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MEETING OF THE ROYAL ASTRONOMICAL SOCIETY

Friday 2014 April 11 at $16^{h}\,00^{m}$
in the Geological Society Lecture Theatre, Burlington House

D. J. SOUTHWOOD, *President*
in the Chair

The President. Hello and welcome. As the Society is a charity, we must have an Annual General Meeting. This year's AGM — the 194th AGM — will take place on Friday 2014 May 9.

It gives me great pleasure to introduce our first speaker, Richard Davis from Jodrell Bank: '*Planck* results and Jodrell Bank's University of Manchester contribution'.

Professor R. J. Davis. The scientific results that I present today are a product of the *Planck* collaboration, including individuals from more than 50 scientific institutes in Europe, the USA, and Canada. *Planck* is a project of the European Space Agency (ESA) with instruments provided by two scientific consortia funded by ESA member states (in particular the lead countries: France and Italy. For the UK this is the UK Space Agency and in the past STFC and PPARC). Today I will be talking about our work at Jodrell Bank Observatory (JBO) and Bruno Maffei and his team when he was based in Cardiff.

The Cosmic Microwave Background (CMB) emanates from a time some 380 000 years after the Big Bang when the Universe cooled to ~ 3000 K and allowed recombination of the protons and electrons to form neutral atomic hydrogen. The main observational objective of *Planck* was to image the temperature anisotropies and polarization of the CMB, over the whole sky, with an uncertainty on the temperature limited by 'natural causes' and an angular resolution ~ 5 arcminutes. This has been achieved. *Planck* is a third-generation space CMB experiment after the initial discovery by Penzias and Wilson with the ensuing *COBE* and then the *WMAP* satellites. *Planck* was sent to L2, a heliocentric orbit some 1·5 million kilometres from Earth, by using an Ariane 5. *Planck* consisted of two cameras: the *Low Frequency Instrument* (*LFI*) radiometers built partly by myself and my team at JBO University of Manchester, and the *High Frequency Instrument* (*HFI*) bolometers built partly by Bruno Maffei and his team in Cardiff. Space-qualified hardware was designed and constructed and tested, and low noise temperatures were achieved at the required frequencies. All of our hardware was space qualified by vibration testing at RAL. The entire *LFI* was assembled and cryogenically tested at Laben, Milan. The whole satellite was then assembled and cryogenically tested at CSL, Liège. We achieved our required specification. The launch by ESA was the most complicated that ESA had considered to date. First it had to eject the nose cone, then *Herschel*, then the cover on *Planck*, and finally *Planck* itself. All of this was carried out perfectly — a tribute to ESA's ability and experience. *Planck* went on to perform perfectly for the nominal mission and then for a further year and a half with all instruments, then for the *LFI*-only extension, making 2·5 years of observation with *HFI* and 4 years for *LFI*. *HFI* ran out of ^{3}He as expected and *LFI* made its case for eight surveys and was sadly switched off with everything still functioning. Both instruments achieved their goals.

JBO is leading research into the low-frequency foreground emission, particularly over the diffuse regions of our Galaxy, and is responsible for much of the anomalous dust measurements. There is a tension between σ_8 (a measure of clustering on an 8-Mpc scale) derived from the CMB and S–Z counts. Two suggestions have been put forward to explain this. One is a change by a factor of two of the Y–M relationship which calibrates the amount of mass from the X-ray temperature. The other proposal, particularly favoured by Richard Battye at JBO, is to say that there must be a limit on the mass of the neutrino. He and Adam Moss have just published a paper proposing a 'sterile' neutrino with a mass of 0·5 eV which together with the other light neutrinos lowers the tension of the value of H_0 which *Planck* measures. There are nine frequency channels: the highest are sensitive to dust, the lowest to synchrotron radiation, whilst the CMB fluctuations themselves lie in the middle channels and we can extract the observed CMB from this. We get a beautiful power spectrum out to an l of 2500. We find that the omega (baryon) value has gone up, the proportion of dark energy is lower, and one of the most exciting results comes from calculating the value of H_0. This we find to be 67 ± 1 km sec^{-1}. The remarkable lensing potential at 143 and 217 GHz and thence the power spectrum and the agreement with ΛCDM is notable. The spectral index of density fluctuations (n_s) turns out to be 0·96, which is clearly seen from the power spectrum as being preferred to 1·00. This value is consistent with that determined by *WMAP* and there will soon be a new value of n_s with a smaller error.

BICEP2 claims to have detected the B-mode, which is the 'smoking-gun' of inflation. We are working hard to come up with polarization results from *Planck* and hope to detect and set limits on the B-modes. In principle, we ought to be able to measure the signals that *BICEP2* claim but that depends on controlling systematic errors and foregrounds, so I really can't say much at the moment. We plan to release our polarization maps at the end of October. One other thing: *BICEP2* is essentially based on one frequency (150 MHz) whereas *Planck* has nine frequency channels.

The President. Any questions?

Rev. G. Barber. Am I right in thinking that *BICEP2* looks at a very small area of sky, whereas *Planck* will give us a complete sky survey.

Professor Davis. I think it's about 50° by 10°, so it's still a reasonable area of the sky.

Rev. Barber. It has to be isotropic for it to be cosmological.

Professor Davis. Yes, while *Planck* covers the whole sky.

Dr. R. E. S. Clegg. Well, congratulations on a fantastic achievement. I hadn't heard before about the sterile neutrino and I wondered what particle physicists' views are on that, with reference to the Standard Model?

Professor Davis. I'm sorry it's not my field but there are some particle-physics measurements that have claimed to have detected the sterile neutrino. I think they work by knowing how many neutrinos they produce, detecting the three active neutrinos and then seeing if there is anything missing. The sterile neutrino doesn't do anything; it doesn't react. There are some experiments that give you an indication that there is a sterile neutrino but I don't know the current status fully.

Mr. M. Hepburn. The peak of the microwave background is just under 200 GHz. Are the two channels you are using equidistant from the peak energy?

Professor Davis. What we refer to as the CMB frequencies are 70 GHz, 143 GHz, 217 GHz, and 353 GHz, where we start seeing a lot of dust.

Mr. Hepburn. What I was interested in was that you showed images which you referred to as "looking at the milk float through the bathroom window". I take it one was the nearest above and the nearest below?

Professor Davis. Yes, 217 GHz is very nearly at the peak and 143 GHz is just below.

The President. Thank you very much, Richard. [Applause.] The next speaker is Peter Grindrod from Birkbeck College: 'Selecting the landing site for the ESA 2018 *ExoMars* rover'.

Dr. P. Grindrod. Mars exploration is driven by the search for life. Despite on-going exploration of potentially habitable environments in the outer Solar System, and the increasing rate of discovery of extrasolar planets, it could be argued, because of the evidence that is required, that the best chance of finding life in the coming decade lies with Mars. In 2018, the European Space Agency (ESA) will launch the *ExoMars* rover and lander to further this exploration. The key science objectives of the *ExoMars* rover are to: (*i*) search for signs of past and present life on Mars; (*ii*) investigate the water/geochemical environment as a function of depth in the shallow subsurface; and (*iii*) characterize the surface environment. To meet these objectives *ExoMars* will drill into the sub-surface to look for indicators of past life using a range of complementary techniques, including assessment of morphology (potential fossil organisms), mineralogy (past environments), and a search for organic molecules and their chirality (biomarkers).

The choice of landing site is vital if *ExoMars*' scientific objectives are to be met, although the first objective probably has the most control on the final site selected. The landing site must: (*i*) be ancient ($\geq$ 3·6 Gyr); (*ii*) show abundant morphological and mineral evidence for long-term, or frequently recurring, aqueous activity; (*iii*) include numerous sedimentary outcrops that (*iv*) are distributed over the landing region (the typical rover traverse range is only a few km, but the uncertainty in the location of the landing site forms an ellipse of size 104 by 19 km); and (*v*) have little dust coverage.

In addition, in order to land and operate safely, various 'engineering constraints' apply, including: (*i*) latitude limited to 5° S to 25° N; (*ii*) maximum altitude of the landing site 2 km below Mars' datum; (*iii*) few steep slopes within the uncertainty ellipse. These constraints are onerous. In particular, the objective to drill into sediments, the requirement for distributed targets within the ellipse, and the ellipse size, make *ExoMars* site selection extremely challenging.

To meet these challenges, a UK consortium has begun an intensive study of the Martian landscape to identify as many *ExoMars* landing sites as possible.

We have converted the current engineering constraints into spatial filters in a Geographical Information System (GIS) to define regions of Mars where landing could be possible. We have used published geological maps of Mars to define areas that are of the appropriate age, and integrated published catalogues of morphological indicators of standing water (*e.g.*, delta-like landforms) and of layered terrains, and of the locations and spectral characteristics of minerals indicative of the action of water.

Using this GIS we identified about 25 study areas that held promise scientifically, and into which one or more landing 'uncertainty ellipses' could be fitted without breaching the engineering constraints. For each of these, we obtained and processed imaging data (from the NASA *Mars Reconnaissance Orbiter CTX* instrument and the ESA *Mars Express Orbiter HRSC* instrument), high-resolution topographic data (again, from ESA's *HRSC*), and mineralogical data (based on infrared spectrometry data obtained by ESA's *OMEGA* instrument and NASA's *CRISM* instrument). Using these data we down-selected to two final sites that were officially proposed to ESA's *ExoMars* Landing Site Selection Working Group, as well as providing input on a third.

In total eight landing-site proposals were submitted and discussed at the 'First *ExoMars* Landing Site' workshop in Madrid in March. Four sites emerged as favourites of the workshop attendees, but the official down-selection to three or four sites will be made by ESA in summer 2014, before undergoing further detailed scientific and engineering-constraint analysis. The final landing site will be chosen by ESA in late 2017, before *ExoMars* launches in 2018.

The President. Questions or comments?

Mr. M. F. Osmaston. ALH 84001, with its 4·5-billion-year age, makes the place it came from especially interesting. Just like on Earth, a lot of effort goes into looking at the very oldest patches of crust. Is there any possible indication of any place that might be preferable to explore, with a crust similar to where that meteorite came from? It had only been in space for 20 million years, so quite recently there has been that sort of crust exposed.

Dr. Grindrod. You can narrow the composition down to broad regions where it might have come from with the limited spatial-composition data we have for the surface. The age might be easier to do, although when you start looking at small areas your age estimates start to become a bit uncertain because the errors over small regions become large. It terms of *ExoMars*, covering an old area, it's a bit of a double-edged sword. Although it's difficult to explore Mars because it's a different planet, actually if you want to try to access the oldest rocks it's maybe easier to get to them on Mars than on Earth. On Earth, we've had four billion years of plate tectonics and water and erosion and a lot of life, which leads to rocks being chewed up, hidden, recycled. On Mars, you may well be looking at some of the oldest crust. I think there is more of it around which matches up with the meteorite. But in terms of finding out exactly where meteorites come from, we are probably not there yet, although some people think they can narrow it down a bit.

A Fellow. An excellent talk. Why are we sending yet another rover to Mars when we've got a giant ball of ice orbiting Jupiter, a moon around Saturn that's spitting out water, and also Titan with emissions of hydrocarbons? Why are we going back to this dry, barren rock?

Dr. Grindrod. The best chance of finding life in the next few decades remains with Mars. I wouldn't argue that there aren't fantastic places in our Solar System and others where life might have existed or still exists. Europa, Ganymede, Titan's oceans, or Enceladus' oceans are great locations. The question comes down to finding conclusive evidence for life. You have to find evidence that you can hold up and say you're confident about. *Viking* taught us that even if you do have positive results, you can go back and say you're not sure. Ultimately this goes back to Carl Sagan popularizing the philosophical quote "extraordinary claims require extraordinary evidence". To find that extraordinary evidence, I think you need more than just a flyby mission, or even landing on the surface of an icy moon, because the habitable environment is actually in the ocean, which is at least 20–30 km below. Therefore, I think the best place to find life is Mars, because we know the targets to go to, they're accessible, and we can put the instruments on a mission that goes to Mars. It may well mean we need to bring a sample back to Earth because we need the precision of a lab. I don't think we should stop exploration but if we want to find life in the next 20–30 years, Mars is the place.

The Fellow. If that is the case, isn't it time for a human mission to give the flexibility of movement on the surface?

Dr. Grindrod. I'm not arguing against a robotic or human mission! I'd like to see both!

Dr. Clegg. I understand that the ancient life on Mars will be underneath the soil. I was wondering about the criteria for the sites, in terms of the aspect of the mechanics of the drilling; getting through the types of deposits and sediments on the top, to find the ancient fossil microbes and so on.

Dr. Grindrod. The main thing about the mechanics of the rover is that it has a drill that can go down two metres and bring a core back up and then analyze that sample. We have to try to pick landing sites that have widespread sedimentary layered rocks. We don't want to start drilling into basaltic lava flows that are hard and where there is a low chance of finding life. We have to pick the areas that look as if they have extensive layered deposits. Drilling down to two metres gets rid of radiation problems. We also target areas that have been exposed geologically recently — in the last few-hundred-million years. It's tough. We need the latest high-resolution images to see that. For most of the landing sites we don't actually have that many. A lot of requests went in for new data and when we get them we should be able to pick out what and where we want to drill.

Professor P. G. Murdin. The criteria that you laid down included both scientific and engineering reasons. If you made a decision based purely on the scientific reasons, which engineering constraints are the critical ones in denying access to your chosen site?

Dr. Grindrod. Someone asked that question to the lead engineer at the workshop and she said that all of them are the most important! The ones that limit us in terms of the area are the elevation, the slopes, and the age.

Professor Murdin. So, it's parachutes and rover design?

Dr. Grindrod. Yes. The age has not been taken into consideration before. *Curiosity* had this amazing system of coming through the atmosphere, meaning it could hit small targets. I honestly don't know where I'd go because when I listen to people make arguments I am convinced every time [laughter]!

The President. I think we're going to leave it there. Thank you very much indeed. [Applause.] The next speaker is James Graham from Berkeley: 'The *Gemini Planet Imager*: early science results'.

Dr. J. Graham. I want to describe the *Gemini Planet Imager* camera project which is designed to image extra-solar planets directly. With the advent of *Kepler* the number of extra-solar planets has increased hugely but the lower-mass planets are really only detectable from occultation of the host star whereas the more massive ice giants can be measured from the induced perturbation in the radial velocity of the star. Direct imaging involves two very challenging boundaries — the ratio in brightness between the host star and the planet, often more than 10^9:1, and the close angular separation, typically about 0″·1. Imaging is affected not only by seeing and diffraction, but also by atmosphere-induced wave-front aberrations. Using the first-generation AO system it was possible to discover a few extra-solar planets by direct imaging, such as β Pictoris b, which has a contrast ratio of 1200:1 with the host star.

About a decade ago we began to think about designing purpose-built AO systems to image extra-solar planets, and some of those are now coming on-line with the largest telescopes. One of them is the *Gemini Planet Imager*. The aberrations in the instrument are well controlled and the AO system is a very-high-quality device. The specific goal was to minimize internal errors and that has been largely achieved by high-density deformable mirrors. In this case we have a mirror mounted upon a silicon chip with an array of 64 × 64 actuators, each element consisting of a capacitor with a plate and a gold membrane. Extensive laboratory tests were required but the instrument achieved first light on the *Gemini South* telescope on 2013 November 11. The detector looks at the *Integral Field Spectrograph* so the raw data are hundreds of thousands of spectra. The host star is imaged on a coronagraph spot whilst an astrometric reference grid is superimposed on the field by means of a 2D dispersing prism in the pupil plane. With this set-up, β Pic b can be imaged in 60 seconds — previous *Gemini* high-resolution imagers required 4000 seconds of exposure time. The r.m.s. wave-front error delivered to the focal plane is about 90 nanometres, which is some three times better than current systems. We still need to understand how to operate the instrument under astronomical conditions. The performance of the system can be judged by the fact that the contrast being achieved is at least an order of magnitude better than any existing system. The peaks in the power-spectra density plots of the tip-tilt system show that we are still getting vibrations originating from the refrigeration system being used to cool the detector. The positional r.m.s. error is a few milliarcseconds but we want to beat it down even more. Combining thirty 60-second exposures gives us an image of β Pic b with a S/N of 100.

Although the instrument is designed as a spectrometer, we want to understand the astrometric performance so we can measure directly the orbital motion of the extrasolar planet. We have been evaluating this by observing close binary stars in the Orion Trapezium cluster, and we believe it is accurate at a level of 5 milliarcseconds, but we have yet to demonstrate long-term stability.

The astrometry shows that β Pic b has reached greatest elongation and is now heading back towards the star. We now have some information about the inclination of the orbit and it matches the interwarp disc in the debris disc. We also know that the eccentricity of the orbit is non-zero. There is a 4% *post-posteriori* probability that at conjunction the planet will pass in front of the disc of β Pic and present an opportunity for transit spectroscopy. This event will occur in 2017 and we hope to get more astrometric data before then to pin down the time of the transit more accurately. By replacing the dispersing prism with a Wollaston prism, this instrument can also be used as an imaging polarimeter allowing us to make images of scattered light in the debris disc.

The instrument is now ready for use, and there is a full data pipeline available to ingest raw images and deliver data cubes. In the longer term, Gemini Observatory has approved an allocation of 890 hours for a survey of 600 exoplanetary targets in the solar neighbourhood with ages between 50 and 150 million years. This will provide the statistics to measure the occurrence of Jovian-mass planets which orbit their host stars at distances between 4 and 40 AU.

The President. Questions?

Professor D. Lynden-Bell. I am much encouraged by these results but for a different reason. I recently got interested in astronomical objects for which one can measure both the sense of rotation and the sense of magnetic field. I found that this was impossible for almost all stars but it was possible for galaxies. It seems to me that you might be close to a breakthrough enabling you to see the sense of rotation rather than just the value of it?

Dr. Graham. That's a very interesting point. I didn't show my other favourite object, Fomalhaut, where we know from interferometry the rotation of the star. The star and the planet seem to be going in opposite directions. Also in debris discs, where there are Doppler measurements that show you the rotation of the debris disc.

Professor Lynden-Bell. I think it is true that you have to resolve something to be able to see the sense of rotation rather than the value.

Dr. Graham. The rotation of the planet?

Professor Lynden-Bell. No, the rotation of the disc, or the star in my case. Nevertheless you have to resolve it to see the direction of rotation.

Dr. Graham. That was the case with *VLTI*. So yes, that is clearly a prototype observation.

The President. This is a major achievement. Thank you very much. [Applause.] Our final speaker is Mark Burchell from the University of Kent: 'Cometary delivery of volatiles to the Moon: what can we learn in the laboratory?'

Professor M. J. Burchell. That the Moon is not as dry as previously thought is now widely accepted by lunar scientists, but the details of how wet/dry, and why, are still emerging. Models which give a lunar origin *via* a giant impact event on the Earth, with subsequent formation of a large Moon close to Earth from the resulting ejected debris, would seem to imply a lunar origin of extreme violence and heating — thus a dry Moon. The very low water content and severely devolatilized lunar surface established from the lunar samples in the Apollo era seemed to be in agreement with that.

However, since the 1970s there have been several advances. For example, a wider range of lunar materials are now available when we include lunar meteorites (which sample a much wider range of lunar sites than do the Apollo and Luna sample-return missions). They can be combined with the greatly improved sensitivity of instruments now available in the laboratory which are used to study the curated samples from the past. And a new generation of missions has been visiting the Moon and subjecting its surface to detailed analysis either from orbit or from the surface (landers or impactors). The magnitude of the recent efforts in lunar missions can be judged by considering that since 1990 there have now been 14 lunar missions, with ten of those launched in the past 11 years. They will undoubtedly continue, further increasing our knowledge of the Moon.

But where does the water come from? And are there other volatiles present as well? The current advanced analysis techniques applied to Apollo samples and lunar meteorites find water in lunar volcanic glasses, apatites, inclusions in olivines, and in plagioclase grains in lunar anorthosites. The levels can be as high as 615–1400 ppm in lunar-melt inclusions. In some cases, the D/H ratios obtained suggest carbonaceous chondrites as the source of the water. One continual source of lunar water is held to arise from the interaction of the solar wind with the upper few mm of the lunar regolith. Evidence for this

H implantation into oxygen-bearing minerals, resulting in evidence for water widespread over the lunar surface, has been reported by several missions in the current era of lunar exploration. This water may well be mobile, migrating to the cold traps of permanently dark craters at the lunar poles, where the *Deep Impact/EPOXI* mission reported up to 0·3% water by weight in 2009. The NASA *LCROSS* mission impacted one of those dark craters at the lunar South Pole in 2010 and reported that the material impacted was up to 5·6% water by weight. Importantly, it also reported the presence of other volatiles, suggesting that a non-solar-wind origin had to be at least a contributor to the water content.

If impacts by asteroids or comets are indeed delivering water and other volatiles to the Moon, then the flux delivered can be estimated. Several simulations have been reported in the last few years which suggest that, with basic assumptions about survival of the materials, impact flux rates over a period of 1 Gyr can explain the observed amounts of water. That material can successfully transfer to the lunar surface in impact events in general has been demonstrated by several reports in the last decade of grains in lunar samples with a non-lunar origin. A recent report found over 30 mineral grains in Apollo-era samples with a non-lunar origin, implying a significant survival rate for this type of material in lunar impacts despite the potentially high impact speeds and extreme shock pressures. But it would be useful to have a more detailed knowledge of the survival rate of volatile compounds in impacts to understand better the delivery of organic and more volatile materials.

We explore this point further with a recent range of laboratory impact experiments which seek to study the transfer of complex organic molecules from projectiles to targets in high-speed impacts. At the University of Kent, for example, in the last few years we have been firing organic-rich rock samples at sand or water targets at speeds of 2–5 km s^{-1}. Those impacts correspond to peak shock pressures of up to 20 GPa. Use of water targets prevents the detection of transfer of water itself, but allows ready detection of other compounds. Accordingly we recover the remains of the projectile from our targets and find the remains of many complex molecules including phytane, ββ-carotane, and three-ring PAHs.

