from particles. Our interaction with the Moon comes from the tides and the variable illumination of the night sky. The Sun is our primary radiation source and also affects us by its magnetic field and solar wind. Seasons arise on Earth because of the obliquity of the ecliptic. Over many thousands of years the obliquity, and the Earth's perihelion, eccentricity, and inclination, change cyclically from the gravitational pull of the Moon and planets. However, the correlation of these cycles with ice ages is not perfect. Many asteroids stray outside the main belt and can strike the Earth. A few are of such a size as can precipitate widespread extinctions but there are many smaller that can reach the Earth's surface relatively harmlessly. Iron meteorites were probably mankind's first source of weapons-grade iron, which in turn affected the course of human history. Comets may have been the source of water on the Earth's surface or even the source of primitive life. Secondary cosmic rays are a further source of interaction between outer space and the Earth's surface. There is an extensive description of supernovae and the part they play in the production of heavy elements, which are vital to the formation of the human body. Supernovae could be dangerous if they exploded too close to the Sun. There is a detailed list of mechanisms which might be unpleasant or even fatal to the human race if the supernova were too close. Hypernovae or gamma-ray bursts would be even worse but fortunately are much rarer. All these are aspects of the author's aim to show the multi-faceted ways that objects outside the Earth affect our lives.

Because of the great breadth of material the book does not go into great detail. It is written in a lively and accessible style which conveys a great deal of information with seemingly little effort. In some places the author's enthusiasm leads him into language reminiscent of a football match, *e.g.*, "a Coronal Mass Ejection pounding down the solar wind ... finally comes to a halt ... where it crunches against the gases of interstellar space". There is only one equation ($E = mc^2$) and all the pictures are in grey-scale. This is a book which does exactly what it sets out to do and is highly recommended. — DEREK JONES.

**The Six-Inch Lunar Atlas: A Pocket Field Guide**, by D. Spain (Springer, Heidelberg), 2009. Pp. 277, 20 × 12·5 cm. Price £19·99/$29·95/€29·95 (paperback; ISBN 978 0 387 87609 2).

This volume is designed as an easy reference companion for the amateur telescopic observer who does not want the inconvenience of using large-scale (and expensive) lunar atlases in dark and damp conditions. It provides finder charts for some sixty popular lunar formations, as well as a more detailed photographic chart for each of those features alongside a short descriptive text. It should be noted, however, that the volume is not a comprehensive atlas of the entire visible surface of the Moon — the concentration on specific features means that many areas go completely undescribed.

Apart from physical convenience, this volume has other positive qualities. For a start, it is engagingly written by an observer who combines experience of telescopic observation with an infectious enthusiasm for his subject. Moreover, for each selected feature three different charts are given that show the area as it would appear in upright, mirror-reversed, and inverted orientations. This allows the observer to map the features shown on the charts to the eyepiece views in binoculars/spotting-scopes, SCTs/refractors with diagonals, and Newtonian reflectors, respectively. This avoids the mental gymnastics otherwise required to reconcile mirror-reversed and inverted views with conventional lunar atlases or maps that usually show north at the top.

However, a volume of this nature stands or falls by the quality of its charts, and those in this volume are, frankly, poor. They are based on digital images taken with the author's six-inch refractor. The combination of modern CCD imaging with a telescope of that size is capable of producing photographs of great clarity and high resolution, but unfortunately many of the images in this book are indistinct and blurred. This fault is compounded by the author's ill-judged decision to introduce spurious contour lines in order "to give the look and feel of topographical maps". The aim may well have been to "enhance the beauty of this atlas" by reproducing the appearance of some of the hand-drawn maps of the great selenographers of the past, but the result is likely only to confuse those for whom the atlas is intended.

So, while one might admire the genuine enthusiasm underpinning this project, and indeed find value for the beginner in some of the descriptions that accompany the charts, it is difficult to recommend it as a telescopic companion. The observer wanting to get to know the stunning surface details of our satellite should turn instead either to Rukl's classic atlas (unfortunately out of print at present), or to one of the laminated field maps based on Rukl's work and published by *Sky & Telescope*. — BILL LEATHERBARROW.

## Other Books Received

**Approaches to Quantum Gravity: Toward a New Understanding of Space, Time and Matter**, edited by D. Oriti (Cambridge University Press), 2009. Pp. 583, 25·5 × 18 cm. Price £60/$110 (hardbound; ISBN 978 0 521 86045 1).

Divided into five parts, which cover fundamental ideas, string theory, loop quantum gravity, discrete quantum gravity, and phenomenology, this text for advanced researchers carries contributions from over thirty experts in the field. Each part is followed by a "Questions & Answers" session in which those experts discuss and clarify the ideas presented.

Although an accepted theory of quantum gravity would probably be of great importance in understanding the very early Universe and astrophysical black holes, the authors are all from the physics and relativity communities. The final chapter, on predictions, by Lee Smolin, mentions entropy of black holes and cosmological horizons and properties of space-times with a cosmological constant as generic consequences of quantum theories of gravity. — Virginia Trimble.

# THESIS ABSTRACTS

## Cosmology: Small and Large

*By Andrew Pontzen*

The ultimate aim of cosmologists is to understand the nature of the Universe in which we live today: both its constituent galaxies and the nature of its large-scale conditions are of interest. In this thesis, we consider two contemporary difficulties relating to observations concerning each of these areas, respectively.

We investigate first the population of $z = 3$ damped Ly-α absorption systems (DLAs) by using a series of high-resolution galaxy-formation computer simulations. The precise rôle of DLAs in galaxy formation remains in debate, but they provide a number of strong constraints on the nature of bound systems at $z = 3$ through coupled information on neutral-H I densities, kinematics, metallicity, and estimates of star-formation activity. Our simulations correctly reproduce a range of observational statistics, including the incidence rate and column-density distributions of DLAs and, for the first time, the distribution of DLA metallicities (with a median of $Z_{\rm DLA} \cong Z_\odot/20$). We link this success to the inclusion of strong stellar feedback in our simulations, inhibiting star formation in low-mass halos. This type of prescription is central to recent progress in matching $z = 0$ galaxy properties and mass–metallicity relations, suggesting that a coherent picture is emerging.

Our description could be undermined if metal-rich DLAs are, after all, present in the Universe, but contain sufficient quantities of dust to obscure their background quasar from optical surveys. Previous efforts to estimate from observational data the severity of such a bias have reached differing conclusions. We place our own constraints on the effect by performing a Bayesian parameter-estimation analysis of a simple dust-obscuration model, using all available observational datasets. Optical measures of the mean metallicities of DLAs are found to underestimate the true value by just 0·1 dex; this confirms that our simulation results do not need to be corrected for such an effect. We verify that, under our model, all observational datasets are consistent and we give reasons for the apparent tensions in previous analyses.

We then turn to the large-scale Universe and in particular the cosmic microwave background (CMB); the constituent photons of the CMB last interacted with matter when the Universe was around one ten-thousandth of its current age. From the perspective of the standard paradigm, in which the Universe is homogeneous and isotropic on large scales, there are anomalous aspects of the CMB signal which have not yet been explained. Consequently, interest in the Bianchi universes, which are homogeneous but anisotropic, has been increasing: Bianchi models have been found to induce temperature anomalies similar to those observed.

The dynamical solutions employed in earlier analyses of the Bianchi CMB are incomplete; we address this problem by deriving the general dynamics of those Bianchi universes which are close to, but not exactly, isotropic. We then compute, in the form of a multipole hierarchy, the CMB radiative-transfer equation for such models. Compared with previous calculations, this enables a more sophisticated treatment of recombination, produces predictions for the polarization of the radiation, and allows us to consider re-ionization.

We use our equations to calculate the polarization signal for the parameters which have been found to mimic the aforementioned large-angle anomalous features observed in the CMB. We predict *B*-mode polarization of magnitude $\sim 1\,\mu$K, inconsistent with known observational limits; these models are consequently ruled out. However, we use our improved dynamical analysis to show that certain Bianchi anisotropies can be hidden in super-horizon modes at early times, thus avoiding any constraints from polarization (and nucleosynthesis) while nevertheless producing non-trivial redshift-zero temperature patterns in flat and open universes. Future work will assess whether such patterns can be matched to anomalies in *WMAP* results. — *University of Cambridge; accepted 2009 December*.