To study this further and to simulate cometary impacts on the Moon, we have recently developed at Kent a two-stage light-gas gun which can fire frozen projectiles. We have used this to fire frozen organic compounds at sand and water targets, again at speeds from 2–5 km s^{-1}. At 2 km s^{-1}, for example, we recover from the target around 44% of dimethylsulfoxide we fire into it. More experiments are needed to increase the impact speeds further to make the shock pressures more representative of those involved in lunar impacts, and this needs to be combined with models of how long the shock pressures and resultant elevated temperatures last. But the results can start to inform larger-scale models of cometary delivery of volatiles to the Moon by combining predicted impact fluxes with survival rates of various compounds. If this is combined with the data on cometary composition from space missions to comets, such as NASA's *Stardust* mission to comet 81P/Wild-2, and the current ESA mission to comet 67P/Churyumov-Gerasimenko, a more detailed understanding of the Moon should emerge.

The President. Questions or comments?

Professor S. Schwarz. Just next to the Moon there is a very wet object; the Earth. There is some belief that a lot of the water on the Earth had to come from somewhere, perhaps from comets. Is there some cross-fertilization between looking to see what happened on the Moon and what's consistent with the amount of water there is on Earth?

Professor Burchell. I could almost have planted that question, because what I didn't say is that one of the reasons we like the Moon is that it's a very good laboratory for long-term processes in this vicinity. Whereas if you look on Earth, everything gets modified by almost everything else, all the time. The Moon is a much more stable platform to accumulate these materials. If we understand the Moon, we would have understood an awful lot more of what happened to the Earth during its history. This is by inference because it's in the same neighbourhood where lots of similar processes are occurring. Today, it is a lot harder on the Earth to find these materials without them having been modified. We look at the Moon in order to see what's going on here. That's one of the objectives. If you look at D/H ratios, depending where on Earth it is, they have been blurred.

The President. If I understand your answer it was 'no'? [Laughter.]

Professor Burchell. Yes, that's a fair summary!

The President. Thank you very much indeed. [Applause.] I will draw the meeting to a close and remind you that there is a drinks reception in the library. The next monthly meeting of the Society will be on 2014 May 9, following the AGM.

SPECTROSCOPIC BINARY ORBITS FROM PHOTOELECTRIC RADIAL VELOCITIES

PAPER 238: HD 22521, BD +15° 1538, HR 4285, AND HR 5835

By R. F. Griffin
Cambridge Observatories

This article treats four single-lined binary systems. HD 22521, a rather neglected star in central Perseus, almost bright enough to qualify for the *Bright Star Catalogue* and with a probable spectral type of about G0 IV–V, has a very eccentric orbit ($e \sim 0{\cdot}65$) and an orbital period of just over 1000 days. BD +15° 1538, though about $8\frac{1}{2}^{m}$, lacks an *HD* entry; it has been classified G7 II. It has an orbit of modest eccentricity and a period a little over a year. The mass function suggests that the unseen companion star ought to be on the verge of detectability in the radial-velocity traces; possibly it is a binary system itself, whereby it could be much fainter than a single star of the same mass. HR 4285, a 6^{m} late-F star near the Plough, has a rich literature but has not previously been known as a binary star; it has a particularly eccentric orbit ($e \sim 0{\cdot}82$) and a period of some 14 years. The orbit is so orientated

(ω near 90°) that the velocity has a very gradual rise and then a very sudden decline which unfortunately was entirely missed the first time round. The radial velocities of two faint stars that have been proposed as common-proper-motion companions of HR 4285 encourage that idea only in the case of the nearer one. HR 5835 is a G8 giant with a 5-year period and an orbit of modest eccentricity.

HD 22521

HD 22521 is quite a bright star, almost bright enough for inclusion in the *Bright Star Catalogue*. It could have featured in the *Supplement*[1] if only someone had bothered to determine its magnitude properly. For such a bright star it has been curiously neglected: even now, we need to rely on magnitudes transformed from *Tycho 2*[2] for the information that $V = 6^{\mathrm{m}}\cdot 74$, $(B - V) = 0^{\mathrm{m}}\cdot 58$. Remarkably, it seems never to have had its spectral type classified on the MK system, but if we go back 96 years to the *Henry Draper Catalogue*[3] we find it classified as G0, which would accord exactly[4] with the colour index if the star were on the main sequence. The (revised) *Hipparcos* parallax[5], however, is unexpectedly small, at $24\cdot 78 \pm 1\cdot 15$ milliseconds of arc: it corresponds to a distance modulus of $3^{\mathrm{m}}\cdot 03 \pm 0^{\mathrm{m}}\cdot 10$ and thus to an absolute magnitude of $+3^{\mathrm{m}}\cdot 7$, with an uncertainty of only about $0^{\mathrm{m}}\cdot 1$, placing it[4] about $0^{\mathrm{m}}\cdot 7$ above the main sequence, midway between luminosity classes IV and V. Evidently HD 22521 has made a significant start on its evolution towards becoming a giant. There is, in fact, a *somewhat* more recent spectral classification of F8, albeit still without a luminosity class, given from the David Dunlap Observatory by Heard[6].

The object is to be found in the middle of the constellation Perseus, about a degree and a half preceding the $3^{\mathrm{m}}\cdot 8$ star ν Per*. HD 22521 features in the *Hipparcos* catalogue with a 'stochastic solution' — that is to say, its trajectory on the sky over the three years of the mission could not be represented simply by a steady proper motion to the precision of the astrometry but seemed to be affected by an additional quasi-random jitter, which led to its classification as 'suspected non-single'. It is perhaps a bit surprising, since the orbital period (as will be shown below) is a little under three years (actually 1009 days, with an uncertainty less than a day), that the original *Hipparcos* reductions did not recognize the orbital nature of the discrepancies from a uniform rectilinear trajectory. Later, however, Goldin & Makarov[8,9] did so. In an initial paper[8] they gave the elements of an orbit with a period of 1119^{+96}_{-63} days or 1091^{+114}_{-74} days, from the reductions made of the raw data by the FAST and NDAC consortia, respectively. Then, after realizing that they could easily improve their method by averaging the 'intermediate astrometric data' before attempting to determine orbit solutions instead of working from the two reductions separately, they offered a revision[9] that was actually almost the same, the new period being 1093^{+101}_{-62} days. The other elements, in all cases, had such large uncertainties as not to be very useful except in the case of the orbital inclination, which in the later version[9] was given as 66^{+6}_{-7} degrees; and the indicated eccentricity was always quite high. Ibukiyama & Arimoto[10] derived "orbital parameters" for a

*The star that appears to answer to that description in *Norton's*[7] is actually not HD 22521 but is the slightly brighter object HR 1097 (HD 22402; $6^{\mathrm{m}}\cdot 42$, B8), about 10′ preceding and slightly north of HD 22521.

number of stars, including HD 22521; they are, however, not the sort that are of particular interest here but are the parameters of the *Galactic* orbits of the stars concerned.

Although the three-year orbital motion had not been recognized in HD 22521 astrometrically before the *Hipparcos* data were studied anew by Goldin & Makarov, the star's substantial proper motion has been known for at least 99 years, since it was determined at Cincinnati by Porter and his colleagues[11,12]. Accurate positional data were available as far back as 1791, the epoch of the position given by Lalande, in whose catalogue[13] it appears as no. 6647, although in the Cincinnati catalogues the star is designated 'Grb 717' after its number in the much later Groombridge[14] catalogue. The Cincinnati proper motion is given[11,12] as $\mu_\alpha = -0''\cdot0161$, $\mu_\delta = -0''\cdot117$, and in the final consolidated listing[12] it is also expressed in polar coordinates as $0''\cdot214$ in p.a. 236°·8. Luyten listed the object in his *Luyten Two-Tenths* [of a second of arc per annum] *Catalogue*[15] as LTT 11201* with a motion of $0''\cdot22$ in 236°. Later[16] he gave almost the same result ($0''\cdot217$ in 237° — incidentally even closer to the Cincinnati value) in his *NLTT*†, where the star is identified by its *BD*[18] number, +42° 803.

Abundance analyses[19–21] of HD 22521 have agreed that it is modestly metal-deficient, with [Fe/H] values of –0·25, –0·28, and –0·15, respectively. The lithium abundance seems quite normal, with a logarithmic value[19] of 2·53 on the usual scale where $\log N[\mathrm{H}] = 12$.

The first radial-velocity measurements of HD 22521 were four that were made at the David Dunlap Observatory in 1939–42 with the 74-inch reflector and a prism spectrograph giving 66 Å mm^{-1} at Hγ; the star was included in a programme that in principle embraced all stars brighter than $m_{pg} = 7^{\mathrm{m}}\cdot59$ in the northern-hemisphere Kapteyn Selected Areas[22]. Although the programme was one to which all the observatory staff contributed, the results were published under the sole name of the Director, Heard[6]. A mean velocity of –39·2 km s^{-1} with a 'probable error' of 2·0 km s^{-1} was given for HD 22521. The spread of the velocities was quite normal for the instrumentation concerned and did not flag up any real variability. Much later, the mean of three velocities obtained with the *Coravel* spectrometer at Haute-Provence (OHP) was published[20], as $-40\cdot5 \pm 2\cdot1$ km s^{-1}; the spread in that case *was* enough to identify the star as a binary, but it is not actually so flagged in the table (accessible only by computer) that is referred to in the paper, even though the $P(\chi^2)$ is listed as 0·000. Reddy *et al.*[19], however, did identify HD 22521 as a binary from the *Coravel* radial velocities.

HD 22521 was placed on the Cambridge radial-velocity observing programme in late 2006 and initially scheduled for monthly observations. After only four months a change of almost 10 km s^{-1} (which has proved to be a large fraction of the binary's complete range) had been witnessed. There are now 54 measurements, all obtained with the Cambridge *Coravel* and listed in Table I, which readily produce the orbit that is illustrated in Fig. 1 and whose elements are given, with those of the other stars treated below, in Table V towards the end

*The designation that *Simbad* egregiously uses as its principal identification for the star.

†*Simbad* ascribes the designation NLTT 11456 to the entry, but no such number appears in the *NLTT* itself, and it is not at all clear where the number comes from; the star is the 34th entry on p. 151 of the catalogue. In imagining an *NLTT* serial number, *Simbad* is deliberately flying in the face of Luyten's public-spirited effort to avoid the unnecessary proliferation of designations which, particularly in recent times, is certainly creating a Tower of Babel[17] for astronomers. "As far as designations are concerned, there has been such a plethora of completely unnecessary . . . new systems used . . . that I decided NOT to assign a running serial number. I have used BD and CoD whenever possible, giving Bayer letters in the notes following, for the very bright stars. For the fainter stars the original discoverers' numbers have been used." — *NLTT*[16], p. 3.

TABLE I

Radial-velocity observations of HD 22521

All the observations were made with the Cambridge Coravel

Date (UT)	*MJD*	*Velocity* *km s^−1*	*Phase*	*(O – C)* *km s^−1*
2006 Nov. 26·06	54065·06	−40·7	0·868	+0·2
Dec. 16·98	085·98	−40·8	·889	−0·2
2007 Jan. 31·83	54131·83	−39·0	0·934	−0·1
Mar. 27·87	186·87	−30·9	·989	−0·1
Sept. 26·14	369·14	−35·8	1·169	+0·1
Oct. 19·11	392·11	−36·6	·192	−0·1
Nov. 17·01	421·01	−37·2	·221	−0·1
Dec. 16·93	450·93	−37·8	·250	−0·2
2008 Jan. 7·96	54472·96	−37·9	1·272	0·0
Feb. 11·83	507·83	−38·7	·307	−0·3
Mar. 7·89	532·89	−38·3	·332	+0·4
31·84	556·84	−39·4	·355	−0·5
Sept. 28·16	737·16	−40·3	·534	0·0
Oct. 22·09	761·09	−40·5	·558	0·0
Nov. 23·04	793·04	−40·8	·589	−0·1
2009 Jan. 2·93	54833·93	−41·0	1·630	−0·1
Feb. 10·87	872·87	−41·0	·668	0·0
Mar. 29·81	919·81	−41·5	·715	−0·3
Oct. 9·12	55113·12	−40·2	·906	0·0
23·21	127·21	−39·7	·920	−0·1
25·11	129·11	−39·5	·922	+0·1
Nov. 24·05	159·05	−37·6	·952	−0·2
Dec. 6·95	171·95	−35·7	·965	0·0
20·93	185·93	−33·0	·978	+0·1
2010 Jan. 1·92	55197·92	−30·5	1·990	0·0
3·89	199·89	−30·4	·992	−0·3
8·91	204·91	−28·9	·997	+0·2
17·89	213·89	−27·8	2·006	+0·1
29·83	225·83	−27·5	·018	0·0
Feb. 17·83	244·83	−29·1	·037	−0·4
Mar. 2·87	257·87	−30·0	·050	−0·2
Apr. 8·84	294·84	−32·7	·086	−0·1
2011 Jan. 31·84	55592·84	−39·3	2·382	−0·1
Apr. 7·81	658·81	−39·7	·447	0·0
Sept. 14·17	818·17	−40·5	·605	+0·2
Nov. 18·03	883·03	−40·8	·669	+0·2
Dec. 7·99	902·99	−41·0	·689	+0·1
2012 Jan. 28·88	55954·88	−41·2	2·740	+0·1
Mar. 1·83	987·83	−41·0	·773	+0·3
July 25·11	56133·11	−40·0	·917	−0·2
Aug. 31·16	170·16	−37·0	·954	+0·2
Sept. 7·19	177·19	−36·2	·960	+0·1
15·18	185·18	−34·9	·968	+0·2
18·17	188·17	−34·5	·971	0·0
Nov. 3·12	234·12	−27·6	3·017	−0·1
18·04	249·04	−27·9	·032	+0·4
22·01	253·01	−28·5	·036	+0·1

TABLE I (*concluded*)

Date (UT)	*MJD*	*Velocity* *km s*$^{-1}$	*Phase*	*(O – C)* *km s*$^{-1}$
2013 Jan. 2·03	56294·03	−31·9	3·076	0·0
Feb. 1·89	324·89	−33·2	·107	+0·5
27·80	350·80	−34·6	·132	+0·2
Dec. 1·04	627·04	−39·7	·406	−0·3
20·03	646·03	−39·4	·425	+0·2
2014 Feb. 2·91	56690·91	−40·0	3·469	−0·1
Mar. 3·78	719·78	−39·9	·498	+0·2

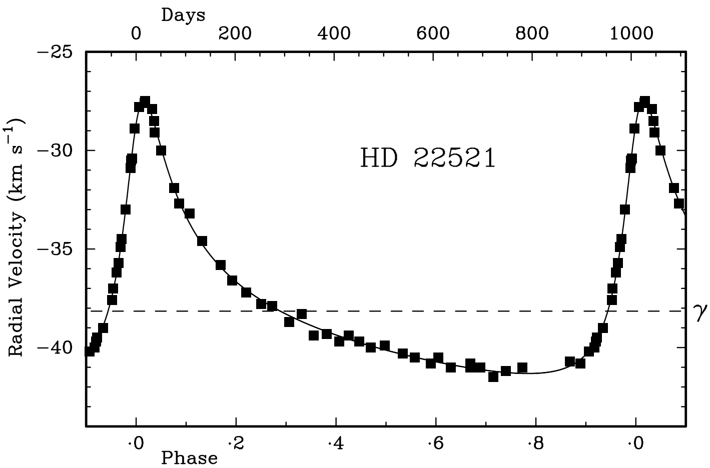

FIG. 1

The observed radial velocities of HD 22521 plotted as a function of phase, with the velocity curve corresponding to the adopted orbital elements drawn through them. All the observations were made with the Cambridge *Coravel*.

of this paper. The measurements referred to in earlier publications[6,20] could not contribute to the orbit as they were not published individually.

Since the initial evolution of a solar-type star is more or less vertically upwards in the H–R Diagram, HD 22521 probably started on the main sequence with much the same colour index as it possesses now, so its mass is probably a little over the Sun's mass, say 1·1 $M_{\odot}$. Then the mass function does not require the secondary star to have a mass greater than about 0·3 $M_{\odot}$, so it is far from surprising that it has not been seen in the radial-velocity traces or as any inflection in the velocity curve in the vicinity of the γ-velocity.

The 'dips' in radial-velocity traces are slightly broader than the minimum width that is given by stars with negligible rotation; if the broadening is largely ascribed to rotation, as seems likely, it is determined at 3·0 km s^{-1} with a standard error of the mean of only 0·2 km s^{-1} — probably unrealistically small as an external error. A rotational velocity of 3 km s^{-1} is given also in Nordström *et al.*'s table[20], where all values are integers and no uncertainties are listed.

BD +15° 1538

At a magnitude of about 8½, BD +15° 1538 is unlucky not to have been honoured with an *HD* entry. The star is to be found in Gemini (no doubt enhancing its likelihood of being double!), about a degree and a half south of the $3^{m}\cdot6$ star λ Gem. It has not been popular with astronomers even though its presence (analogous to that of HD 22521) in one of the Kapteyn Selected Areas[22] might be expected to have encouraged an interest in it: there is no ordinary *UBV* photometry, and we have to fall back on transformation from *Tycho 2*[2] for the information that $V = 8^{m}\cdot46$, $(B - V) = 1^{m}\cdot57$. There is, however, an MK classification, albeit from an objective-prism spectrogram, of K7 II, from Abastumani[23]. There is, unfortunately, no parallax determination to validate the high luminosity. The *only* paper specifically retrieved by *Simbad* concerning the object is de Medeiros & Mayor's *A catalog* [*sic*] *of rotational and radial velocities for evolved stars*[24], where the star is identified as a spectroscopic binary from just two radial-velocity observations which yielded a mean value whose uncertainty is listed as 7·63 km s^{-1}, from which one might divine that the individual observations differed by twice that quantity.

BD +15° 1538 was added to the writer's observing programme at the end of 2002, shortly after the individual observations underlying the catalogue paper[24] were made available through the Centre de Données Stellaires in Strasbourg; it was one of about 60 stars adopted as a result of a scrutiny of that list. By the end of the second observing season, in early 2004, the orbit was securely established and its period of about 381 days was determined to within less than a day. There was, however, a huge gap in the phase coverage of the observations owing to the closeness of the orbital period to one year; it could be repaired, obviously, only at a rate of about 16 days a year, and that explains why publication of the orbit has been deferred another decade. There are now 49 Cambridge radial velocities, set out in Table II, at the head of which are the two measurements made with the OHP *Coravel* and obtained through Strasbourg from de Medeiros & Mayor[24]; they have been adjusted, as is usual for OHP velocities in this series of papers, by +0·8 km s^{-1}. The orbital period obtained from the Cambridge observations alone is 380·96 ± 0·15 days. Then one of the OHP measures, which more than double the time base of the data set, falls at a phase of rapid change of velocity and has an unacceptable residual of +2·0 km s^{-1}, which is largely mended when the OHP data are included in the solution of the orbit — they have rather arbitrarily been given half-weight. The period is then increased to 381·15 ± 0·07 days; it is the only one of the orbital elements to be changed by more than its original standard deviation. (Giving full weight to OHP has hardly any further effect, giving the period as 381·17 days with a formal standard error reduced to 0·05 days.) The solution with OHP half-weighted yields the elements that are listed in Table V near the end of this paper; the corresponding diagram of the orbit appears here as Fig. 2. Although at first sight it looks very much like a sine curve, in fact it has an eccentricity of about 0·1 that is non-zero by about twenty standard deviations and so is *very* secure.

As befits a star of its spectral type, BD +15° 1538 gives radial-velocity traces showing agreeably deep 'dips' — they have 'equivalent widths', defined analogously to those of spectral lines, of about 6·5 km s^{-1}. No dip attributable to the secondary star has been noticed in the traces. The eye of faith might possibly see a tendency in Fig. 2 for the plotted points in the vicinity of the γ-velocity to fall nearer to the γ-velocity than they ought to do, at any rate on the rising side of the curve, as would occur if there were a weak secondary that

TABLE II

Radial-velocity observations of BD +15° 1538

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

Date (UT)	*MJD*	*Velocity* $km\ s^{-1}$	*Phase*	*(O – C)* $km\ s^{-1}$
1986 Oct. 28·20*	46731·20	−27·9	0·915	+0·5
1988 Mar. 9·90*	47229·90	−12·6	2·223	+0·4
2002 Dec. 11·17	52619·17	−24·0	16·363	+0·5
2003 Jan. 6·08	52645·08	−30·8	16·431	−0·1
27·09	666·09	−35·6	·486	−0·3
Feb. 15·06	685·06	−39·1	·536	−0·3
Mar. 16·92	714·92	−42·7	·614	+0·1
27·89	725·89	−43·8	·643	−0·1
Apr. 6·88	735·88	−44·1	·669	0·0
15·86	744·86	−44·0	·693	+0·2
Oct. 12·20	924·20	−10·7	17·163	−0·3
28·17	940·17	−12·5	·205	−0·5
Nov. 4·19	947·19	−13·2	·224	−0·2
13·16	956·16	−15·1	·247	−0·5
28·16	971·16	−17·5	·286	+0·1
Dec. 8·13	981·13	−19·9	·313	0·0
15·17	988·17	−21·9	·331	−0·4
2004 Jan. 9·11	53013·11	−27·1	17·397	+0·5
15·06	019·06	−28·7	·412	+0·3
30·11	034·11	−32·4	·452	0·0
Feb. 9·03	044·03	−34·5	·478	+0·1
22·93	057·93	−37·1	·514	+0·3
Sept. 21·18	269·18	−11·5	18·068	+0·5
2005 Apr. 3·90	53463·90	−41·8	18·579	−0·5
Nov. 4·22	678·22	−10·3	19·142	−0·2
2006 Sept. 30·20	54008·20	−16·6	20·007	+0·5
Nov. 1·21	040·21	−10·8	·091	+0·1
Dec. 9·15	078·15	−11·0	·191	+0·3
2007 Sept. 16·18	54359·18	−26·9	20·928	−0·2
Oct. 5·19	378·19	−20·9	·978	−0·4
18·23	391·23	−17·0	21·012	−0·4
Nov. 3·23	407·23	−12·9	·054	0·0
2008 Sept. 20·20	54729·20	−30·8	21·899	−0·4
28·20	737·20	−28·5	·920	−0·7
Oct. 9·20	748·20	−25·1	·949	−1·0
17·22	756·22	−21·1	·970	+0·4
2010 Jan. 30·01	55226·01	−11·8	23·202	0·0
Mar. 1·91	256·91	−17·2	·284	+0·2
Nov. 28·19	528·19	−18·1	·995	+0·3
Dec. 12·17	542·17	−14·2	24·032	+0·5
2011 Jan. 19·07	55580·07	−9·7	24·131	+0·3
Oct. 1·20	835·20	−40·7	·801	−0·5
16·22	850·22	−36·3	·840	+0·6
Nov. 28·26	893·26	−24·1	·953	−0·5
Dec. 10·14	905·14	−19·3	·984	+0·4

TABLE II (*concluded*)

Date (UT)	*MJD*	*Velocity* *km s⁻¹*	*Phase*	*(O–C)* *km s⁻¹*
2012 Sept. 19·16	56189·16	−44·1	25·729	−0·4
Nov. 6·23	237·23	−35·0	·856	+0·4
18·17	249·17	−31·5	·887	+0·4
2013 Oct. 24·22	56589·22	−41·3	26·779	+0·3
Nov. 9·19	605·19	−38·1	·821	+0·5
2014 Feb. 25·88	56713·88	−10·6	27·106	−0·2

*Observation[24] retrieved from CDS; weight ½.

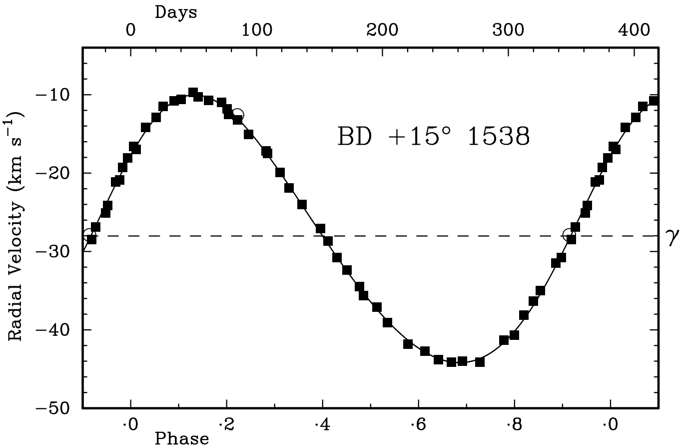

FIG. 2

As Fig. 1, but for BD +15° 1538. The two observations plotted with open circles were made by de Medeiros & Mayor[24] with the OHP *Coravel* and made available through the CDS.

is blended with the primary dip at those times. A plot (not reproduced here) of equivalent width against phase for all 49 observations individually does not, however, give any impression of reinforcement of the areas of the dips at phases near the γ-velocity.

Among the orbital elements, the mass function is quite significant, at nearly 0·2 $M_{\odot}$, but what its significance actually *is* depends upon the mass of the primary star. With no parallax to help us, and with the only spectral classification depending on an objective-prism spectrum, any mass estimate is bound to be insecure. For primary masses of 1, 2, and 4 $M_{\odot}$, the minimum masses demanded for the secondary are about 0·9, 1·3, and 1·9 $M_{\odot}$, corresponding to main-sequence types of about G5, F5, and A8, with absolute magnitudes of 5·1, 3·4, and 2·3, respectively. We can pretty well rule out the combination of $M_1 = 1$, $M_2 \gtrsim 0·9$, which ought to have a minimum Δm of only half a magnitude, so the radial-velocity traces would be sure to appear double-lined. The case with

$M_1 = 4\ M_\odot$ and at least an A8 secondary is unappealing, unless indeed the primary star is more luminous than its K7 II classification would warrant, because the admixture of the light of the hot companion would make the system as a whole substantially less red than the unadulterated late-type star. The combination could scarcely be as red as the observed system, unless indeed there is very significant interstellar reddening. The system is in fact almost as red as late-type stars of normal types ever are, so there is little scope for allowing any substantial contribution from a much hotter component; and one can hardly postulate that the secondary should be an evolved star when the primary is a high-luminosity object that is only just now evolving itself. The least objectionable possibility appears to be the middle one, with a primary having a mass of about 2 $M_\odot$ and the secondary being a main-sequence star of about type F5, not bright enough, even in the blue, seriously to detract from the redness of the primary. There is, however, another class of possibilities in which the secondary object is itself a binary system.

The Cambridge radial-velocity traces, when reduced as if they referred to a star in the normal range of luminosity (dwarf to giant) suggest a rotational velocity of a little over 4 km s^{-1} with a formal standard error of only 0·2 km s^{-1}. The OHP value, derived from only two observations, and believed to be calculated from an increased baseline width to take account of the higher 'turbulence' parameters often associated with objects more luminous than normal giants, is '<1·0'. The writer would not argue with that, and should probably offer his own result as '$\lesssim$4'.

HR 4285 (HD 95241)

HR 4285 is a 6^m star in Ursa Major, about 2° south-preceding ψ UMa and 1° following ω UMa. In epoch-2000 maps it sits almost on the 11-hour meridian, which also goes nearly through the 'Pointers' of the Plough. If they are used 'backwards' by just half their distance from the Pole Star they point to HR 4285. Accordant *UBV* photometry by Eggen[25], Häggkvist & Oja[26], and Imagawa[27] has shown the star to have a *V* magnitude of 6·02 and colour indices of $(B-V) = 0^m{\cdot}57$, $(U-B) = 0^m{\cdot}01$. The spectral type (F8 in the *HD*[28], F7 in an early Dominion Astrophysical Observatory (DAO) paper[29], G0 at Mount Wilson[30]) has been given as F9 V by (Anne) Cowley[31], writing under her sole name, but as F7 V soon afterwards[32] when she collaborated with Bidelman. In the last-mentioned paper the star is misidentified with ADS 7682, which is actually HR 4265 (55 Leo); it is surprising that Bidelman, from whose encyclopaedic knowledge of stellar identities and properties I sometimes benefited, would have been party to such a mistake.

The parallax of HR 4285 has been given[5] as 22·55 ± 0·38 milliseconds of arc — unusually precise — and corresponds to a distance modulus of 3·23 ± 0·04 magnitudes, so we know the absolute magnitude to be $+2^{m}{\cdot}8$, with very little uncertainty. That is about one magnitude brighter than an F7 V star is supposed[4] to be; this case is rather analogous to that of HD 22521 discussed above — indeed, the magnitudes, spectral types, and parallaxes of the two stars are all quite similar to one another.

There has been considerable interest (reflected in a literature of 71 papers retrieved by *Simbad*) in HR 4285, seemingly largely owing to its recognition as being modestly metal-weak ([Fe/H] ~ –0·3) and in particular Li-weak; the writer refrains from quoting so many references, though he notes a discordance in the observed equivalent widths given for the Li I λ6707-Å line between the < 0·6 mÅ given by Lambert, Heath & Edvardsson[33], the 1·0 of Romano *et al.*[34], and the 2·0 of Takeda *et al.*[35,36]. Pereira & Drake[37] claim that Edvardsson *et al.*[38] identified HR 4285 as one of five 'CH subgiant' stars, but that is hard to confirm from the cited paper, which says that those stars (plus one other already known) "may now be classified as Barium dwarfs" — *not* 'CH subgiants'. Edvardsson *et al.* add that "The provenance of our barium dwarfs will be assured if it is shown that they are spectroscopic binaries." That is, obviously, done here for one of them, but it may be mentioned that in another case (that of HR 107) a few years' monitoring of the radial velocity has not brought to light any variation. In the case of HR 4285, Edvardsson *et al.*'s abundance analysis showed logarithmic Fe and Ba relative abundances of –0·30 and –0·07, respectively, so the apparent barium enhancement was quite modest, even in relation to iron in the same star, and in absolute terms (relatively to the Sun) was non-existent.

The radial velocity of HR 4285 was first measured at the DAO, Victoria, soon after the inauguration of that Observatory, with its 72-inch telescope and Cassegrain prism spectrograph giving a dispersion of about 30 Å mm^{-1} at Hγ. Six plates were exposed and measured personally by the Director, (J. S.) Plaskett, in 1919 and 1920, and published[39] promptly in 1921. A comment in the publication reads, "Lines of good quality and accordant measures make the probable error of measurement less than 0·5 km. per plate." Inasmuch as the total time span of the observations was little more than a year, during which the actual velocity of the star (which was near apastron) varied only by about 0·4 km s^{-1}, the binary nature of the object was not discovered. The six measures are listed at the head of Table III.

Three plates were taken in 1925 with the Mt. Wilson 60-inch reflector at 37 Å mm^{-1} at Hγ and published as a mean by Adams *et al.*[40]. Much later the individual dates and velocities were listed by Abt[41]; it is seen there that two of them were taken on the same night, and those have been averaged before insertion in Table III. The first of them is attributed an unusually bad 'probable error' for observations with the relevant instrument, whereas the 'error' column is blank in the case of the second one. It is impossible now to tell whether the taking of the second plate immediately was prompted by there being something obviously wrong with the first one; since the two are in quite good agreement, however, it does not make a lot of difference whether the two results are averaged or the first one is rejected.

No fewer than 20 measurements[42] were made in 1976–79 with the photoelectric radial-velocity spectrometer[43] at the Erwin W. Fick Observatory at Ames, Iowa; they were assigned individually to three different categories of reliability, but in Table III categories A and B have been lumped together and only C (the worst one, into which only four of the measurements fell) is distinguished. All the published observations[39,41,42] have been increased by 0·8 km s^{-1} to take account of the systematic discrepancy that has seemed[44] to exist between the present author's velocities and those on the supposedly more truthful 'IAU system' (refs. 45, 46). Furthermore, in deference to the systematic corrections advised in Table 3 of the *Radial-Velocity Catalogue*[47], additional increases have been applied, of 1·0 km s^{-1} to the DAO measurements and of 0·5 km s^{-1} to the Mount Wilson ones.

HR 4285 was put onto the writer's observing programme in 1993 on the recommendation of Dr. J. Tomkin of the University of Texas. It was observed three times per season for the first three observing seasons, and then — when nothing appeared to be happening to it — the frequency of observations fell to one a year just when, perversely enough, the star shot through a periastron passage in its very eccentric orbit, and it was necessary to wait 14 years to see

TABLE III

Radial-velocity observations of HR 4285

Except as noted, the sources of the observations are as follows:
1919/20 — DAO[39]; 1976–79 — Fick[42] (both weight 0)
1993–1998 — OHP Coravel (weight ¼); 1999–2014 — Cambridge Coravel (weight 1)

Date (UT)	*MJD*	*Velocity km s^{-1}*	*Phase*	*(O – C) km s^{-1}*
1919 Mar. 9·32	22026·32	−4·1	$\bar{5}$·571	+2·2
24·37	041·37	−5·2	·574	+1·1
Apr. 14·20	062·20	−4·6	·578	+1·7
30·18	078·18	−5·1	·581	+1·2
1920 Feb. 27·38	22381·38	−5·2	$\bar{5}$·639	+0·8
Mar. 31·30	414·30	−3·5	·645	+2·5
1925 Apr. 13·24*	24253·24	−6·4	$\bar{5}$·996	+1·1
May 1·26*	271·26	−10·2	$\bar{4}$·000	−1·0
1976 Apr. 2·22	42870·22	−7·1	$\bar{1}$·546	−0·6
May 12·21	910·21	−11·2	·554	−4·8
Dec. 21·45	43133·45	−7·9	·597	−1·7
1977 Mar. 1·31	43203·31	−8·5	$\bar{1}$·610	−2·3
15·18	217·18	−6·4	·613	−0·2
Apr. 6·19	239·19	−7·9	·617	−1·8
12·11	245·11	−6·0	·618	+0·1
25·17	258·17	−3·9	·620	+2·2
1978 Jan. 10·40	43518·40	−8·9	$\bar{1}$·670	−3·0
23·38	531·38	−4·4	·672	+1·5
Feb. 8·28	547·28	−5·2	·676	+0·7
24·30	563·30	−3·8	·679	+2·0
Mar. 27·26	594·26	−6·3	·684	−0·5
Apr. 7·21	605·21	−6·2	·687	−0·4
26·12	624·12	−5·2	·690	+0·6
May 11·08	639·08	−10·5	·693	−4·7
11·09	639·09	−3·8	·693	+2·0
Dec. 14·48	856·48	−5·1	·734	+0·5
21·48	863·48	−3·5	·736	+2·0
1979 Mar. 12·28	43944·28	−7·5	$\bar{1}$·751	−2·0
1993 Feb. 11·08	49029·08	−4·9	0·721	+0·7
Mar. 18·98	064·98	−5·0	·728	+0·6
July 6·86	174·86	−5·5	·749	0·0
Dec. 27·13	348·13	−5·6	·782	−0·3
1994 Feb. 19·08	49402·08	−4·5	0·792	+0·7
Apr. 29·90	471·90	−5·5	·805	−0·4
Dec. 13·15	699·15	−5·3	·849	−0·5
1995 Jan. 3·08	49720·08	−4·6	0·853	+0·2
June 3·89	871·89	−4·5	·882	0·0
1996 Apr. 2·99	50175·99	−3·2	0·940	+0·7
1997 July 22·84	50651·84	−11·8	1·030	0·0
1998 Apr. 28·90	50931·90	−10·1	1·084	−0·2
July 7·86	51001·86	−9·3	·097	+0·4

TABLE III (*continued*)

Date (UT)	*MJD*	*Velocity* *km s⁻¹*	*Phase*	*(O–C)* *km s⁻¹*
1999 Feb. 18·27†	51227·27	−9·0	1·140	0·0
July 10·24†	369·24	−9·3	·167	−0·6
Nov. 4·58†	486·58	−8·4	·190	+0·1
Dec. 20·15	532·15	−8·3	·198	+0·1
2000 Feb. 11·08	51585·08	−8·1	1·208	+0·2
Apr. 21·96	655·96	−8·0	·222	+0·2
Dec. 2·24	880·24	−8·2	·265	−0·3
2001 Feb. 22·08	51962·08	−7·4	1·280	+0·4
May 4·95	52033·95	−7·6	·294	+0·1
Nov. 1·22	214·22	−7·6	·328	−0·1
2002 Jan. 1·16	52275·16	−7·8	1·340	−0·4
Mar. 8·04	341·04	−7·2	·352	+0·2
May 1·95	395·95	−7·3	·363	0·0
July 3·90	458·90	−8·0	·375	−0·7
Dec. 5·22	613·22	−7·1	·404	0·0
2003 Jan. 6·15	52645·15	−6·9	1·410	+0·2
Mar. 2·02	700·02	−7·0	·421	0·0
May 14·90	773·90	−6·9	·435	+0·1
Nov. 4·23	947·23	−6·8	·468	0·0
2004 Jan. 9·17	53013·17	−7·2	1·481	−0·4
Mar. 1·04	065·04	−6·3	·491	+0·4
May 21·92	146·92	−6·7	·506	−0·1
Dec. 26·20	365·20	−6·6	·548	−0·1
2005 Mar. 18·99	53447·99	−6·4	1·564	0·0
May 4·94	494·94	−6·2	·573	+0·1
Nov. 5·24	679·24	−6·3	·608	−0·1
2006 Jan. 29·13	53764·13	−6·2	1·624	−0·1
Mar. 22·96	816·96	−5·7	·634	+0·4
May 10·95	865·95	−6·1	·643	−0·1
July 2·92	918·92	−6·0	·653	0·0
Nov. 19·27	54058·27	−5·8	·680	0·0
2007 Jan. 14·20	54114·20	−6·0	1·691	−0·2
Mar. 22·03	181·03	−5·5	·703	+0·2
May 18·93	238·93	−5·8	·714	−0·1
July 7·90	288·90	−5·8	·724	−0·2
Nov. 24·25	428·25	−5·7	·751	−0·2
2008 Jan. 6·24	54471·24	−5·4	1·759	0·0
Mar. 30·93	555·93	−5·1	·775	+0·2
May 18·93	604·93	−5·3	·784	0·0
July 8·90	655·90	−5·2	·794	0·0
Dec. 7·27	807·27	−5·0	·823	0·0
2009 Jan. 14·18	54845·18	−5·1	1·830	−0·1
Feb. 11·10	873·10	−4·8	·835	+0·1
Mar. 26·97	916·97	−4·8	·844	0·0
Apr. 19·90	940·90	−4·9	·848	−0·1
May 17·91	968·91	−4·8	·854	0·0
June 11·92	993·92	−4·8	·858	−0·1
Dec. 1·24	55166·24	−5·1	·891	−0·7

TABLE III (*concluded*)

Date (UT)	*MJD*	*Velocity km s⁻¹*	*Phase*	*(O–C) km s⁻¹*
2010 Jan. 31·10	55227·10	−4·1	1·903	+0·2
Feb. 21·09	248·09	−4·2	·907	+0·1
27·05	254·05	−4·1	·908	+0·1
Mar. 22·99	277·99	−4·0	·913	+0·2
Apr. 17·89	303·89	−4·0	·917	+0·1
May 17·87	333·87	−4·0	·923	+0·1
June 11·90	358·90	−4·1	·928	−0·1
July 4·93	381·93	−4·0	·932	0·0
Nov. 24·27	524·27	−3·9	·960	−0·3
Dec. 19·23	549·23	−3·5	·964	+0·1
2011 Jan. 19·16	55580·16	−3·6	1·970	0·0
Mar. 14·00	634·00	−3·7	·980	+0·3
Apr. 6·98	657·98	−4·3	·985	+0·1
May 9·92	690·92	−6·0	·991	−0·3
10·92	691·92	−5·7	·991	0·0
June 2·91	714·91	−7·5	·996	−0·1
26·91	738·91	−9·4	2·000	+0·2
Nov. 28·25	893·25	−12·1	·030	−0·3
Dec. 18·31	913·31	−11·7	·034	−0·1
2012 Jan. 27·12	55953·12	−11·2	2·041	+0·1
Mar. 8·07	994·07	−10·9	·049	0·0
Apr. 10·97	56027·97	−10·7	·056	0·0
May 11·95	058·95	−10·6	·061	−0·1
July 27·87	135·87	−9·9	·076	+0·2
Dec. 2·27	263·27	−9·4	·100	+0·2
2013 Feb. 15·07	56338·07	−9·4	2·115	0·0
May 4·96	416·96	−9·2	·130	−0·1
Dec. 20·25	646·25	−8·6	·173	0·0
2014 Feb. 6·10	56694·10	−8·3	2·183	+0·2
Apr. 8·00	755·00	−8·3	·194	+0·1

* Mount Wilson photographic observation[41]; weight 1/20.
† Observed with DAO 48-inch telescope; weight ¼.

another one! (In extenuation, it could be pleaded that in the 1990s the timing of the writer's observations was not a matter of free choice, as he had no operational instrument on the home site and was dependent upon occasional observing runs granted to him as a guest investigator.) The whole declining 'branch' of the velocity curve was traversed in nine months between the measurements made in the 1996 and 1997 observing seasons. Of course that event galvanized increased attention to the star, and when the Cambridge '*Coravel*' radial-velocity spectrometer was at last brought into operation at the end of 1999: measurements were resumed at a cadence of about four or five observations a year, a frequency that was appropriately increased when the next periastron passage appeared to be imminent. The date of that occurrence could not be anticipated at all accurately, but the increase in frequency that may appear in retrospect to have been made unnecessarily early represented, at the time, a sensible insurance policy against missing the sudden periastron event a second time. The anxiety felt on that score may be recognized in the orbital period prematurely proposed[48] by the writer in 2003, long before he had witnessed the complete orbit. Relying (a bit unwisely, as it now transpires) on the early DAO

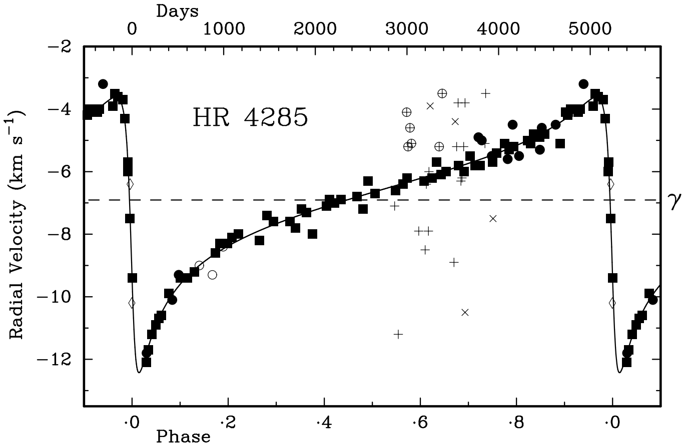

FIG. 3

As Fig. 1, but for HR 4285. The filled squares plot the Cambridge radial velocities as in the preceding figures, and the filled circles plot those made with the OHP *Coravel*. Three open circles near phase ·2 represent observations made with the spectrometer at the DAO 48-inch telescope. Two open diamonds on the steep descent plot the Mount Wilson observations[40,41] that have been used to refine the orbital period. The open circles with crosses in them are the early photographic measurements[39] from the DAO, which were not included in the solution of the orbit. The plusses and crosses represent velocities[42] from the Fick Observatory spectrometer, which also were omitted from the solution; the plusses refer to velocities to which the observers attributed qualities A and B, while the crosses represent those of quality C, the least-good one.

radial velocities[39], and admitting that there was an ambiguity in the number of orbital cycles that had taken place since their epoch, he suggested a period of 3949 ± 22 days, which is now seen to be about 59 standard deviations adrift!* Altogether the writer has made 91 radial-velocity measurements of HR 4285. Of those, the first 13 were made with the OHP *Coravel*, then three with the DAO radial-velocity spectrometer, and finally 75 with the Cambridge *Coravel*. They are all set out in Table III. The usual adjustment of +0·8 km s^{-1} has been made to the OHP velocities; the DAO ones have been reduced with respect to Cambridge reference stars and ought to need no correction; and the Cambridge *Coravel* ones have been subjected to an empirical correction of –0·4 km s^{-1} to put them into systematic agreement with the (adjusted) OHP ones. In the solution of the orbit, the Cambridge observations have been given full (unit) weight, while the OHP and DAO ones have been weighted ¼. The old DAO photographic velocities have not been included in the solution, although they are plotted in the orbit graph in Fig. 3. Similarly, the Ames velocities have been zero-weighted; they are unusually ragged, and although their authors did not conclude from them that the star really varied in velocity, they actually seem to indicate a progressive rise at about seven times the real rate of velocity increase. Thus the orbit depends largely on the writer's 91 measurements, but its period has been refined by the inclusion of the old Mount Wilson observations, as recounted in the ensuing paragraphs; it is illustrated by Fig. 3, and its elements have been included in Table V below.