A full copy of this thesis can be requested from: app26@ast.cam.ac.uk

## On the Geometry of Gravitational Lensing and Its Applications

*By Marcus Werner*

Among the many scientific anniversaries of 2009, two stand out in gravitational lensing. The first successful observation of this effect by the eclipse expedition of the Royal Society and the Royal Astronomical Society was reported in 1919 in *The Observatory* (**42**, 389), and the first extragalactic gravitational-lens system was discovered by Walsh, Carswell & Weymann in 1979 (*Nature*, **279**, 381). Over the past thirty years, then, gravitational lensing has become an important tool in galactic astrophysics and cosmology to detect dark matter and to constrain modified theories of gravity. Moreover, gravitational-lensing theory itself is mathematically interesting, with applications of singularity theory to caustics and topological invariants to image counting. In this dissertation, applications of gravitational-lensing theory in the weak-deflection limit (or strong lensing) are discussed, as well as more geometrical aspects of the theory itself. Two approaches to lensing are applied: the standard quasi-Newtonian thin-lens impulse approximation, and the optical metric, which governs the geometry of spatial light rays.

After a brief review of lensing and its history, which also includes a sketch of the 'prehistory' of the subject, a new geometrical explanation for a class of universal magnification invariants is proposed. If a light source is close to a caustic, then the sum of the signed magnifications $\mu_i$ of the highly magnified image multiplets obeys $\Sigma_i \mu_i = 0$. This has long been known to hold for folds and cusps, where this relationship plays an important rôle in the problem of dark substructure and the flux-ratio anomaly. Recently, it was shown by Aazami & Petters (*J. Math. Phys.*, **50**, 032501 & 082501, 2009) that this is true for higher singularities as well. Here, a new interpretation in terms of Lefschetz fixed-point theory is given, both for generic singularities and umbilics in lensing. In this framework, images are considered as fixed points of a suitably defined map. It therefore appears that at least some magnification invariants can be regarded as a consequence of a deep result in fixed-point theory.

Proceeding from regular to singular images, multiple Einstein rings are considered thereafter. Arcs of multiple concentric Einstein rings are now being observed, so it is worthwhile to investigate in more detail how many Einstein rings can be formed by multiple lenses and sources collinear on the optical axis. It is shown that at most one Einstein ring can be formed by a single lens, using a fixed-point method and a weak condition imposed on the lens model, namely that the projected surface density $\kappa$ always be smaller than the average $\bar{\kappa}$ within the radius (which, of course, does not even imply monotonicity of the surface-density profile). If there are two lenses in different planes, a background source may in fact produce two Einstein rings, and this is shown explicitly for two Schwarzschild lenses and singular isothermal spheres. The resulting image configurations if circular symmetry is broken are also discussed. This yields the first example of a magnification invariant for lenses in different planes.

Going beyond the quasi-Newtonian approximation to include gravitomagnetism, we revisit lensing by Kerr black holes next, and begin by giving a simple derivation of image magnifications and positions based on a degeneracy of rotating and non-rotating lenses at post-Newtonian order. This yields new magnification relations, showing also how the magnification invariant of the Schwarzschild lens is modified in the Kerr case, and a set of six lensing observables constructed from the image positions and fluxes. Supposing that images can be resolved, this would allow the measurement of the angular-momentum parameter and, hence, would complement other studies of black-hole rotation (for example, using accretion discs) and the Cosmic Censorship Conjecture. It is argued that, at least in principle, this should be possible in the near future.

Finally, returning to geometrical properties of lensing theory itself, the weak-deflection limit is considered in the context of optical geometry. This offers a new interpretation of gravitational lensing as a partially topological effect. Also, it turns out that the deflection angle can be found by integrating outwards from the light ray, which is in rather surprising contrast to the usual description in terms of mass enclosed within the impact parameter. This method is applied explicitly to the Schwarzschild lens, the Plummer model, and the singular isothermal sphere. In the latter example, the optical metric describes a cone, which shows a formal connection to lensing by cosmic strings in this case. The method is also used to investigate how an axisymmetric shape of the lens affects the deflection angle. — *University of Cambridge; accepted 2009 October.*

A full copy of this thesis can be requested from: werner@math.duke.edu

## OBITUARY

### *Joan Eileen Perry* (*1919 – 2010*)

We are sad to report that Joan Perry died in an Eastbourne nursing home on 2010 Feb 18, just a few days short of her 91st birthday. Joan was brought up in Bath and joined the Nautical Almanac Office (NAO) there in 1943 August as a shorthand typist. On promotion in 1947 April she became NAO Secretary, a post which she held for the next 18 years, and which included responsibility for the NAO's library.

When the war-scattered sections of the Royal Observatory (renamed the Royal Greenwich Observatory (RGO)) were reunited at Herstmonceux, she moved to the village in 1950 and remained there for the rest of her life. During the mid-1950s, she was involved in helping the RGO-based then-Editors of this *Magazine*, Guy Porter and Philip Gething, by addressing envelopes for the despatch of *The Observatory*, a tedious task in the pre-computer age.