*The DAO measurements, dating from soon after MJD 22 000, were at the velocity level that HR 4285 had reached towards MJD 50 000, shortly before the sudden decline. It looked at the time as if the interval of nearly 28 000 days must represent either six or seven cycles. In fact it has turned out to be, in principle, five, but because the DAO measures have a systematic offset from the velocity curve and really fall near phase ·6 rather than the ·9 that had been supposed, the 28 000-day interval actually represents about 5·3 cycles of 5200-odd days.

The Cambridge observations, by themselves, yield a period of 5258 ± 34 days. The disappointingly large uncertainty arises from the complete lack of observations during the sudden decline of velocity in 1996/7; the timing uncertainty of the actually observed periastron passage in 2011 was very much less, only a day or so. It so happens, however, that the three old Mount Wilson observations[40,41] (treated as two by the averaging, noted above, of two taken on the same night) fall extremely close to the velocity curve at the epoch of sudden decline. They are almost miraculously well placed in time, symmetrically straddling the mid-point of the decline. Their antiquity gives them a lot of leverage on the orbital period, and it would seem negligent not to attempt to capitalize on it.

Taken absolutely literally, they show a decline of 3·8 km s^{-1} in an interval of only 18 days, at a time (six orbital cycles, 86 years) before the one that the writer observed in 2011, which shows a decline of 1·7 km s^{-1} over the corresponding 18-day interval of phase. The introduction of the old observations into the solution of the orbit, with a weight of 1/20, changes the orbital period by less than half a standard deviation, to 5243·8 ± 1·3 days. Experiments with assigning different weights to the Mount Wilson data show that halving or doubling their weight makes no difference whatever to the derived orbital period — evidently there is enough elasticity in the period indicated by the recent series of observations for the solution to be perfectly willing to accommodate itself exactly to the 1925 velocities. Assigning different offsets, to see the effect of systematic uncertainty in the relative zero-points of the different series of measurements, shows that for changes up to ±2 km s^{-1} in the offset applied to the old observations, a ±1-km s^{-1} change in offset produces a change of a little less than ∓2 days in the resulting orbital period. Thus we can realistically expect that the period noted just above can be relied upon to within three or four days. There is, perhaps, a small but ugly possibility that the 1925 observations are much less reliable than we are supposing and that the effort made here to refine the period by their use is misguided and misleading. It may be noted that when the next decline has been witnessed in 2025*, even if the measurements made then are no better than those made in 2011, the period should be determined to within about 2 days from that orbital cycle alone.

The most noteworthy feature of the orbit is its eccentricity of 0·82, which is high but could not be claimed as exceptional, as it is exceeded by 14 of the stars (their number now approaching 500) whose orbits have been presented in this series of papers. The mass function is very small, and for a primary star whose own mass may be estimated as rather more than one solar mass it does not require the secondary to be more than about 0·25 $M_{\odot}$, so it is not surprising that no evidence has been seen of it in radial-velocity traces.

The radial-velocity traces of HR 4285 show 'dips' that are modestly broader than the lower limit found for other stars, which must represent the zero-rotation limit. The broadening in HR 4285 is taken to be largely the result of rotation, which is thereby quantified at $v \sin i = 4{\cdot}52$ km s^{-1} with a formal standard error of 1·3 km s^{-1} for each individual observation and only 0·15 km s^{-1} for the mean. The slightly cavalier way in which the calculation assumes rotation to be the *only* parameter affecting the line-width prompts caution in accepting that the result can be relied on to better than 1 km s^{-1}, however small its formal standard

*The circumstances of the 2025 periastron passage are less favourable than those of 2011, when only the final stages of the sudden decline were missed when the star got out of reach: something like half the descent will already have taken place before the object becomes reasonably accessible in the dawn sky in 2025.

error may be. The mean value would imply rotation in 11·2 days for a star of one solar radius. A main-sequence star of HR 4285's type of F7 is expected[4] to have a radius of about 1·15 $R_{\odot}$; it has been shown in the second paragraph of this section, above, that HR 4285 is about one magnitude above the main sequence, which implies a radius larger by a factor of about 1·6, putting it between 1·8 and 1·9 $R_{\odot}$. For that radius, the observed value of $v \sin i$, taken literally, would correspond to rotation in 20·6 days. By repeated measurements of variable *H* & *K* chromospheric emission Isaacson & Fischer[49] have proposed rotational periods for many late-type stars, and for HR 4285 they have given it as 16 days. Comparison of that figure with the one just derived for $v \sin i$ yields a value of $\sin i$ that corresponds to an axial inclination of about 52°, but it must be admitted that the assumptions and possible errors that underlie that result, exacerbated by the slow variation of $\sin i$ with i when $\sin i$ is approaching unity, mean that the formal value of the inclination is to be taken only as indicative.

The cited paper[49] gives in addition two other quantities concerning HR 4285 (like the rotation period, they are in a large table that is accessible only on the Web and is not actually part of the printed paper). The two quantities are quite surprising. One is the log(age) of 5·61 in units of Gyr, which is approaching 30 000 times the supposed age of the Universe; the other is that the star exhibits a radial-velocity 'jitter', given to a precision of one millimetre per second as 4·258 m s^{-1} — it is difficult to imagine how such a figure could be ascertained (if at all) unless the authors thereof had first determined the orbit of the star to a precision orders of magnitude better than the present writer is able to offer here.

There are two relatively faint stars, fairly close to HR 4285, that have been considered to be actual companions rather than unrelated objects. The nearer of the two, at a distance of 37″ in p.a. 150°, must have a proper motion that is very similar to that of the principal star, since the two have kept station together for the last 50 years while their proper motions have carried both about 8″ across the sky. The pair, identified as KUI 53 in the *Index Catalogue of Double Stars*[50] (*IDS*)* is attributed a *V* magnitude of 11·7; if it is a real physical companion to HR 4285, its absolute magnitude must be about $8^{m}\cdot5$, so it should be of very-late-K type. It is to be seen only with difficulty in the finding field of the Cambridge telescope, even when the normally-on dim artificial illumination of the field is turned off (the illumination enables the observer to see the entrance slit of the *Coravel* spectrometer, which is a tiny aperture in a surface that is otherwise a mirror and appears as a small black rectangle in the centre of the field). It was only when he came to write this paper and was educating himself from the literature that the author found that the faint star is a c.p.m. companion

*KUI is the abbreviation that designates G.P. Kuiper as the 'discoverer'. Kuiper himself did not, as so many observers of 'visual' double stars have done, claim ownership or priority in that way for the double stars that he discovered. In fact the first measurement of the system with which we are concerned here was published by van den Bos, in a 1960 Yerkes publication[51] that includes a number of Kuiper discoveries ascribed simply to 'Kpr' without discrimination by number. Kuiper's early interest in visual double stars, manifested in his PhD work and then a fellowship at Lick in 1933–35 under Aitken, was increasingly supplanted by an interest in planetary studies, which culminated in his leaving the directorship of the Yerkes Observatory in 1960 in order to found the Lunar & Planetary Laboratory at the University of Arizona. In dutifully tidying up, at that juncture, his double-star work, he published in a 35-page paper[52] in the *ApJ Supplements* a lot of measurements that he had made some 25 years previously at Lick, and turned over to van den Bos (whom he thanks in the preface to that paper for preparing that material for publication) a lot of unpublished double-star observations that he had made at Yerkes. Evidently van den Bos worked closely with Kuiper, and it is in the *Index Catalogue*[50], compiled by Jeffers & van den Bos, that the KUI designations first appear — and their successive numbers there are in RA order, demonstrating that they were all assigned at that one time, evidently by the compilers of the *Catalogue*.

to HR 4285 and therefore of interest to him. With a putative B magnitude of about 13·0, it is almost too faint to be measured for radial velocity with the *Coravel*. An effort was made to observe it on 2014 May 23·92, when it distinctly showed a 'dip' in the radial-velocity trace at a velocity of $-6{\cdot}0 \pm 1{\cdot}8$ km s^{-1} — agreeing well with the principal star's γ-velocity of $-6{\cdot}9$ km s^{-1}. The dip was shallow, and the velocity determined from it was accordingly rather imprecise, because the photon rate from the star was largely swamped by the dark count from the photomultiplier in the *Coravel*, which is at ambient temperature; the observation would more profitably have been attempted on a cold night in the winter. All the same, the fact that one, albeit rather rough, radial-velocity measurement of the faint star agrees with the γ-velocity of the bright one goes quite a long way towards confirming the pair as a physical binary system.

The more distant of the two companions is about 15′ from HR 4285 itself and has its own *Hipparcos* number. Although attention was drawn to it by Lepine & Bongiorno[53] (who, after the fashion of 'visual' double-star observers, find it named it after themselves as 'LEP 38' in the *Washington Double-Star Catalogue*[54], as if it were not already satisfactorily identified in the literature), the very fact that such an 11^{m} star was observed by *Hipparcos* at all demonstrates that its interest had already been recognized by others. In its case, it was Luyten who had first noticed its large proper motion, analogous to that of HR 4285 although he did not point that out himself, and had catalogued[55] it as LP 214–17. Its parallax[5] of $23{\cdot}0 \pm 2{\cdot}1$ milliseconds of arc is indistinguishable from that of HR 4285 and certainly could be considered as *prima facie* evidence that the two stars are related to one another. They also form a common-proper-motion pair, although not to the precision that one might hope — the difference in their motions in RA is about 20 milliseconds per annum, many times its own listed uncertainty. *Tycho 2* photometry[2], transformed by *Simbad*, gives the V and $(B-V)$ magnitudes as $10^{m}{\cdot}85$ and $0^{m}{\cdot}93$, respectively. The colour index of the companion is that of a main-sequence star with a type of about K1, but the parallax shows the absolute magnitude to be about $7^{m}{\cdot}6$, corresponding to about K6 V. Despite the misgivings that the significant apparent astrometric and photometric discrepancies might warrant, Dhital *et al.*[56] included the pair as a double system in their catalogue, for which they claimed the likelihood of false inclusion of unrelated stars to be less than 5%. They gave the projected separation of the stars, with literally incredible precision, as 43891 AU; they also gave the 'spectral types', estimated from red–IR photometry and not from spectra at all, as K0·6 and K7·2. The supposed companion star was measured for radial velocity at Cambridge on 2014 May 14·99, 15·97, and 23·94, with results of +27·3, +26·7, and +25·9 km s^{-1}, with internally estimated uncertainties of 0·5 km s^{-1} in each case. Without an increased time-base one cannot be certain either whether the velocity is constant or whether the mean discrepancy of about 33 km s^{-1} from the γ-velocity of HR 4285 could be due to the companion's motion in a short-period binary system, but the prospects of that being the case seem pretty bleak.

HR 5835 (HD 139906)

HR 5835 is a 6^{m} star in a visually barren region of the sky about 20° north of the little circlet of Corona Borealis. For its magnitude and $(B-V)$ colour index ($5^{m}{\cdot}83$ and $0^{m}{\cdot}83$, respectively) we are indebted to a 'private communication' made in 1970 by Häggkvist & Oja to the Centre de Données Stellaires, which, however, fortunately did not honour the privacy but published the information for us to use. The *Simbad* 'measurements' section of the bibliography for

HR 5835 does not record any MK type, but one of the papers in the bibliography is that of Cowley & Bidelman[32] (already referred to in connection with HR 4285 above), which gives the type as G8 III. The (revised[5]) *Hipparcos* parallax of 8·66 ± 0·58 milliseconds of arc translates to a distance modulus of $5^{m}\cdot 31 \pm 0^{m}\cdot 15$ and thus to an absolute magnitude close to $+0^{m}\cdot 5$. The original *Hipparcos* publication[57] notes that the parallax came from an 'acceleration solution', implying that the star is a binary; that prompted an (unsuccessful) effort[58] to resolve it by speckle interferometry.

The radial velocity of HR 5835 was first measured at the DAO from four plates taken at the 72-inch reflector in a ten-week interval in 1924 and measured by Christie[59], who was then a young man employed as a summer assistant. The four velocities have been transcribed to the head of Table IV here. The best part of a century elapsed before de Medeiros & Mayor[24] reported that they had found HR 5835 to be a spectroscopic binary from five observations made with the OHP *Coravel*. They subsequently (2002) made the individual measurements available through the Centre de Données Stellaires, and it was from that listing that the star was selected for further observation from Cambridge. The same information as was given by de Medeiros & Mayor, but with the curious omission of the actual radial velocity, was published anew shortly afterwards in a different journal by de Medeiros, da Silva & Maia[60].

Comparatively recently, HR 5835 has featured in a paper that is already noted above in connection with HR 4285, that of Isaacson & Fischer[49], who have proposed that HR 5835 has a rotation period of 42 days. They have also listed two quantities quite similar to those that the writer admitted finding so extraordinary regarding HR 4285 — a radial-velocity 'jitter' of 4·416 m s^{-1}, somehow assessed to a millimetre per second without any determination of the orbital motion that has a range ten million times greater, and an age which, when the logarithmic value given is unpacked, is more than 5×10^{14} years. Another rather unusual paper is that of de Bruijne & Eilers[61], which has a huge table (not part of the printed paper but available by computer, in the modern fashion) that tells us what precision is needed, star by star, for radial velocities, to avoid impairing the amazing precision promised by *Gaia* for proper motions. In the case of HR 5835 the listed precision is 131·73 km s^{-1}! If only the authors had omitted stars whose radial velocities were already known plenty accurately enough for the purposes of *Gaia*, the table might have been greatly abbreviated without loss of anything but unwieldiness. The number for HR 5835 is hardly useful — the radial velocity could have been *guessed* more than sufficiently accurately! The entries for HD 22521 and HR 4285, among the stars treated above, could equally have been omitted. If the table had been reduced so that only the entries where new and better radial velocities were genuinely needed for the avowed purpose were retained, it might have served a purpose that it cannot serve if every potential user has individually to look up what is known about each of many thousands of stars. A (non-binding!) resolution has been made that future papers in the series of which this present one is a part will not refer to the matter[61] again, even though *Simbad* seems dutifully to have entered the reference into the bibliographies of many of the vast number of stars that *Gaia* is hoped to observe.

Since the Cambridge observations began in 2002, 63 have been made, covering rather more than two revolutions of the orbit; they are included in Table IV. The star passes less than 2° to the south of the Cambridge zenith and, because its right ascension is not very far from that of the winter solstice, it can be observed on any night of the year, although only at large hour angles around

TABLE IV

Radial-velocity observations of HR 5835

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

Date (UT)	*MJD*	*Velocity* *km s⁻¹*	*Phase*	*(O–C)* *km s⁻¹*
1924 May 21·35*	23926·35	−14·1	$\overline{15}$·152	−0·4
June 8·31*	944·31	−12·3	·161	+1·2
July 4·30*	970·30	−12·6	·176	+0·5
29·22*	995·22	−12·0	·190	+0·7
1986 June 3·96†	46584·96	−2·6	$\overline{3}$·682	−0·4
1987 May 10·06†	46925·06	−6·9	$\overline{3}$·870	+0·1
1992 Mar. 26·14†	48707·14	−7·0	$\overline{2}$·855	−0·6
1993 Apr. 8·12†	49085·12	−14·6	$\overline{1}$·064	0·0
22·07†	099·07	−14·9	·072	−0·3
2002 May 31·03	52425·03	−9·1	0·911	0·0
July 13·98	468·98	−10·0	·936	+0·3
Aug. 27·86	513·86	−11·2	·960	+0·3
Sept. 26·87	543·87	−12·5	·977	−0·2
Nov. 14·76	592·76	−13·5	1·004	−0·2
2003 Feb. 21·24	52691·24	−14·5	1·058	0·0
Mar. 19·11	717·11	−14·6	·073	0·0
Apr. 8·11	737·11	−14·5	·084	+0·1
May 8·00	767·00	−14·7	·100	−0·1
June 13·02	803·02	−14·1	·120	+0·2
July 7·92	827·92	−14·0	·134	+0·1
Aug. 3·89	854·89	−13·5	·149	+0·3
Sept. 14·81	896·81	−13·1	·172	+0·1
Oct. 11·83	923·83	−12·9	·187	−0·1
Nov. 5·74	948·74	−12·7	·201	−0·4
2004 Jan. 15·27	53019·27	−11·2	1·240	−0·1
Mar. 2·21	066·21	−10·1	·266	+0·1
Apr. 7·13	102·13	−9·4	·286	+0·1
May 7·09	132·09	−8·6	·302	+0·3
June 17·00	173·00	−8·0	·325	+0·2
July 16·96	202·96	−7·4	·341	+0·2
Aug. 10·97	227·97	−7·3	·355	−0·1
Sept. 3·90	251·90	−6·8	·369	0·0
Oct. 25·81	303·81	−6·3	·397	−0·4
Nov. 26·70	335·70	−5·8	·415	−0·3
2005 Jan. 9·29	53379·29	−5·0	1·439	−0·2
Mar. 23·19	452·19	−4·2	·479	−0·3
Apr. 22·07	482·07	−3·5	·496	+0·1
May 23·06	513·06	−3·2	·513	+0·1
June 22·98	543·98	−2·8	·530	+0·2
July 17·95	568·95	−2·7	·544	+0·1
Aug. 16·85	598·85	−2·6	·560	0·0
Sept. 12·83	625·83	−2·1	·575	+0·3
Oct. 27·74	670·74	−2·1	·600	+0·1
Nov. 29·70	703·70	−2·0	·618	+0·1

TABLE IV (*concluded*)

Date (UT)	*MJD*	*Velocity* *km s⁻¹*	*Phase*	*(O–C)* *km s⁻¹*
2006 Mar. 2·20	53796·20	−2·1	1·670	0·0
Apr. 4·11	829·11	−2·3	·688	−0·1
May 6·11	861·11	−2·5	·705	−0·2
June 4·00	890·00	−2·6	·721	−0·1
8·95	894·95	−2·6	·724	0·0
July 2·96	918·96	−2·6	·737	+0·2
Aug. 1·98	948·98	−3·3	·754	−0·2
Sept. 8·83	986·83	−3·3	·775	+0·3
Oct. 24·75	54032·75	−4·0	·800	+0·3
Nov. 26·28	065·28	−5·3	·818	−0·4
2007 Jan. 14·30	54114·30	−6·1	1·845	−0·1
Feb. 15·25	146·25	−6·6	·863	+0·1
Mar. 22·16	181·16	−7·9	·882	−0·3
Apr. 16·10	206·10	−8·2	·896	+0·1
30·06	220·06	−8·9	·904	−0·2
May 30·04	250·04	−9·5	·921	0·0
June 26·97	277·97	−10·1	·936	+0·2
July 18·94	299·94	−10·8	·948	+0·1
Aug. 26·84	338·84	−11·8	·970	+0·1
Oct. 15·76	388·76	−13·1	·997	0·0
Dec. 11·28	445·28	−14·4	2·028	−0·4
2008 May 3·05	54589·05	−14·7	2·108	−0·2
2011 Sept. 12·82	55816·82	−3·8	2·787	+0·1
Oct. 19·75	853·75	−4·7	·807	−0·2
2013 Oct. 28·73	56593·73	−11·7	3·217	+0·1
2014 Feb. 26·22	56714·22	−9·6	3·283	0·0
Mar. 23·18	739·18	−9·1	·297	0·0
May 15·07	792·07	−8·1	·326	0·0

*Published DAO observation[59]; weight 0.
† Observation[24] retrieved from CDS; wt. ¼.

the date of conjunction with the Sun. In fact Table IV shows that the observing seasons slightly overlap! — the earliest morning observation was on November 26 in 2006, whereas in the previous year the latest evening measure was on November 29.

The Cambridge observations alone give the orbital period as 1806·9 ± 2·5 days. Inclusion of the five OHP velocities from about five revolutions back, retrieved from the Centre de Données Stellaires and given a weight ¼ in the solution, refines the period slightly, to 1808·3 ± 2·0 days, while making negligible changes to the other elements. Unlike the situation with HR 4285, this time the early DAO measurements sit nicely near the calculated velocity curve, with residuals that would appear to qualify them for inclusion in the solution with a weight of about 1⁄30; the significant offset of the analogous measurements in the case of HR 4285, however, dissuades the writer from trying to utilize them. The orbit is shown in Fig. 4 and its elements appear in the last column of Table V.

Formally, the mean projected rotational velocity of HR 5835 is found from the Cambridge observations to be 2·94 ± 0·17 km s^{-1}, but the value is normally not claimed to be accurate to better than ±1 km s^{-1}. The same quantity is

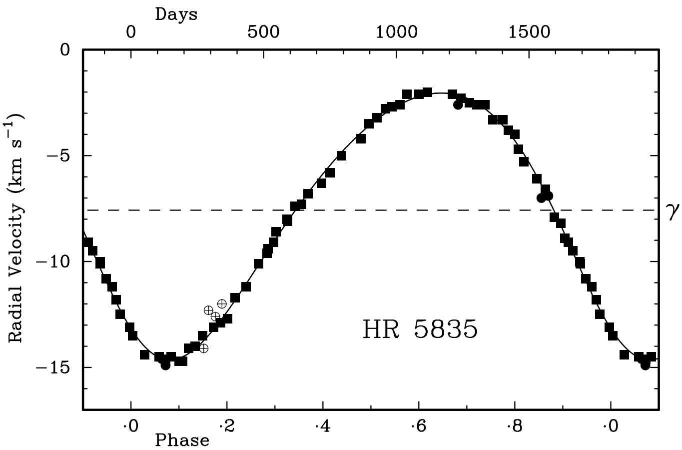

FIG. 4

As Fig. 3, but for HR 5835. Here, in addition to the Cambridge measurements, there are five velocities, plotted with filled circles, that were obtained[24] with the OHP *Coravel* and made available through the CDS; there are also four early DAO photographic velocities[59] from about 16 cycles back, which were not used in the solution of the orbit but are in quite good accord with it.

listed by de Medeiros & Mayor[24], from their five observations, as 3·1 km s^{-1}, with the same *caveat*. A star like HR 5835, whose radius might conservatively be estimated at 12 $R_\odot$, rotating in the 42-day period asserted by Isaacson & Fischer[49], ought to have an equatorial rotational velocity of about 14 km s^{-1}. It is not at all nice to deduce from the observed mean $v \sin i$ that $\sin i$ has to be about 0·21 and that the orbital inclination, therefore, is only about 12°; the likelihood of such a small inclination — it implies that we see HR 5835 from a direction only 12° from its pole of rotation, the probability of which is equal to that of the area of a polar cap of radius 12° in comparison with the area of a hemisphere, *viz.*, about 2%. The possible uncertainty of the $v \sin i$ value cannot extricate us from that improbability; a critical review of the evidence for a 42-day rotation period would seem to be called for.

TABLE V

Orbital elements for HD 22521, BD +15° 1538, HR 4285, and HR 5835

Element	*HD 22521*	*BD +15° 1538*	*HR 4285*	*HR 5835*
P (days)	1009·4 ± 0·6	381·15 ± 0·07	5244 ± 4:	1808·3 ± 2·0
T (MJD)	55207·7 ± 0·7	54005·4 ± 2·9	55736·5 ± 2·6	54394 ± 10
γ (km s^{-1})	−38·15 ± 0·03	−28·02 ± 0·07	−6·91 ± 0·03	−7·58 ± 0·03
K_1 (km s^{-1})	6·92 ± 0·05	17·08 ± 0·09	4·40 ± 0·09	6·29 ± 0·04
e	0·655 ± 0·004	0·098 ± 0·005	0·823 ± 0·006	0·158 ± 0·006
ω (degrees)	326·0 ± 0·7	302·6 ± 2·8	107·9 ± 1·5	140·1 ± 2·0
$a_1 \sin i$ (Gm)	72·6 ± 0·6	89·1 ± 0·5	181 ± 5	154·5 ± 0·9
$f(m)$ ($M_\odot$)	0·0150 ± 0·0004	0·194 ± 0·003	0·0085 ± 0·0007	0·0451 ± 0·0008
R.m.s. residual (wt. 1) (km s^{-1})	0·20	0·38	0·21	0·19

Acknowledgements

I am much indebted to Dr. Brian Mason of the US Naval Observatory, who is in charge of the *Washington Double-Star Catalogue*[54], for his prompt and good-natured assistance with all questions relating to visual double stars, and in particular for much of the information included in the extensive footnote on p. 260 above.

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PISCO2: THE NEW SPECKLE CAMERA FOR THE NICE 76-CM REFRACTOR

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We present the new speckle camera *PISCO2*, made in 2010–2012 for the 76-cm refractor of Côte d'Azur Observatory. It is a focal-plane instrument dedicated to the observation of visual binary stars using high-angular-resolution speckle-interferometry techniques partly to overcome the degradation caused by atmospheric turbulence. Fitted with an EMCCD detector, *PISCO2* allows the acquisition of short-exposure images that are processed in real time by our specially designed software. Two Risley prisms are used for correcting the atmospheric dispersion. All optical settings are remotely controlled. We have already been able to observe faint, close-binary stars with angular separations as small as 0″·16, and visual magnitudes of about 16. We have also measured some particularly difficult systems with a magnitude difference between the two components of about 4 magnitudes. This level of performance is very promising for the detection and study of large sets of yet unknown (or partly measured) binaries with close separation and/or large magnitude difference.

Introduction

This paper presents the new speckle camera *PISCO2* (*Pupil Interferometry Speckle camera and COronagraph*, 2nd version) made in 2010–12 for the 76-cm refractor telescope (*Grand Equatorial de l'Observatoire de la Côte d'Azur*, hereafter L76, see Plate 1). *PISCO2* is a focal-plane instrument (see Plate 2) the purpose of which is to provide high-angular-resolution images using speckle-interferometry techniques. Those techniques allow us partly to overcome the degradation caused by atmospheric turbulence[1].

PISCO2 is a simplified version of *PISCO* that was developed in 1993 for the 2-metre *Bernard Lyot* telescope (Pic du Midi, France). *PISCO* is a multi-purpose focal instrument with many observing modes: pupil interferometry, pupil-mask aperture synthesis, SCIDAR atmospheric-turbulence measurements, grism spectroscopy, coronagraphy, and Shack–Hartmann wave-front sensing. A detailed presentation can be found in ref. 2. Since 2004 *PISCO* has been operated on a dedicated 1-m telescope in Merate (Brera Observatory, Italy) (see, *e.g.*, refs 3 & 4).

The optical design of *PISCO2* (Plate 2) is similar to that of *PISCO* but the observing modes are reduced, and are mainly limited to speckle observations. Indeed, *PISCO2* was specially designed for the observation of visual binary stars. Associated with an electronic detector, it allows the acquisition of enlarged short-exposure images exhibiting 'speckles'. Those images can then be processed as first suggested by Labeyrie[1], to provide high-angular-resolution information.

PISCO2 was specially designed for the Nice 76-cm refractor belonging to Observatoire de la Côte d'Azur (OCA). Built in 1887, when it was the largest refractor in the world, this famous telescope has a free aperture diameter of 74 cm and a focal length of 17·89 m. It is one of the largest refractors still in operation in the world. It has mainly been devoted to binary observation since its construction. The good quality of its optics makes Airy rings clearly visible when the seeing is good, and that happens very frequently, despite the proximity to the city of Nice.

Paul Couteau[†] is probably the most famous astronomer who has used it. He was the architect of the renovation of the refractor from 1965 to 1969[5], and many binaries from his impressive catalogue[6] were measured with that telescope[7,8]. When he retired in 2000, one of his closest collaborators, R. Gili (hereafter RG), decided to continue the long story of binary observations with the L76. Although he was an experienced binary-star observer with a filar micrometer, RG wanted to use more modern techniques, such as precise binary measurements on short-exposure CCD images that he had already obtained in collaboration with other colleagues[9–12].

For this new operating mode, it soon appeared that the L76 needed a serious revision and that a specially designed speckle camera was needed for improving the efficiency and quality of the observations. The 76-cm lens was then dismounted, thoroughly cleaned, and the two (crown and flint) components were fitted into a new improved mechanical mount. The dome motorization was thoroughly revised, both the electronics and the mechanics.

In 2008, two webcams were fitted to the existing magnifying optics of the hour angle and declination circles to allow their reading from a dedicated control computer. This allowed the observer safely to control the telescope while remaining seated in front of a control computer. Before this modification, for pointing at any object with the telescope, the observer had to move to each

[†]Died 2014 August 28.

of the two co-ordinate circles and then climb on top of a ladder to view the star in the finder. Obviously, this could be dangerous in the darkness, especially when the observer started getting tired and feeling sleepy! Owing to the great length of the telescope (about 18 m), this was particularly dangerous when the telescope was pointing to low-elevation targets. A few months later, a new ANDOR DV885 camera was acquired for speckle observations, and replaced the ANDOR LUCA camera that was formerly used for that task. That ANDOR LUCA camera was installed on the Zeiss 25-cm finder, and was thus able to transmit field images to the control computer. This happened to be a decisive improvement to the pointing procedure, and since then both the L76 telescope and its focal instrumentation have been operated from this computer by a single observer.

Focussing the telescope was another hazardous operation, especially for observations made by a single observer (by far the most frequent case). For CCD or EMCCD observations, the observer had to climb on the top of a large step-ladder to actuate the big focussing hand-wheel, then go down to check the quality of the CCD image on the computer screen. This had to be done a few times until satisfactory focussing was achieved. Furthermore, this operation had to be done in total darkness, which was necessary to avoid saturating the camera.

The few thousands of measurements published by Gili & Agati[13] and Gili & Prieur[14] were obtained in those difficult conditions. Indeed, the original focussing system was part of the L76 mechanics and could not be motorized easily without a thorough modification of that historical instrument. Consequently, an important specification for the design of *PISCO2* was to include a remote-control focussing capability.

Introduction to PISCO2

The decision to build a new speckle camera for the L76 was taken in 2009. The main idea was to ease and speed up the observations while extending the observable domain to lower-elevation targets. The basic constraints were simplicity, lightness, small overall dimensions, and low cost. The last constraint was rather severe since most of the expenditure had to be covered by personal funds. For this design, we profited by our experience in binary-star observations with the L76 and with *PISCO* on other telescopes.

PISCO2 was made entirely at OCA between 2010 and 2012. Most of the mechanical parts were machined in the OCA workshops. When possible, complete manufactured units were integrated into *PISCO2* to reduce the development time and the cost. For example, that was the case for the remote-control units dedicated to the motorized focussing or the angular control of the Risley prisms.

Optical design

The optical layout (see Plate 2) is similar to that of *PISCO*[1]. An achromatic lens L1 of focal length F_1 is placed at a distance F_1 from the primary focal plane of the telescope. This lens thus creates a collimated beam which is used for placing the Risley prisms and the filters. A second achromatic lens L2 focusses this parallel beam onto the image plane of the detector. A retractable mirror and a set of two lenses (L3 and eyepiece) enable a visual inspection of the images. The Risley prisms are located very close to the pupil plane. Unlike *PISCO*, there is no field lens in the focal plane of the telescope. This improves the overall transmission, but imposes a longer distance for the collimated beam.

PISCO2 can use different detectors, which may have different pixel sizes. The adaptation can be done by changing the lens L1, and choosing its focal length accordingly. For instance, two L1 lenses of 50- and 100-mm focal length have been used for the ANDOR DV897 and DV885 detectors, respectively.

The available filters are the IRC (IR-cut), which is a low-pass filter rejecting all wavelengths above 700 nm, the Schott BG39, which has a band-pass between 350 and 600 nm, and the AF (anti-fringe or *V*-block), which has a band-pass 450–650 nm; the AF filter considerably reduces the secondary spectrum of the 76-cm refractor, with no significant loss of energy in the *V* band. When combined with the transmission of the lenses and the quantum-efficiency response of the detector, the resulting transmission curve of those filters is close to a standard *V* filter with a maximum around 570 nm.

Most optical settings of *PISCO2* can be remotely controlled with a computer including focussing, filter selection, and Risley-prism correction. Motorized focussing and filter-wheel selection are controlled by ASCOM interface programs provided by the corresponding manufacturers. Focussing is driven by a stepping motor whose step corresponds to a translation of 4 μm, with a full range of 40 mm. Risley prisms can be set by the THORLABS program which works with a USB interface.

Description of the detectors

The *PISCO2* instrument was successively fitted with two EMCCD detectors from ANDOR Technology: an iXON DV885 and an iXON DV897 (see ref. 15). We first used the DV885 belonging to RG, which is equipped with a front-illuminated EMCCD chip. We then used the DV897 belonging to FV, which is more recent and has a better performance. It has a back-illuminated EMCCD with a higher quantum efficiency and is fitted with a more elaborate cooling system. Another advantage of the DV897 is its higher reading frequency.

The main characteristics of the two detectors are given in Table I. For each one, we indicate its full format in pixels (Col. 2), the pixel size in μm (Col. 3), the digitization depth in Col. 4, *i.e.*, the number of bits per pixel used for encoding the output values, the maximum frequency rate (Col. 5) used for reading out the pixel data, the theoretical quantum efficiency of the detector (Col. 6), and the cooling temperature that was used during our observations (Col. 7).

The quantum efficiency values in Col. 6 of Table I are those given by the EMCCD chip constructor for wavelengths in the range 550–720 nm. The overall effective efficiency is unfortunately much smaller. With *PISCO* in Merate (Italy), we have made some comparative tests in 2011 with the iXON DV885 and the *PISCO* ICCD cameras[4]. For speckle observations, the DV885 was roughly equivalent to the ICCD. Note that the ICCD camera is fitted with an *R*-photo-cathode amplifier whose quantum efficiency is only 7%!

TABLE I

Main characteristics of the ANDOR iXON EMCCD cameras

Name	*Format* (*pixels*)	*Pixel size* (*μm*)	*Digitization* (*bits*)	*Read freq.* (*MHz*)	*Quantum Eff.* (*%*)	*Max.cooling T.* (*°C*)
DV885	1004 × 1002	8 × 8	14	27	60–65	−70
DV897	512 × 512	16 × 16	14	10	80–92	−90

For both detectors, the image transfer is performed through a dedicated link between the detector and a CCI-22 frame-grabber board installed on a PCI slot of the acquisition computer, which allows a reading frequency as high as 27 MHz. This would correspond to an acquisition rate of 27 full-size images per second. In practice, we used a lower readout frequency (5·13 MHz) to reduce the noise in the images. Those detectors can be used in EM mode, which reduces the read-out noise of the output register to less than one electron.

We wrote a specially designed program (BUILDSPECK1, see Plate 3) for handling the data acquisition of those two detectors. This program controls the electronic settings and the basic functions of the EMCCD detectors. It also performs real-time processing of speckle-interferometry observations.

Exposure times of elementary frames are set in the range 20–30 ms for speckle observations. The standard format of the acquisition window is 128 × 128 pixels which corresponds to a field of view of 9″·5 × 9″·5 for the DV897 camera. For faint objects or wide pairs, a wider field of 256 × 256 pixels on the detector can be used with a binning factor of 2 × 2 which thus amounts to 128 × 128 pixels for the elementary frames. The EM gain is generally set to values of about 170–200 and 3000 for the DV885 and the DV897, respectively. To avoid saturation on bright objects, the EM gain can be reduced or even put to 'off', which corresponds to observing in conventional CCD mode.

Correction of the atmospheric dispersion with Risley prisms

For ground-based observations of astronomical objects, the atmosphere behaves like a dispersive prism[16]. Polychromatic images are spread into a small vertical spectrum. This effect can be neglected for observations close to the zenith, but is very strong at low elevations, and can severely degrade the angular resolution. For instance in the visible, for a $\Delta\lambda = 250$-nm band-pass centred at $\lambda = 500$ nm, the typical atmospheric dispersion is $\Delta\theta = 1''$ for an elevation $h = 60°$ and $\Delta\theta = 2''$ for $h = 30°$.

PISCO2 contains an atmospheric-dispersion corrector to circumvent this problem. This corrector is similar to that of *PISCO*[2] and is based on Risley prisms[17,18]. They consist of two identical sets of prisms (see Plate 4) that can be rotated to produce a chromatic dispersion tuneable both in amplitude and direction. Each set is made of two prisms that have different indices and roof angles, and that are glued together in an upside-down position.

As with *PISCO*, we have used the same combination of Schott glasses (F4, SK10) that was used at Kitt Peak in the combinations proposed by Wallner & Wetherel[18], and which are close to the atmospheric dispersion curve. The F4 + SK10 combination has the advantage of low cost and was efficient enough for our purpose.

The Risley prisms of *PISCO2* have been designed to have a null mean deviation, and a dispersion allowing atmospheric correction from the zenith down to an elevation of 30°, when using the DV897 detector. The F4 and SK10 prisms have a roof angle of 10°·0 and 9°·92, respectively. The tolerance on the roof angle is 6 arcmin, and the surface accuracy is $\lambda/4$ (for $\lambda = 550$ nm). Those specifications lead to a reduction of the residual dispersion down to a level smaller than 0″·01 for any object located at an elevation larger than 30°, with the AF filter (450–650-nm band-pass). That is much smaller than the diffraction limit of 0″·16 of the 76-cm refractor.

During the observations, a specially designed program (PISCO2_RISLEY.CPP) computes the elevation of the star and the atmospheric dispersion inferred from models[19]. The Risley prisms are then rotated with the THORLABS remote-control program, so that their total dispersion has the same magnitude as the atmospheric dispersion and an opposite direction. The observations have shown that the correction is very good (see Plate 4), even for objects whose declination is as low as –7°, which is the lower pointing limit for the present instrumentation setup, imposed by the camera cable length.

Scale calibration with a grating mask

The on-sky pixel scale of the whole instrument (telescope and *PISCO2*) can be calibrated in an absolute manner with a grating mask placed in front of the refractor objective lens. This is the method used for calibrating *PISCO* in Merate, as described in detail by Scardia *et al.*[3]. We present here the procedure we followed in 2012 September for calibrating the scale of the DV897 detector.

A grating mask was mounted on the entrance baffle of the telescope. This mask was originally designed for the calibration of the OCA 50-cm refractor. It has a diameter of 50 cm and a period of $p = 22{\cdot}43 \pm 0{\cdot}10$ mm. To obtain measurements with high precision, we used a narrow-band filter, centred on $\lambda = 570$ nm, with a bandwidth of 10 nm. The corresponding period of the diffraction pattern was then $\lambda/p = 5''{\cdot}241$. For this calibration, we observed the single star ε Leo. The measurements were made on the mean of a series of a few 1000-image data cubes. The equivalent focal length with *PISCO2* and the DV897 detector was found to be $44{\cdot}66 \pm 0{\cdot}2$ m and the scale $0''{\cdot}0739$ per pixel.

The 76-cm refractor has actually a free aperture of 74 cm. The corresponding diffraction limit λ/D is $0''{\cdot}16$ with $\lambda = 570$ nm. The sampling of the detector mounted on *PISCO2* is thus less than half this diffraction limit for $\lambda = 570$ nm and so is compatible with the Nyquist–Shannon criterion, and therefore allows measurements down to the diffraction limit.

The calibration of the origin of the position angles was done by recording star trails caused by the diurnal motion. We used the largest available field for this purpose, which was $53'' \times 40''$ with the DV897.

Conclusion

The first observations have shown that *PISCO2*'s performance has reached the initial goal. Fitted with remote-control components such as a filter wheel, a motorized focussing system, and an atmospheric-dispersion corrector, this instrument is very easy to operate.

PISCO2 is dedicated to the observation of visual binary stars. In the last few years, it has already permitted us to obtain numerous measurements, with an average rate of about 2100 objects/yr. With the DV897 detector, we have been able to observe faint, close-binary stars with angular separations as small as $0''{\cdot}16$ and visual magnitudes of about 16. We also have measured some particularly difficult systems with a magnitude difference between the two components of about 4 magnitudes.

In future, we intend to use *PISCO2* for observing large sets of yet-unknown (or partly measured) binaries with close separations and/or large magnitude differences, many of which could not be measured by space missions. *PISCO2* may thus provide a significant contribution to stellar physics.

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STELLAR MULTIPLICTY IN THE σ ORIONIS CLUSTER: A REVIEW

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The nearby, young, extinction-free σ Orionis cluster is acknowledged as a cornerstone for studying stellar and sub-stellar formation and evolution, especially at very low masses. However, the relatively limited knowledge of multiplicity in the cluster is dispersed among numerous papers and proceedings with very different aims and, therefore, is difficult to apprehend even for researchers in the subject. Here, I review comprehensively the sexdecuple system σ Ori in the central arcminute, and all close (ρ = 0·4–4 arcsec) and wide (ρ > 4 arcsec) binaries, triples, hierarchical multiples, and spectroscopic binaries in the cluster that had been reported in the literature up until 2014. I conclude with a brief enumeration of the steps that should be taken in the near future for gaining a clear picture of the multiplicity in the σ Orionis cluster.

Introduction

Regardless of what we call them, The Big Three, *Ζωνη* (*Zone*), *Balteus*, *Shen*, *Tres Marías*, *Oriongürtel*, *Ceinture d'Orion*, Jacob's Rod, *Magi*, Golden Yard-arm, *Iṣus Trikāṇḍā*[1] or Orion's Belt, the three blue supergiant stars Alnitak (ζ Ori), Alnilam (ε Ori) and Mintaka (δ Ori) form the most prominent asterism in the sky. Since ancient times, they have attracted the attention of sky watchers, seamen, astronomers, and even poets. The fourth brightest star in Orion's Belt, just one degree south of Alnitak and about 2^{m} fainter than the three main stars, is σ Ori (*Quae ultimam baltei præcedit ad austrum*, 48 Ori, HD 37468). In spite of not having been catalogued by Ptolemy (137 AD) or Ulugh Beg (1437)[2], σ Ori is, with $V \sim 3^{m} \cdot 8$, visible with the naked eye as a single star[3–5]. However, it is actually a Trapezium-like system that contains six early-type stars, including the massive astrometric 'binary' σ Ori AB and the rotationally variable B2 Vp star σ Ori E. Remarkably, σ Ori is the principal source of IC 434, the emission nebula against which the famous Horsehead dark nebula (Barnard 33) is silhouetted.

The σ Ori multiple system has taken on a great significance in the last two decades because of the homonymous star cluster that surrounds it, σ Orionis[6–8], which has become one of the best laboratories in the sky to study star and brown-dwarf formation[9–11]. With an age of about 3 Myr, and a distance 385 pc, nearly free of extinction, the open cluster in the Ori OB1b association has been the subject of numerous works on X-ray emission[12,13], disc frequency[14–16], presence of Herbig–Haro objects[17,18], photometric variability[19–22], accretion rates and frequency[23–26] and, especially, mass function at low stellar and sub-stellar masses, down to below the deuterium-burning limit[27–31]. In spite of its importance as a test-bed for models of high- and low-mass star formation and evolution, the issue of the multiplicity in the σ Orionis cluster has not been addressed yet in an exhaustive manner. Here I compile *all* available information on multiplicity in σ Orionis prior to 2014. As with any other review, retrieved and re-measured data are so heterogeneous that they can hardly be the subject of a serious statistical analysis, but instead shed light on previous scattered, difficult-to-find works on the topic, as well as pave the way for future high-resolution imaging and spectroscopic surveys.