A further promotion in 1965 saw her appointed as RGO Librarian, during which time she played a valuable part in the preparation of many of the Observatory's publications (*RO Annals, R(G)O Bulletins, etc.*), including editing with Bob Dickens the proceedings of the tercentenary conference, *The Galaxy and the Local Group*.

She was awarded the Queen's Silver Jubilee Medal in 1977 and retired in 1979. In addition to her official duties she was active in the RGO Social and Sports Club, serving as secretary from 1950–56, playing in the RGO Comets table-tennis team, and as organizer of the ballroom-dancing section, an interest that she continued long after her retirement. Joan was also staff-side secretary of the RGO Whitley committee for many years. In all these activities her colleagues were ever appreciative of her meticulous attention to detail and her impeccable handwriting. — GEORGE WILKINS, ROGER WOOD & DAVID STICKLAND.

## ERRATA

While the Editors and author were focussed on getting the layout of Table II in Professor Griffin's paper on the *CABS3* stars to their (and his) satisfaction (see the last issue — **130**, 64), they must have taken their eyes off the ball regarding the actual numbers appearing in that table. The table regrettably contains three errors which are corrected here: the mean velocity of HD 136655 should read $-31{\cdot}03$ km $s^{-1}$; that for HD 184591 should read $-36{\cdot}91$ km $s^{-1}$; and that for HD 195434 should be read as $-51{\cdot}08 \pm 0{\cdot}21$ km $s^{-1}$.

## CORRIGENDUM

For arcane technical reasons (that have now been dealt with!), Fig. 2 of the paper by Cano & Smith in the February issue (**130**, 14, 2010) appeared with a number of the symbols so faint that even a magnifying glass rendered them difficult, if not impossible, to discern. So below, we present a new version of that figure and at the same time tender our apologies for this lapse in the standards that *The Observatory* tries to maintain.

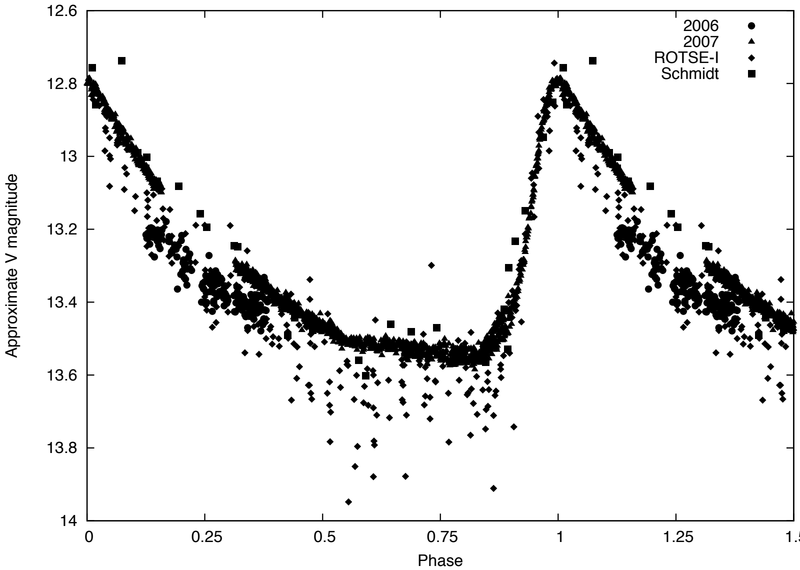


FIG. 2

The light-curve of DY And, folded on a period of 0·6030897 days. Circles are the 2006 Sussex data, triangles (the majority of the points on the main curve) are the 2007 Sussex data, filled diamonds are the ROTSE-I data, and filled squares are the data from Schmidt[6]. By eye, the asymmetry in the light curve is 0·15 ± 0·05, confirming the RRab classification[5,6].

## *Here and There*

MIGHT OCCULT CAPELLA

Titan revolves around Saturn, whose orbit is inclined at 26° 44″ to the ecliptic … — *A&A Review*, **17**, 110, 2009.

OF COURSE

The inner 600 light years of our Galaxy is a harsh realm, drenched in radiation, powerful stellar winds, crashing shock waves and, of course, the 4·3 billion solar mass black hole. — *Astronomy Now*, 2009 August, p. 13.