A bit of history

The first multiple system in σ Orionis was reported in 1779 in the *Tabula Nova Stellarum Duplicium* by Mayer[32], who catalogued what we call now σ Ori AB, D, and E[33]. A few weeks after the announcement, W. Herschel promptly made the first accurate measures of angular separation (ρ) and position angle (θ) of the triple system[34,35]. Decades later, Dawes[36] discovered σ Ori C, five magnitudes fainter than AB. It was not until the end of the 19th Century when Burnham[37] realized that the brightest star in the (up-to-then) quadruple σ Ori system was in its turn a very close binary of $\rho \sim 0'' \cdot 25$, later dubbed "the most massive binary with an astrometric orbit"[38,39]. A sixth, massive, OB-type component, which made Burnham's pair a triple, was confirmed recently with high-resolution spectroscopy by Simón-Díaz *et al.*[40]. As described below, the existence of new low-mass stars at less than $1'$ from σ Ori AB may make the system at least a sexdecuple[41,42].

The *Washington Double Star Catalogue* (*WDS*[43]) lists 13 cluster pairs with angular separations between $3'' \cdot 3$ and $8' \cdot 7$ (Table I). Eight pairs are associated with σ Ori itself, and the remaining five ones with two sky asterisms containing the stars HDE 294271/2 and TX Ori/TY Ori. Tabulated astrometric

TABLE I

Wide pairs in the σ Orionis cluster tabulated by the Washington Double Star Catalogue

WDS	*Primary (Mayrit No.)*	*Code*	*Secondary (Mayrit No.)*	*ρ arcsec*	*θ deg.*
05387–0236	σ Ori Aa, Ab (Aa, Ab)	BU 1032 AB[37]	σ Ori B (B)	0·250±0.006	100·9±0.5
		STF 762 AB,C[50,51]	σ Ori C (11238)	11·43±0.06	237·8±0·4
		STF 762 AB,D[50,51]	σ Ori D (13084)	12·98±0.03	84·20±0·12
		STF 762 AB,E[50,51]	σ Ori E (42062)	41·555±0.004	61·720±0·008
		STF 3135 AB,F[50,51]	HDE 294271 (208324)	209·6	324
		TRN 19 AB,G[52]	σ Ori IRS1 (3020)	3·32±0·06	19·6±1·4
		SHJ 65 AB,H[53]	HD 37525 (306125)	306·7	125
		SHJ 65 AB,I[53]	HD 37564 (524060)	524·1	60
05386–0233	HD 294271 (208324)	STF 761 AB[50,51]	HDE 294272 A (182305)	67·8	203
		STF 761 AC[50,51]	HDE 294272 B (189303)	71·8	209
		STF 761 AD[50,51]	BD –02 1324D (240322)	32·9	309
05386–0244	TX Ori (521199)	PLT 1 AB[54]	TY Ori (489196)	40·0	55
		DAM 51 AC[55]	[WB2004] 21 (…)	16·9	33

measurements of ρ and θ come from the *WDS* except for σ Ori A,B (average of three measurements by Docobo *et al.*[44] in 2004·10), AB,C (by 2MASS[45] in 1998·828), AB,D (by *Hipparcos*[46] in 1991·25), AB,E (by *Tycho-2*[47] in 1991·25), and AB,G (by Caballero[48] in 2003·688). Compare those values with those provided by Mason *et al.*[49]. The notations σ Ori 'F' to 'I' are not used at all in the literature. Fig. 1 illustrates the heart of the σ Ori trapezium.

Note that the *WDS* codes in the third column do not match the discoverer in all cases, Mayer and Dawes, and not Struve, being the discoverers of σ Ori D and E, and C, respectively. Besides, σ Ori IRS1, which is described extensively below, was *not* discovered by Turner *et al.*[52], nor did they provide astrometric data for the first time.

As a final comment on Table I, the third star in the WDS 05386–0244 system, [WB2004] 21[56], is a cluster interloper. There is a fourth star near WDS 05386–0244, namely Mayrit 508194[57,58] (S Ori J053836·7–024414), which is not catalogued by the *WDS*. It is, however, a *bona fide* cluster member located at $\rho \sim 45''$, $\theta \sim 89°$ to the primary and only $\rho \sim 25''$, $\theta \sim 152°$ to the secondary.

The σ Ori trapezium

"Perhaps the finest multiple star in the sky visible to both northern and southern observers, σ Ori is a system of five stars, four of which are visible in a small telescope [...]. This region of Orion's belt is an astrophotographer's dream"[59]. Those stargazer's sentences illustrate not only the great interest of the σ Ori trapezium to amateur astronomers, but also an extended misconception about the actual number of early-type stars in the system. Regrettably, that error is also widespread among professional astronomers, who also stress the importance of the late-O and early-B stars in σ Ori as a key trigger for the stellar formation in the Horsehead Nebula[60–63].

The astrophysical parameters of all the stars in the central cusp of the σ Orionis cluster are important for investigating a wealth of topics: (*i*) the high-mass stars in the σ Ori trapezium shape many, if not all, photo-dissociation regions, remnant molecular clouds, bright-rimmed clouds, cometary globules, and small reflection clouds in the Ori OB1b sub-association, especially the Horsehead Nebula[64–67] and a nearby bow-shock dust wave[68,69]; (*ii*) turbulence injection in the intracluster medium *via* ultraviolet heating and photo-erosion of pre-existing cores, also originating in high-mass stars, may explain the high frequency of brown dwarfs and 'isolated planetary-mass objects' in the cluster[70–74]; (*iii*) the top of the (initial) mass function, up to ~20 $M_\odot$[58,75,76]; (*iv*) heliocentric distances and dynamical masses of the most massive components[39]; and, of course, (*v*) multiplicity in all mass domains.

Apart from σ Ori Aab, B, C, D, E, and IRS1 in Table I, there are six other late-type cluster members at $\rho < 1'\cdot0$ from σ Ori A, with features of youth (near-infrared excess due to circumstellar disc, X-ray emission, Li I λ6707·8Å in absorption, Hα λ6562·8 Å in emission) and found in all-sky surveys, which are listed in Table II. Tabulated angular separations and position angles were measured from 2MASS[45] data obtained on 1998·828. There are, however, more faint objects in the central arcminute of the cluster, generally ascribed as components of the σ Ori multiple system. Below, I enumerate and review the 16 known stars in the 1-arcmin-radius central area. In parenthesis, *N* indicates the increasing number of components. For this enumeration and in the rest of the paper, I use the Mayrit nomenclature. The Mayrit catalogue[11] and its subsequent additions and corrections is so far the most comprehensive list of σ Orionis members and candidates free of contamination by fore- and background interlopers, and is routinely used by other authors worldwide. Given the diversity of surveys and searches in the open cluster, the homogeneous use of the Mayrit nomenclature facilitates the easy recognition and writing of most objects in σ Orionis, where typical names are as complex as [BZR2001] S Ori J053825·4−024241, [W96] rJ053827−0242, 2MASS J05382732−0243247 or [HHM2007] 488, just to give a few examples. Besides, the Mayrit number provides the angular separation and position angle with respect to the cluster centre (*e.g.*, Mayrit 42062 is the star at $\rho = 42''$ and $\theta = 62°$ with respect to σ Ori AB).

TABLE II

Cluster members not listed in WDS and at $\rho < 1'\cdot0$ to σ Ori A

Mayrit No.	*Sp. type*	*ρ arcsec*	*θ deg.*	*Features of youth* *Disc*	*X-rays*	*Li I*	*Hα*
21023[77,78]	M:[78]	20·61 ± 0·10	23·5 ± 0·4	...	Yes[13,78]	...	...
30241[78]	K–M:[78]	29·81 ± 0·06	241·14 ± 0·16	Yes[78,79]	Yes[78,80]	...	...
36263[78]	M3·5:[26]	35·73 ± 0·06	263·17 ± 0·11	Yes[79]	...	Yes[26]	Yes[26]
50279[78]	M6·0:[26]	50·07 ± 0·06	279·06 ± 0·06	Yes[79]	No?[13,78]	Yes[26]	Yes[26]
53049[78]	M1·0:[26]	53·47 ± 0·06	49·17 ± 0·09	Yes[78,79]	Yes[12]	Yes[26]	Yes[26]
53144[78]	M5·0:[26]	53·36 ± 0·06	144·18 ± 0·10	...	Yes[13,80]	Yes[26]	Yes[26]

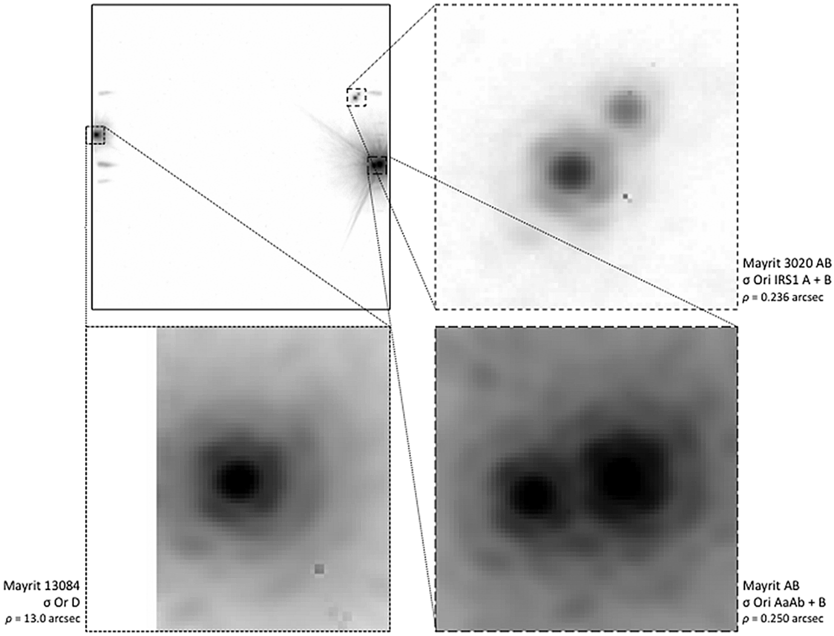

FIG. 1

Colour-inverted *Ks*-band image of σ Ori Aab, B, IRS1A, IRS1B, and D taken with *NACO* at the *Very Large Telescope UT4* in 2004 October during instrument commissioning for astrometric calibration. Top left panel: full field of view of approximate size of 13·6 × 13·6 arcsec^2. Remaining panels: sub-images, about 1 arcsec in size, centred on σ Ori IRS1 A,B (Mayrit 3020 AB; top right), σ Ori Aab,B (Mayrit AB; bottom right), and σ Ori D (Mayrit 13084), at 13·0 arcsec to the east of σ Ori Aab,B. North is up, east is to the left. Names and angular separations are labelled.

Mayrit Aa,Ab,B = *σ Ori Aa,Ab,B* (N = 3; see Table I).

Since its discovery by Burnham[37], the tight binary BU 1032 AB in the very centre of the cluster has not yet completed a whole revolution. Fortuitously, the first astrometric orbit of σ Ori AB was computed by Siegrist[81]. Her four-page manuscript was published in Spanish by a journal with a very limited distribution, and it may have gone unnoticed for ever if it were not for colleagues at the Universidad Complutense de Madrid. As she remarked, given the low quality of her data (and limited and sparse time coverage — the latest astrometric observation was made by Müller in 1950·20; two world wars happened in between), her orbit should be considered provisional. In spite of it, she already pointed to the pair having a low eccentricity and a period longer than a century. Better orbital parameters were determined later by other authors[82–85]. The most recent astrometric orbit was presented by Turner *et al.*[86], who tabulated P = 156·7±3·0 yr, a = 0·2662±0·0021 arcsec, and e = 0·0515±0·0080. Although suspected by some authors throughout the whole

20th Century[87,88], it was not until 120 years after Burnham's discovery that Simón-Díaz *et al.*[40] demonstrated the binary actually to be triple. They first obtained solutions for the radial-velocity curves of components Aa and Ab, resulting in a highly eccentric orbit ($e \sim 0{\cdot}78$) with a spectroscopic period of 143·5±0·5 d (400 times smaller than the astrometric period). They assigned spectral types O9·5 V, B0·5 V, and early-B to Aa, Ab, and B, respectively (before that, it was thought that σ Ori B was B0·5 V). Lately, two teams have been able to resolve σ Ori Aa and Ab, which are separated by less than 8 mas, with the *Navy Precision Optical Interferometer*[89] and *Michigan Infra-Red Combiner* for the *CHARA Interferometer*[90]. Using unpublished radial-velocity data, both teams provided preliminary estimates of stellar masses ($M_{\rm Aa} = 15{\cdot}6$–$16{\cdot}7\ M_\odot$ and $M_{\rm Ab} = 12{\cdot}4$–$12{\cdot}8\ M_\odot$) and distance ($d = 380$–385 pc, which matches Caballero's[39] triple-scenario distance of $d \approx 385$ pc). Simón-Díaz *et al.* (in prep.) provide a detailed spectroscopic analysis of the triple system and calculate an improved period of the spectroscopic–interferometric pair with an accuracy of 11 min.

Mayrit 3020 A,B = σ Ori IRS1A,B ($N = 5$; see Table I).

A "dust cloud next to σ Ori" was discovered in the mid-infrared by van Loon & Oliveira[91]. They explained the dense core and extended emission in a fan-shaped morphology, pointing away from the high-mass stellar system, as a photo-evaporating proto-planetary disc. Next, Caballero[92] imaged the central star of σ Ori IRS1 for the first time and, later[48] reported the first astrometric observation with near-infrared adaptive optics. Previously, Sanz-Forcada *et al.*[93] had found its X-ray counterpart with *XMM–Newton*, but were unable to determine its real nature. Later, other authors imaged σ Ori IRS1 with *Chandra*[13,78,80]. Finally, Hodapp *et al.*[94], using near-infrared integral-field spectroscopy, discovered that σ Ori IRS1 is actually a photo-eroded pair of a very-low-mass star and a brown-dwarf proplyd. The only astrometric observations of σ Ori IRS1 A and B have been made by Bouy *et al.*[41], who measured $\rho = 0''{\cdot}2363 \pm 0''{\cdot}0024$, $\theta = 318^\circ{\cdot}1 \pm 0^\circ{\cdot}4$ and $\Delta K_s = 2^{\rm m}{\cdot}19 \pm 0^{\rm m}{\cdot}01$ on 2004·776 (with *NACO/VLT*), and $\rho = 0''{\cdot}2429 \pm 0''{\cdot}0036$, $\theta = 317^\circ{\cdot}0 \pm 0^\circ{\cdot}7$ and $\Delta K_s = 2^{\rm m}{\cdot}17 \pm 0^{\rm m}{\cdot}07$ on 2007·914 (with *MAD/VLT*).

Mayrit 11238A,B = σ Ori Ca,Cb ($N = 7$; see Table I).

The familiar star σ Ori C has been imaged tens of thousands times with telescopes of all sizes, but has been poorly investigated spectroscopically[95]. Again, its companion candidate was discovered by Caballero[92], first measured by Caballero[48] ($\rho \sim 2''{\cdot}0$, $\theta \sim 20^\circ$ on 2003·688), and characterized astrometrically in detail by Bouy *et al.*[41] ($\rho = 1''{\cdot}9915 \pm 0''{\cdot}0039$, $\theta = 11^\circ{\cdot}5 \pm 0^\circ{\cdot}7$ on 2007·914). The magnitude differences between σ Ori Ca and Cb, of $5^{\rm m}{\cdot}50 \pm 0^{\rm m}{\cdot}07$ in H and $5^{\rm m}{\cdot}05 \pm 0^{\rm m}{\cdot}14$ in K_s, would locate the companion in the very-low-mass-star domain, close to the sub-stellar boundary, if it belonged to the cluster.

Mayrit 13084 = σ Ori D ($N = 8$; see Table I and Fig. 1).

It is a bright, single, normal B2 V star with faint (wind-driven?) X-ray emission[13,95].

Mayrit 21023, 30241, and 36263 ($N = 11$; see Table II).

They are three cluster members with known features of youth[11] closer to the cluster centre than σ Ori E.

Mayrit 42062 A,B = *σ Ori Ea,Eb* ($N = 13$; see Table I).

The famous, helium-rich, magnetically active, radio and X-ray emitter, short-period rotationally variable, spectroscopically peculiar star σ Ori E (B2 Vp; 7–8 $M_\odot$) has been extensively studied in the literature[95–107]. However, nobody has yet tried to confirm, or use in their rather complex models, the tight duplicity claimed by Bouy *et al.*[41]. They found a companion candidate to σ Ori E, 3–4^m fainter in K_s, at $\rho \sim 0''\cdot330$ and $\theta \sim 301°$ on 2007·914 (note the corrected angle; Bouy, priv. comm.). According to Caballero *et al.*[13,108], the numerous X-ray flares[109] may come from the K–M-type secondary at 100–150 AU, while the X-ray low-amplitude modulation may have its origin in the plasma trapped in heterogeneous magnetospheric clouds that transit across the disc of the B2 Vp primary[110].

Mayrit 50279, 53049, and 53144 ($N = 16$; see Table II).

They are another three young stars within the innermost 1′, but further from the cluster centre than σ Ori E. Interestingly, Mayrit 50279 is, with $J \approx 14^{m}\cdot0$ and $M = 0\cdot09$–$0\cdot08\ M_\odot$, the faintest object with features of youth in the area[11], even fainter than the brown-dwarf proplyd σ Ori IRS1 B.

I have not enumerated the cluster-member candidate [BNL2005] 3.01 67 (at $\rho = 53''\cdot42 \pm 0''\cdot06$, $\theta = 144°\cdot16 \pm 0°\cdot02$ to σ Ori A), which displays low-gravity features, manifested by weak pseudo-equivalent widths of alkali lines[111], and very faint X-ray emission[13,80,112], but which seems actually to be an M2·5 V spectroscopic binary in the field[26].

Within a 60-arcsec-radius circle, there are many more catalogued sources with unknown membership status[41]. However, most of them (including the relatively bright sources 2MASS J05384652–0235479 and 2MASS J05384454–02353249[77,78]), with only two- or single-band photometry, must be faint reddened stars and galaxies in the background under reasonable assumptions of spatial distribution, mass function, and contamination[30,113–115].

Close binaries outside the cluster centre

To date, apart from the σ Ori system itself, only another five bright stars in the cluster have been targeted with high-resolution ($0''\cdot15$–$0''\cdot25$) imaging with adaptive optics (with *NAOMI* at the 4·2-m *William Herschel Telescope* at epoch 2003·688)[48,92]. Two of them, the stars Mayrit 306125 and 528005, turned out to be close binaries with angular separations of $0''\cdot4$–$0''\cdot5$. Another eight cluster pairs with angular separations between $\sim0''\cdot5$ and $\sim3''$ (~200–1200 AU at the cluster distance) have been reported by the author in other works from data obtained with the 2·5-m *Isaac Newton*[48], 1·5-m *Carlos Sánchez*, and 0·80-m *IAC80* telescopes[48,78], asymmetries of stellar profiles in 2MASS images[11], and digitized photographic plates[13,116]. The ten close-binary candidates, which are not fully resolved into two in standard observations from the ground, are listed in Table III. Some pairs lack relevant data, such as accurate angular separation, position angle, or magnitude difference in a certain photometric band. However, that gap will soon be filled by an analysis of UKIDSS near-infrared data[117,118]. 'NE' and 'SE' in position angle stand for reported elongations in the north-east and south-east directions, respectively. All primaries, being either in physical or visual systems, are very young mid-K to mid-M dwarfs except for the also-young B5 V star Mayrit 306125.

Of the ten close-binary candidates, only one has been investigated as a double system in some detail: Mayrit 92149 AB. Caballero[78] proposed that the primary

TABLE III

Reported close binaries not listed in WDS and at ρ > 1′·0 to σ Ori A

Star (*Mayrit No.*)	*ρ* *arcsec*	*θ* *deg.*	*Δmag* (*band*) *mag.*
[W96] rJ053847–0237	~1·9[78]	~60[78]	1.1±0·4 (*V*)[78]
(92149 AB)[8]	(2·1)[30]	(64)[30]	0·80±0·17 (*R*)[78]
			0·62±0·10 (*I*)[78]
			0·337 (*Z*)[30]
			0·381 (*Y*)[30]
			0·468 (*J*)[30]
			0·548 (*H*)[30]
			0·828 (*K*)[30]
[W96] rJ053834–0234 (168291 AB)[26]	~3·5[13]	NE[13]	…
HD 37525 (306125 AB)	0·47±0·04[92]	189±7[92]	≥0·5 (*H*)[92]
[W96] 4771–899 (528005 AB)	0·40±0·08[92]	170±10[92]	0·337±0·019 (*H*)[92]
[W96] rJ053859–0247 (707162 AB)	~1·0[48]	…	~0·0 (*R*)[48]
2E 1486 (1106058 AB)	<3[11]	…	…
V605 Ori (1245057 AB)	<3[11]	…	…
[SWW2004] 118 (1411131 AB)	<3[11]	…	…
2E 1464 (1564349 AB)	~0·5[48]	…	~0·8 (*R*)[48]
[SE2004] 6 (1610344 AB)	~3·0[116]	SE[116]	…

had a circumstellar disc from the magnitude differences from the blue optical to the near-infrared. Earlier, Sherry *et al.*[58] had tabulated two objects separated by 0″·75 and with roughly the same VRI_CJHK_s magnitudes at the coordinates of Mayrit 92149 (SWW 102 and 149), but it is not known whether they actually recognized the pair (they also tabulated two objects, SWW 4 and SWW 159, separated by only 0″·011 at the coordinates of the single star Mayrit 126250). Lodieu *et al.*[30] recovered and tabulated accurate coordinates and magnitudes of the two stars in the previously-known pair using UKIDSS data[117], from where I derived the *ρ*, *θ*, and *Δmag* values in parenthesis in Table III.

Wide binaries outside the cluster centre

Some photometric surveys for new σ Orionis member candidates have identified additional young binary candidates with angular separations $\rho > 4''$ that are not tabulated by the *WDS* and still require a careful study. Table IV lists the 16 published pairs in 12 systems, together with discovery references and recomputed *ρ*, *θ*, and Δ*K* values from UKIDSS data from Lodieu *et al.*[30]. The new angular separations, position angles, and magnitude differences match previous determinations within uncertainties. The tabulated magnitude differences of the two companions of Mayrit 208324 are actually ΔK_s because of saturation of the primary in the UKIDSS image. The values of *ρ*, *θ*, and Δ*K* of the two systems containing the 'isolated planetary-mass object' *candidates* S Ori 68 and S Ori 74 were derived from *VISTA* data[31].

TABLE IV

Wide binaries not listed in WDS and at $\rho > 1'\cdot0$ to σ Ori A

Primary (Mayrit No.)	Secondary (Mayrit No.)	ρ arcsec	θ deg.	ΔK mag.
HD 294271 (208324)	[HHM2007] 614 (214321)[48,79,92]	10·62 ± 0·02	266·7 ± 0·2	(4·63 ± 0·06)
	[HHM2007] 606 (219320)[48,79,92]	18·72 ± 0·02	268·8 ± 0·2	4·83 ± 0·05
[W96] 4771–1051 (260182)	S Ori J053844.4–024030 (270181)[29,48]	11·46 ± 0·02	160·3 ± 0·2	2·0856 ± 0·0016
	S Ori 74 (...)[125]	11·90 ± 0·10	3·2 ± 1·0	9·0:
	S Ori J053844.4–024037 (277181)[29,48]	18·34 ± 0·02	168·1 ± 0·2	3·477 ± 0·004
V507 Ori (397060)	S Ori 7 (410059)[48,126]	14·10 ± 0·02	40·6 ± 0·2	2·638 ± 0·002
[SE2004] 70 (487350)	S Ori 68 (483350)[12,120]	4·59 ± 0·10	136·0 ± 1·0	4·0 ± 0·3
[W96] 4771–899 (528005 AB)	S Ori J053847.5–022711 (530005)[48,92]	7·69 ± 0·02	286·9 ± 0·2	1·5934 ± 0·0008
[SE2004] 94 (856047)	S Ori J053926.8–022614 (860047)[120,121]	4·64 ± 0·02	75·6 ± 0·2	2·802 ± 0·015
2E 1484 (863116)	2MASS J05393660–0242222 (866116)[127]	4·92 ± 0·02	167·9 ± 0·2	1·6360 ± 0·0007
[W96] 4771–962 (968292)	SO210868 (958292)[48,68]	9·92 ± 0·02	97·4 ± 0·2	0·3869 ± 0·0007
V2750 Ori (1087058)	S Ori J053946.3–022631 (...)[57,128]	5·87 ± 0·02	265·4 ± 0·3	≥6·0
HD 37686 (1359007)	HD 37686 #2 (...)[48]	5·50 ± 0·02	203·8 ± 0·3	5·68 ± 0·02
OriNTT 429 (1415279 AB)	[SWW2004] 22 (1416280)[126,129]	12·15 ± 0·02	4·2 ± 0·2	2·5683 ± 0·0019
[SE2004] 6 (1610344)	2MASS J05381428–0210177 (...)[116]	4·85 ± 0·02	240·2 ± 0·3	4·25 ± 0·02
	USNO-A2.0 0825–01615246 (...)[116]	8·18 ± 0·02	244·1 ± 0·3	6·8 ± 0·2

I provide for the first time Mayrit numbers for the cluster members and candidates S Ori 68 (483350), S Ori J053926·8–022614 (860047), and 2MASS J05393660–0242222 (866116). However, I do not provide them for the interloper stars and distant galaxies S Ori 74, S Ori J053946·3–022631, HD 37686 #2, 2MASS J05381428–0210177, and USNO-A2·0 0825–01615246.

Following the author's cluster centre-separation–pair-separation diagram[119], only three pairs among the nine possible cluster binaries in Table IV would have probabilities of chance alignment < 1 %.

Mayrit 487350 + 483350 ($\rho \sim 4''\cdot6$).

It is the well-known brown-dwarf–'planetary-mass-object' pair candidate [SE2004] 70 + S Ori 68, whose components still lack an irrefutable confirmation of true membership in σ Orionis[30,31,120].

Mayrit 856047 + 860047 ($\rho \sim 4''\cdot6$).

It is a curious example of X-ray emission assigned originally to a faint brown-dwarf candidate[121] that later was found to be the secondary of a close pair[12]. The high-energy emission is originated instead in the primary, which is a very-low-mass star $2^{m}\cdot8$ brighter in the *J* band.

Mayrit 863116 + 866116 ($\rho \sim 4''\!\cdot\!9$).

The primary is a T Tauri star that has been investigated spectroscopically[75,122,123] and its X-ray emission was already detected by the *Einstein* space mission. The companion candidate has been catalogued by 2MASS and SDSS DR9[124], and its optical and near-infrared colours are consistent with cluster membership. Because of its relatively wide separation and brightness ($r' \sim 15^{m}\!\cdot\!0$), it is a suitable spectroscopic target for 4-m-class telescopes or larger. If confirmed, the presence of a nearby young M-type component may explain the peculiar X-ray variability of Mayrit 863116 (it displayed a flaring event superimposed on a sinusoidal short-term variation[13,108]). Besides, there is a second, much fainter companion candidate to Mayrit 863116 at $\rho \sim 5''$ to the NNW, which is probably in the background.

There are also three more systems with angular separations 8–12″ and low probabilities of chance alignment at ~1%: Mayrit 528005 AB + 530005, Mayrit 968292 + 958292, and Mayrit 1415279 AB + 1416280. At least one of the components in each pair shows the Li I spectral line in absorption (both components in the case of Mayrit 528005 AB + 530005), while two of the three 'pairs' may actually be triple because of spectroscopic duplicity of one of the components.

Spectroscopic binaries

In spite of the attention given to radial-velocity surveys for spectroscopic binaries in σ Orionis, between the first report of a suspected spectroscopic binary in 1904 (of σ Ori A itself[87]) and the first confirmed one with measurement of lithium abundance in its two components[130], a century passed. In turn, between the discovery of this K-type, weak-line T Tauri, double-line spectroscopic binary and the first dedicated radial-velocity surveys, another decade elapsed[25,26,112] (but see Wolk[8]). Regardless of the use of large facilities (*e.g.*, *AF2/WYFFOS* at the *William Herschel Telescope*, *FLAMES* at the *Very Large Telescope*), only 16 spectroscopic-binary candidates are known to date, and only four of them have accurate orbit determinations[26,40].

I compile in Table V the 16 known reliable single-line (SB1) and double-line (SB2) spectroscopic binaries in σ Orionis. They are not the only SB candidates reported in the cluster area. For example, Kenyon *et al.*[25] found duplicity of the field star [BZR99] S Ori 20[116]. Besides, Maxted *et al.*[112] claimed duplicity of three photometric cluster-member candidates, one of which was later classified as a non-member SB1[26]; the membership status of the other two stars remains unknown, as no photometric survey has picked them up. The bright stars Mayrit 1116300 (HD 37333, unresolved with adaptive optics[48,92]), Mayrit 524060 (HD 37564, which previous studies have suggested is probably not a member of the Orion OB1 association[131]), and σ Ori B have also been proposed to be SBs, but solely on the basis of wide-band photometry[132,133]. Finally, according to Alcalá *et al.*[122,123], high-resolution spectra of Mayrit 863116 (2E 1484) display a broad cross-correlation function, probably due to its high rotational velocity of $v \sin i \approx 150$ km s^{-1}, and not to unresolved spectroscopic duplicity[75]. In Table V, I also provide for the first time a Mayrit number for the cluster member S Ori 36.

Triples (and higher orders)

I conclude this review on multiplicity in σ Orionis with an enumeration of the triple (and sextuple) system candidates in the cluster, apart from the massive triple σ Ori Aa, Ab, B.

TABLE V

Known spectroscopic binaries in σ Orionis

Mayrit No.	*Binary*	*Type*	*P (d)*
Aab	σ Ori Aa,Ab	SB2[40]	$143{\cdot}5 \pm 0{\cdot}5$[40]
102101 AB	[W96] rJ053851–0236	SB2[26]	$8{\cdot}72 \pm 0{\cdot}02$[26]
114305 AB	[W96] 4771–1147	SB[28]	…
240355 AB	[SWW2004] 144	SB2[26]	$8{\cdot}52 \pm 0{\cdot}01$[26]
258337 AB	[HHM2007] 633	SB1[12]	…
332168 AB	[SWW2004] 205	SB1[26]	…
344337 AB	2E 1468	SB1[26]	…
453037 AB	[W96] rJ053902–0229	SB2[8]	…
459224 AB	S Ori J053823·6–024132	SB2[112]	…
547270 AB	Kiso A–0976 316	SB1[26]	…
633095 AB	S Ori 36	SB1[25]	…
873229 AB	Haro 5–7	SB2[112]	…
1415279 AB	OriNTT 429	SB2[130]	7·46[130]
1436317 AB	[KJN2005] 72	SB1[25]	…
1482130 AB	S Ori J054000·2–025159	SB1[25]	…
1493050 AB	[OJV2004] 24	SB2[112]	…

Mayrit 528005 AB + 530005 ([W96] 4771–899 AB–C)

The system is made up of a bright K3 binary T Tauri star of separation $s \sim 140$ AU[8,92] (Table III) and a mid-M candidate companion with features of youth at $s \sim 3000$ AU[23,79] (Table IV), and with a probability of chance alignment of only ~1%.

Mayrit 1415279 AB + 1416280 (OriNTT 429 AB–C)

It is a system very similar to the previous one, except for the primary being a K2–3 spectroscopic binary with $P = 7{\cdot}46$ d[48,130] (Table V) and the secondary being a photometric cluster member at $s \sim 4700$ AU[11,58] (Table IV) in the outskirts of the cluster.

Mayrit 260182 + 270181 + 277181 ([W96] 4771–1051 A–B–C)

This curious triple asterism is formed by two low-mass stars and a high-mass brown dwarf, all of them with young features, separated by 4400–7100 AU[23] (Table IV). Bihain *et al.*[125] reported a fourth component candidate with a sub-stellar mass below the deuterium-burning limit, namely S Ori 74, but new, more accurate *VISTA* photometric data do not support the candidacy of that object[31].

Mayrit 208324 + 214321 + 219320 + 182305 + 189303 + 240322 (BD–02 1342A–F)

Struve[50] catalogued the quadruple system STF 761 (WDS 05386–0233) for the first time (Table I). It consists of four bright early-type stars: HDE 294271 [A], HDE 294272 [BC], which is in turn a binary separated by $\rho = 8''{\cdot}54$[49] ($s \sim 3300$ AU), and the poorly investigated star BD–02 1342D [D] (B5 V, B9.5 III, B8 V, and probably late A, respectively[75,134,135]). Two centuries later, two much fainter companions were discovered at $s \sim 4100$–7200 AU to

HDE 294271[48,92], which have been reported to be *bona fide* cluster members in subsequent works[26,31,79] (Table IV). Therefore, WDS 05386–0233 becomes the only known sextuple system in the σ Orionis cluster.

Summary and conclusions

I have made a comprehensive literature review of multiplicity in σ Orionis. First, I enumerated 16 stars in the innermost arcminute of the cluster, which are candidate members in the σ Ori trapezium. All of them but Mayrit 11238 B (σ Ori Cb) are confirmed young cluster members in a deep gravitational well of about 60 $M_{\odot}$. If they were gravitationally bound, σ Ori would be a sexdecuple system, which would increase to an N-tuple with $N > 16$ if any of the numerous faint photometric cluster member candidates reported by Bouy *et al.*[41] turned out to show young features. But where does the multiple system finish and the open cluster begin? Actually, does this question have a meaning now, if in less than 10 Myr the system will be torn apart because of a pair of supernova explosions (σ Ori Aa, Ab), some main-sequence turn-offs (D, E, and, perhaps, B), and a consequent dramatic mass drop? Those questions are connected to the Mayrit nomenclature, introduced by the author[78], which does not follow the classical terminology in naming the bright stars in the trapezium, but instead equalizes the cluster and the multiple system (*e.g.*, σ Ori C, which is located at $\rho \approx 11''$ and $\theta \approx 238°$ with respect to the cluster centre defined by the bottom of the gravitational well, is Mayrit 11238).

Outside the central arcminute, only ten close binaries with angular separations in the approximate interval $0''\cdot4$–$3''\cdot0$ have been reported (by the author). Of them, only two have been imaged with adaptive optics, which shows a clear lack of high-resolution imaging surveys for close binaries in the σ Orionis cluster.

I also listed other reported systems with $\rho > 4''\cdot0$. Of the 16 tabulated systems, 11 have both primaries and secondaries that pass cluster-membership criteria, but only six have probabilities of alignment of the order of 1% (and three less than 1%). It is still under debate whether those six wide systems are physically bound today or will remain so until the eventual disruption of the σ Orionis cluster within the Galactic disc.

Of the 16 known spectroscopic binaries in σ Orionis, nine are double-line binaries and only four have had their orbital periods determined, which range between 7–9 d for the low-mass pairs and ~140 d for the eponymous σ Ori Aa, Ab, B triple system. Finally, I report one sextuple system and three triples, of which one involves a spectroscopic binary and one a tight binary resolved only with adaptive optics.

As mentioned in the introduction, this review on multiplicity is limited by the heterogeneity and incompleteness of the data. Any attempt to derive a frequency of multiplicity of the cluster from these data, of about 10% if one accounts for the known cluster members and multiple systems compiled here, makes no sense, or at least, must be understood only as an attempt to impose a lower limit on that frequency. However, this review is useful for guiding future multiplicity studies in σ Orionis. Next steps can be, for example: (*i*) High-resolution imaging surveys with public UKIDSS and *VISTA* data down to $\rho \sim 0''\cdot4$ and/or with inexpensive lucky-imagers at 2-m-class telescopes down to $\rho \sim 0''\cdot2$. Adaptive-optics systems at larger telescopes could help with the follow-up and characterization of the most interesting companion candidates (*e.g.*, below the hydrogen-burning limit). (*ii*) High-resolution spectroscopic surveys with spectrographs at 4–8-m-class telescopes for measuring accurately orbital periods of known single- and double-line spectroscopic binaries, for mass determination, and to look for new ones. (*iii*) Intermediate-resolution spectroscopy for characterizing some poorly-investigated secondaries, with questionable youth features or even no spectral-type determination at all.

Unfortunately, a radial-velocity survey at the 10-m s^{-1} level for distinguishing between true and false pairs within the cluster, which would be the definitive 'binary test' of wide pairs, is beyond the capabilities of current technology.

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REVIEWS

The Starry Sky Within, by A. Henchman (Oxford University Press), 2014. Pp. 294, 24 × 16·5 cm. Price £60 (hardbound; ISBN 978 0 19 968696 4).

When this title came up for review, with its subtitle *Astronomy and the Reach of the Mind in Victorian Literature*, I put in a bid, thinking that it sounded rather intriguing as I have an interest in Victorian astronomers. The first sentence on the inside cover reads "Tracing unexplored connections between nineteenth century astronomy and literature, *The Starry Sky Within* offers new understanding of literary point of view as essentially multiple, mobile and comparative". Oh dear, I thought, this could be hard work.

The book is divided into two parts each of three chapters. Part I, called 'Observers in Motion' contains an opening chapter on 'Astronomy, Optics and Point of View' in which the author describes some of the astronomical principles which appear in some of the works of the poets in her circle of interest. In this part of the book these are Thomas de Quincey and Alfred, Lord Tennyson. At the outset I should lay my cards on the table. I have not read either of those poets. De Quincey seems to be rather notable for his lifelong and regular opium habit. He may well have been under the influence when he described the monstrous face which he could see in John Herschel's drawing of the Orion Nebula. In Tennyson, however, we seem to be on safer ground. The author spends some time discussing *In Memoriam*, a very long poem written in memory of a close friend, Arthur Hallam, who died aged 22. It gave Tennyson a lot of trouble and took 17 years to write. In it he compares human beings to stars and planets and even evokes the phenomenon of refraction to express the idea that anticipation of a certain event can lead one to see something before it actually appears — as is the case when the Sun rises from out of a flat horizon. Another well-discussed topic of the author is parallax, and I quote: "Literary parallax is a particular form of point of view that compels the reader to move through radically different optical positions and notice the visual results of his own motion through space". This gives a flavour of the author's style — as I said above, it can be quite tough going, but when pointed out these allusions can be quite powerful. Tennyson was exposed to astronomers whilst a student at Cambridge and was known to have a collection of astronomical treatises at home. In later life he owned a telescope and visited observatories with more powerful instruments to view double stars and nebulae. In return, there was also an awareness in the work of poets and writers of the time. For instance, Sir Robert Ball, the famous popularizer of astronomy, often quoted Tennyson in his books such as *The Story of the Heavens* (1885).

Part II is called 'Astronomy and the Multiplot Novel' and largely concentrates on the work of Thomas Hardy and George Eliot. Hardy seems to have had quite a practical interest in astronomy and whilst preparing *Two on a Tower*, a short love story involving an astronomer, he was issued with an invitation to visit Greenwich Observatory, but there is no proof that the visit ever took place[1]. David Wright[2], also writing in this *Magazine*, talks about the possible inspiration for the tower of the novel. The author seems not to have been aware of those references, which is a little surprising as the research which has gone into the book is impressive. There are 30 pages of end notes and more than 400 entries in the bibliography, although only about two dozen of them are overtly astronomy textbooks.

All-in-all an interesting book; perhaps its most lasting effect is to encourage me to seek out some of these works of literature and explore the Universe through the eyes of the poets and writers. — ROBERT ARGYLE.

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Mission à Berlin, Lettres à Jean III Bernoulli et à Elert Bode — Lalandiana II, by Jerôme Lalande, edited by Simone Dumont & Jean-Claude Pecker (Ed. Vrin, Paris), 2014. Pp. 390, 13·5 × 20·5 cm. Price €34 (about £28) (paperback ; ISBN 978 2 7116 2537 6).

This volume, in French, is the continuation of two books reviewed earlier in these pages: first, the biography of Joseph Jérôme Lefrançois de Lalande (1732–1807), by Simone Dumont, and second, *Lalandiana I*, a collection of letters between Lalande and Louise Dupiéry, as well as between Lalande and Honoré Flaugergues, material commented upon and annotated by Dumont & Jean-Claude Pecker (see *The Observatory*, **129**, 35 & 288, 2009).

The current volume is structured in three parts: (*i*) the correspondence relating to Lalande's stay in Berlin (1751–1752) at the Court of Frederick the Great to measure the parallax of the Moon in conjunction with observations carried out at the Cape of Good Hope by Nicolas-Louis de Lacaille; (*ii*) the exchanges with Jean III Bernoulli, especially on the transits of Venus; and (*iii*) the letters between Lalande and Johann Elert Bode leading those two, among other things, to propose new constellations, including several that are obsolete nowadays. Interestingly the latter have been re-translated into French by Dumont and Pecker from the German translations that Bode had published in Berlin in the *Astronomisches Jahrbuch* and *Ephemeriden* [*Astronomical Yearbook* and *Ephemeris*].

Each section of the book is introduced and commented upon by Dumont and Pecker who added, for readers not specialized in astronomy, technical sections on the determination of the lunar parallax, the transits of Venus, the measurement of the parallax of the Sun, as well as on celestial catalogues and atlases. The editors have also included a substantial biographical section (82 pages!) on the characters mentioned in the letters.

One can only praise such a precious work for historians of astronomy and beyond, and look forward to the announced publication of the upcoming *Lalandiana III* volume that will gather together the letters between Lalande and Baron von Zach. — A. HECK.

The Great Refractor of Meudon Observatory, by Audouin Dollfus (Springer Heidelberg), 2014. Pp. 150, 24 × 16 cm, Price £90/$129/€106·99 (hardbound; ISBN 978 1 4614 7287 2). [Previously published in French in 2006 by CNRS Editions, Paris.]

I find astronomical pilgrimages very moving. Recently I have visited three telescopes for the first time. Two years ago I peeked precariously over the rim of the huge Arecibo radio dish in Puerto Rico (and tried hard to concentrate on its astronomical achievements and not James Bond clinging to the receiver antenna). And last year I stood in awe on the steps of the 5·2-m, 200-inch giant on Mount Palomar near San Diego, California. Much closer to home I recently climbed to the sixth floor of the old Manchester Municipal School of Technology to wonder at the beauty of the *Godlee* 1903 double telescope.

There is another very worthy site for astronomical pilgrimage just over the English Channel, 9 km from the centre of Paris in a south-western suburb, this being the 'grande lunette' at the Meudon Observatory. This jewel at the heart of French scientific heritage is an architectural wonder built on the site of the old Chateau Neuf.

In the book under review we are transported back to the 'good old days' when astronomers actually looked through telescopes and physically wrestled with the complex controls instead of just sitting in an air-conditioned control room typing instructions into computers. The Meudon double telescope is a huge refractor, the main instrument having an 83-cm (33-inch) achromatic doublet lens of 1640-cm focal length, this instrument being twinned on the same equatorial mount with a 62-cm (24-inch) photographic telescope which took 18 × 24-cm glass photographic plates. It came into use in 1896 and for many years was the largest active telescope in Europe. It is a marvellous machine and should be on the 'must visit' list of any astronomer in northern France.

This book describes the construction and use of the instrument in great detail. It also reviews the observational highlights, underlining the advantages at the time of the superb resolving power coupled with the purity and quality of image. Audouin Dollfus (the author, and an astronomer who spent his whole working life at the Meudon Observatory) used it to investigate planetary surfaces and atmospheric details using polarimetry and spectroscopy. Bernard

Lyot used it to produce the first graphs of the polarization of scattered light from the Moon, Venus, Mars, and Mercury as a function of phase angle. Henri Deslandres (the first director of the Meudon Observatory) used it to image stars and investigate their radial velocities. Eugène-Michel Antoniadi used it to produce superb drawings of the surface of Mars (discrediting the prevalent 'canal' theories) and also the first detailed maps of Mercury. Paul Muller made numerous micrometer measurements of double stars.

This book is comprehensive, thorough, extremely well illustrated, and has an extensive reference section. It spirits you romantically back to a golden age. My only quibble is the English prose. Audouin Dollfus deserves better (he died in 2010 October, aged 85, four years after the publication of the French edition). The translation from French to English is stilted and pedantic and not even up to university-student standard. This tends to spoil somewhat what is actually an excellent addition to a rather too limited collection of books about great telescopes. — DAVID W. HUGHES.

Carl Størmer: Auroral Pioneer, by A. Egeland & W. J. Burke (Springer, Heidelberg), 2014. Pp. 195, 24 × 16 cm. Price £90/$129/€106·95 (hardbound; ISBN 978 3 642 31456 8).

With his background in space physics, Professor Alv Egeland is the ideal scientist to write about Carl Størmer, an iconic name in auroral research. Størmer was born on 1874 September 3, and the authors give a detailed account of his early life, his parents, and Størmer's growing interest in mathematics, astronomy, and botany. Had Størmer's interest in botany prevailed over mathematics it is unlikely that his name would be linked to the aurora today, but his natural interest in mathematics and the teachers who encouraged him are fully described and discussed in Chapter 2.

It seems that the experiments of Kristian Birkeland stimulated Størmer to undertake auroral investigations and that resulted in his writing a book with Birkeland. Størmer felt that the descriptions of the ever-changing aurora were difficult to record and thought that they might be better recorded on photographs. Having developed a camera which could take short exposures of the aurora, he eventually took 100 000 photographs of which 50 000 were used in measurements of the height of auroral forms.

The authors vividly describe the thoroughness and dedication with which Størmer approached his work, often in very cold conditions for many hours followed by complex and time-consuming calculations using simultaneous photographs from a number of stations. In addition to their analysis of Størmer's data, Egeland & Burke reveal a great deal about Størmer himself. Throughout his childhood and in later years he seems to have been a very sociable person who shared his enthusiasms with many and who was, in turn, a popular companion, father, and grandfather.

The numerous figures in the book are adequate in quality but are occasionally on the small side, making it difficult to see detail, especially text and numbers on technical figures. On a number of occasions when the reader is referred to a figure, they find that it has no relevance to the text or, indeed, is the wrong figure entirely. However, those minor and infrequent irritations do not detract from the quality and depth of the biography of this great scientist.

This is a book about the man, not his mathematics, and the reader does not require special skills in mathematics or physics. However, for those who have seen, or harbour hopes of seeing, the lights in the northern sky, this is a book worth reading as it will infect the reader with some of Størmer's magic and will make the experience so much more meaningful. For me, the picture painted by the authors is one which makes me regret not having encountered this man in the years which were common to us both. — KEN KENNEDY.

Taking the Back off the Watch: A Personal Memoir, by Thomas Gold, edited by Simon Mitton (Springer, Heidelberg), 2012. Pp. 232, 23·5 × 15·5 cm. Price $129 (about £78) (hardbound; ISBN 978 3 642 27598 3).

The watch in question was one the young Gold received as a present from his father, who had served as a lieutenant in the Austrian army during World War I. He insisted on taking it apart and eventually succeeded in putting it back together. It worked just fine for many years thereafter, but there was one part left over. It is hard not to feel that this event somehow presaged the structure of several of Gold's theories, though his own interpretation was that it means he simply had to understand how things worked by examining them closely. The editor describes his function as having been to tighten the narrative, correct minor factual and historical errors (not all of them), and tone down some critical comments. Mitton writes that he did not add anything, and that the changes were ones that a competent copy editor and a publisher leery of legal action would have required.

The volume contains much of both the man and his science. I focus on the science and suggest you read the book yourself for the war stories (both World War II and scientific wars, with Richard Woolley and others). Gold devoted most words to his theory of hearing, steady-state cosmology, the lunar surface, pulsar energetics, and some non-standard opinions about the Earth and the origins of oil, methane gas, and perhaps hard, black coal.

His pre-war work with Richard Pumphrey garnered him a fellowship at Trinity College, after which he never bothered to complete a PhD (though a DSc came along later). The cochlea acts as a tuned resonator with feedback, and he predicted one cause of extreme tinnitus and a new class of hair cells, both later found. After about 40 years of neglect, Gold's theory was rediscovered, largely confirmed, and credited to him. Science is indeed a self-correcting process, though it can take decades, and he probably expected all of his later ideas to be winners.

This brings us to steady-state cosmology (1948 and thereafter), to which he remained wedded unto death. In opposition to evolutionary universes, he claimed that galaxies at large redshift don't look younger than here and now. True when the maximum was $z = 0{\cdot}5$ or thereabouts, but might the Hubble Deep Field sources finally have persuaded him that the Universe has changed over billions of years? In the lead-up to Apollo landings, Gold firmly stated that the lunar surface would be covered with very fine powder, probably not safe to walk upon. Powder yes, but walkable, both demonstrated by astronaut footprints.

His mechanism for the alignment of interstellar grains to produce polarization of starlight competed with that of Leverett Davis and Jesse Greenstein, whom he properly cites. The modern view is closer to Gold's spinning grains than to Davis and Greenstein's magnetic grains. Hall and Hiltner get no credit for discovering the polarization in 1949, so I mention them here.

Onward to pulsars, for which there is no doubt that his 1968 and later explanation of strongly magnetic, rapidly rotating neutron stars was the right answer, and that he had mentioned 17 years before that radio emission from other sources should be strongly variable if they were magnetized, compact objects. But not a word do we hear of either Franco Pacini or Lodewijk Woltjer, who had predicted rotating, magnetized neutron stars in 1967. And Pacini in those days was a few doors down from Gold's office at Cornell. They both also eventually became presidents of the International Astronomical Union.

Finally, a large fraction of Gold's later career was devoted to the idea that oil and methane, and perhaps some forms of coal, were not biogenic but primordial, part of the material assembled 4·55 Gyr ago and still leaking out. Supplies in that case could be enormously larger than expected from dead dinosaurs, single-celled organisms, or anything in between. He made a number of predictions about where to find those 'non-fossil' fuels, partly tested and perhaps confirmed by drilling in Sweden and Russia. He coupled these ideas with terrestrial structure that he describes in a way that suggests he really had no confidence in mantle convection and plate tectonics as a cause of volcanoes and earthquakes or as a heater and compressor of 'fossil fuels'. Part of his picture is outgassing as a trigger for earthquakes and such. Full support for Gold's Earth is not to be found today, but, in an interesting coincidence, page 55 of the 2014 April issue of *The Observatory* quotes Robert White in his Harold Jeffreys Lecture as saying "There has been very little gas monitoring in Iceland. It's only very recently that we've realized how important the gas is to triggering microearthquakes." Yes, science is a self-correcting process, and Tommy may yet at least partially win on this one. It is sad, therefore, that his name is most often associated with steady-state cosmology. There are lots more topics, lots more quarrels, some wonderful pictures, including the 1958 Solvay Conference (participants' names can be read with a small magnifying glass) and one of the Cambridge Radio Club in about 1951, which includes both Gold and Alan Turing; and a personal postscript from his widow Carrie Gold. She remembers most strongly his gentleness. For others of us, it was his playfulness — jumping the Trinity College steps, claiming to improve swimming records with a "minimum circumscribed porpoise", folk dancing at *The Bridge* at Clayhithe, averring that all positive human qualities are correlated, meaning that the very intelligent are also better looking, stronger, and healthier than average. Well, he was. — VIRGINIA TRIMBLE.

Dark Matter and Cosmic Web Story, by J. Einasto (World Scientific, Singapore), 2014. Pp. 350, 23·5 × 15·5 cm. Price £76/$115 (hardbound; ISBN 978 981 4551 04 5).

Progress in the field of cosmology has happened at such a rate in the last few decades that many concepts that at one time seemed bizarre and outlandish have now become firmly embedded in the mainstream of the subject. Nowadays we happily teach undergraduate students about the overwhelming evidence for the existence of a dominant component of dark matter in the Universe and usually gloss over the sometimes tortuous processes by which this evidence was acquired and interpreted. This book, by Estonian astronomer Jaan Einasto, attempts to put the story of the rise of dark matter in the broader context of astronomy and cosmology in the latter part of the 20th Century. The tale is set against a period of momentous political change; during this time the Cold War thawed, the Iron Curtain fell, and Estonia and the other Baltic states finally gained their independence.

The perspective offered by this book on both political and cosmological developments is definitely its strength. Einasto and his team at the Tartu Observatory did heroic pioneering work in the 1970s on the systematic collection of galaxy redshifts with only meagre resources at their disposal. Those efforts paved the way towards the monster programmes of today, such as those deriving from the Sloan Digital Sky Survey, which have played such a crucial role in establishing the current cosmological paradigm. Einasto's account of the gradual unveiling of the 'Cosmic Web' of galaxies and large-scale structure derives its fascination from his involvement in the early stages of this field. It is also interesting to read his reflections on the personalities of astronomers that one would otherwise only know as names associated with theoretical ideas or observational discoveries.

There is much to enjoy in this book but for anyone considering buying it it's not all that easy to read. English is not Einasto's first language and at times that shows. The title will give you an idea of what is in store; surely there should have been a definite article in there? For £76 the publishers might have paid more attention to the copy-editing. At that price this is definitely for specialists only, but it is a valuable historical document and worth reading for anyone interested in the history of cosmology. — PETER COLES.

Fundamental Planetary Science, by J. J. Lissauer & I. de Pater (Cambridge University Press), 2013. Pp. 583, 25 × 19 cm. Price £75/$125 (hardbound; ISBN 978 0 521 85330 9), £35/$60 (paperback; ISBN 978 0 521 61855 7).

We live in an age where spacecraft such as *Cassini* orbit distant worlds in the Solar System, and also where our knowledge of planets beyond the Solar System is rapidly evolving. Future missions such as the *JUpiter ICy moons Explorer* (*JUICE*) and *Juno* will investigate the icy moons and magnetic fields of the Jovian system. All of those types of planetary bodies, and more, are usefully described and summarized in this book. Each chapter has very useful 'key concepts' summaries at its end, as well as problems suitable for, say, an undergraduate course in the relevant topic.

The introductory Chapters 1 and 2 'set the scene' very well by including an inventory of the Solar System and moving on to fundamental aspects of orbital dynamics, including one of the better descriptions I have seen of the phenomenon of tidal torque on a body. Chapter 3 provides us with a nice connection to the physics of stellar structure, and we learn how key concepts, such as hydrostatic equilibrium, which underpin stellar structure, may also play a role in determining the sizes and densities of planets. Stellar nucleosynthesis is also described, and provides a good segue into Chapter 4 which covers energy balance, solar heating, and radiative energy transport. The text throughout provides a good level of detail without becoming overly complex, and clear illustrations, graphs, and beautiful colour plates are in abundance.

Chapter 5 provides a natural development of what has gone before and includes topics such as the thermal and ionospheric structure of different planetary atmospheres. In Chapter 6, we delve inside planetary bodies and learn about their surfaces and interiors — gravity, plate tectonics, volcanism, and cratering are key topics here. Chapter 7 then takes us out into the magnetospheric environments of magnetized worlds, and the related phenomenon of auroral emissions. The Sun is also an important driver of magnetospheric dynamics, although it is solar wind, rather than solar radiation, which is relevant in that context.

Chapters 8 and 9 usefully subdivide into topics related to giant planets and terrestrial planets. In Chapter 10, we encounter planetary satellites (moons), including a description of the remarkable satellite Enceladus, whose extended atmosphere (plumes of water vapour, dust, and ice), produced a magnetic signature during an early *Cassini* flyby.

The description of exoplanet-detection techniques and observations in Chapter 14 provides a natural complement to the *in-situ* and remote-sensing techniques related to Solar System work. The chapter on 'Planets and Life' is certainly interesting, and includes some material on the formation and evolution of life on Earth, genetic inheritance, and intelligence and technology. The following section on detecting extraterrestrial life, understandably, raises questions which remain open. Nevertheless, I would recommend the book as a whole to students or other scientists working on planetary topics. — NICHOLAS ACHILLEOS.

L'exploration des planètes, by T. Encrenaz & J. Lequeux (Belin, Paris), 2014. Pp. 224, 24·5 × 18·5 cm. Price €24·50 (about £20) (paperback; ISBN 978 2 7011 6195 2).

This book is an interesting discussion of the development of our knowledge of the Solar System, not least because, being French, it is written from a slightly different viewpoint to the majority of English-language works. Some of the historical information was new to me, such as the way in which early planetary observations were made at the Paris Observatory — by placing an objective lens on the parapet and observing through a hand-held eyepiece from the ground. (A situation, one imagines, even worse than using one of the gigantic 'aerial' telescopes employed elsewhere.) Similarly, a slightly different perspective is offered by the inclusion of details of the work of many Continental scientists, whose contributions are often minimized in books that tend to concentrate on British and American astronomers.

But apart from the historical treatment, this is also an excellent account of the current status of planetary studies and the relevance of exoplanet discoveries to our views on the formation and evolution of the Solar System. (I was struck by the map of sub-surface water on Mars (p. 114), which I had not seen previously.) The discussion of the composition and evolution of planetary atmospheres is excellent — not surprising, given that this is Thérèse Encrenaz's speciality — as are the descriptions of the relevance of comets and of the TNOs in the outer Solar System. It is completely up-to-date, with mentions (albeit brief) of various space missions such as *Stardust*, *Dawn*, *New Horizons*, *Chang-E* (and *Hutu*), and forthcoming missions such as *MAVEN* and *JUICE*.

I am doubtful of the validity of the statement (p. 13) that Tycho Brahe picked up a suggestion of Aristarchos of Samos in proposing the Tychonic system of the planets, especially given that we do not have any actual writings by Aristarchos. Thomas Heath in his *Aristarchos of Samos: The Ancient Copernicus* notes the idea by Tannery that it was Apollonius who modified the heliocentric system of Aristarchos into a 'Tychonic' version. One error occurs in the boxed item on p. 138 on interferometry in the statement that the image of Betelgeuse, obtained by IOTA in Arizona (*Astronomy & Astrophysics*, 2009), is the first image of a star other than the Sun. In fact, Betelgeuse was the first to be imaged by speckle interferometry (developed by Antoine Labeyrie) back in the 1980s.

Although the book is intended to be moderately popular in tone, I am not certain that some of the material (especially some of the 'boxed' items — material in boxes is a feature of Belin books) is really adequately explained. In particular, the details of isotopic dating on p. 151, which includes mathematical operators, is likely to be confusing. One surprising usage is the substitution of the Greek letter 'gamma' (γ) for the zodiacal sign for Aries (♈) for the First Point of Aries. This occurs several times and is even described in a Glossary entry as 'point gamma'.

To summarize: a refreshingly different, but comprehensive, account of the development and current state of our knowledge of the planets in the Solar System. — STORM DUNLOP.

The Science of Solar System Ices, edited by M. S. Gudipati & J. Castillo-Rogez (Springer, Heidelberg), 2014. Pp. 657, 24 × 16 cm. Price £153/$229/€181·85 (hardbound; ISBN 978 1 4614 3075 9).

This is an interesting, eclectic, or eccentric collection of chapters, depending upon your point of view. It represents the output of a workshop, 'The Science of Solar System Ices', held in California in 2008. The fact that it has taken so long for these contributions to appear is scandalous. None of us is without guilt in missing deadlines but this is really too long! The editors acknowledge this fact even in the second sentence of the preface. The excuse they give is "… a consequence of the large number of activities that have kept the planetary ice community busy for the last 3 years…". However, the activities listed are all ones that have primarily involved only the US community, not those beyond US shores. This highlights another unease I have about this volume. Of the 52 chapter authors, almost 70% are from US institutions. No doubt the USA is the dominant single nation in these activities, but this is surely an unbalanced set of authors, at least from the viewpoint of geographical distribution.

Despite those criticisms, there is much to interest and engage those with either a research or merely an academic interest in the study of Solar System ices. The contributions are quite inter-disciplinary — physicists, chemists, modellers, experimentalists, ground- and space-based observers are all here. And the chapters are generally very liberally referenced, thus providing a rich source of contextual information. However, to this reviewer, the editing appears lax. A random search reveals that Titan appears once as "Tiran", the caption for Figure 10.22 refers to four images yet only three are present, the referencing style is not uniform, odd words are missing, and "Solar System" appears both with and without capitalization. Quite inexcusably, we read on page 267 that Comet Halley was imaged "in 1986 by the Rosetta spacecraft"! Furthermore, two languages seem to be used, namely English (UK) and English (USA). Perhaps those are mostly trivial matters and only of concern to this particular pedant. The indexing also leaves much to be desired. For example, there are three entries for Titan, all relating to one section of one chapter, yet the many other discussions of Titan throughout the book are completely missing!

I suspect that the structure and contents of the book reflect the attenders at the Workshop — or rather those who submitted their contributions — rather than an *ab-initio* division of the subject matter into its logical components. For example, I noted that Chapter 9 on 'Cratering on Icy Bodies', with about 23 pages of text, is immediately followed by a chapter entitled 'Geology of Icy Bodies', which contains a 22-page section on 'Impact Cratering on Icy Bodies'! It does rather smack of a work cobbled together rather than a well-crafted and thought-through *magnum opus*.

Despite these carpings, and in between my cursing at the various instances of carelessness, I found much to enjoy and absorb — I think others would too. But at the outrageous price of £153, it must surely be a buy for libraries only. — JOHN ZARNECKI.

Formation of the Solar System: A New Theory of the Creation and Decay of the Celestial Bodies, by V. I. Ferronsky & S. V. Ferronsky (Springer, Dordrecht), 2013. Pp. 305, 24 × 16 cm. Price £90/$129/€106·95 (hardbound; ISBN 978 94 007 5907 7).

On reading this book one cannot help but feel that it must have been much easier to understand when it was in its original Russian edition (published by Science World, Moscow, 2012). The translation is not just bad, it is absolutely appalling, and thus confusing and obfuscating. This is so off-putting that one is left with the unfortunate, and misplaced, feeling that the underlying science might be gobbledegook, just like the English prose.

V. I. Ferronsky works at the Water Problems Institute of the Russian Academy of Science. S. V. Ferronsky has passed away. Their book is highly mathematical, and based on a detailed analysis of the potential hydrostatic and dynamic equilibrium of the planetary and satellite bodies in our Solar System during their formation and evolution. Much is made of the virial theorem and the pioneering work of Clairaut, Clausius, and Euler. Solutions of Jacobi's *n*-body problem are much in evidence. In the final chapters the authors move on to the physics of fluid spheres, and concentrate on the complexity of the Earth's interior, precession, nutation, oblateness, and tidal interactions. The book ends by applying their theories to the Universe in general.

This is not a book for the faint hearted. Good degree-level mathematics is an essential, plus an ability to read between the lines of the dire translation. — DAVID W. HUGHES.

Mercury, by T. J. Mahoney (Springer, Heidelberg), 2014. Pp. 328, 26 × 18 cm. Price £117/$179/€139·09 (hardbound; ISBN 978 1 4614 7207 0).

On my desk as I write is a copy of the old NASA *Atlas of Mercury* by Davies *et al.* (1978), a volume resulting from the *Mariner* flybys of the 1970s, when about half the planet's surface was observed. An atlas of the planet's entire surface is therefore long overdue. This book is the first (Volume 1, number 1) in a new series by Springer to come under the general title *Gazetteer and Atlas of Astronomy*, and it really fills that need. The purpose of this ambitious series is to "list, define and illustrate" every named object in the sky within a single reference work.

In this book the author has attempted something similar to what the late Jürgen Blunck achieved so well for Mars in the 1970s: a gazetteer of all the names ever given to features upon the planet's surface. Naturally the naming had to await the completion of the mapping so beautifully accomplished by the *Messenger* mission. Although the craft quickly mapped the areas missed by *Mariner*, mapping was not totally complete until each area had been caught under different angles of illumination, and of course months and years had to elapse between the several fly-bys, after which the craft was inserted into Mercurian orbit (in 2011). In the last few months, a complete map of the surface has finally been released (see *Sky & Telescope* for 2014 March). It is therefore a pity that this book should have gone to press just months before this final chart became available: the author in his Preface and on page 47 notes that the information is complete up till 2012 December (but see below), and on page 23 we see the slightly incomplete global mosaic upon which this book is based.

Mercury begins with information as to how to use the Gazetteer, explaining the way in which entries have been made, and a guide to pronunciation. In a note about etymology, Mahoney notes that "as anglicization of foreign names often gives rise to ambiguities, all names are traced back to their original form."

We then have an overview of the planet, including three telescopic maps, and useful details of the planet's orbit such as the spin–orbit resonance. Spacecraft missions are then detailed, with a summary of the instrumentation carried by each craft. Then comes information about Mercury's crust and its internal structure, followed by a very useful and detailed Glossary. Next we have the largest part of the book, the Gazetteer, where there is also a note about each feature in the text, giving coordinates, a description, and a short biographical note. The Gazetteer is nicely arranged, it looks very comprehensive, and it is easy to use.

The Gazetteer is followed by a Mercury Atlas. The planet has been divided up into 15 quadrangles: two for the poles, five covering the equator, and eight covering the tropical and temperate bits in between. Thus we have regions such as the Beethoven and Shakespeare quadrangles, and each section is systematically mapped over several pages, with names given on each map.

Following the Atlas we have a good detailed description of Mercurian Nomenclature in Appendix 1, and this actually contains (on pp. 265–266) an update listing new names assigned up to 2013 June 25. Other Appendices cover Non-Roman Alphabets, Mercury Data, Mercury Transits (the next is in 2016), and the Mercury Timeline.

The author explains how Antoniadi's classical names were largely retained by the IAU when it became clear, during the 1960s, that the long-assumed 88-day period was incorrect. Apart from Antoniadi, only Lowell ever assigned names to albedo features, though there were several other individuals who compiled important telescopic maps (such as Wegener, who combined Antoniadi's and Lowell's systems). For the historical record, it is good to see Lowell's names listed here too, even if his linear features never had any objective existence. His Memoir, entitled 'New Observations of The Planet Mercury' was obscurely published in volume 12 of the *Memoirs of the American Academy of Arts and Sciences* in 1897, though Lowell's drawings did appear in some mainstream astronomical periodicals. What a shock it gave even that old canallist Schiaparelli to receive a copy of Lowell's *Memoir* from its author in 1909! And he told Lowell so, though Lowell seems never to have replied. I mention this episode because the primary 1897 reference is only given in the classified index and in the index for Appendix 5, rather than among the 851 references from the Gazetteer. Occasionally for biographical details I found a secondary source replacing a primary one. This is a very small point, however, and the extensive list of references is impressive. There are over 1000 references in all, whose listing represents a truly enormous effort.

It is a pity that Mercury has been largely given over to artists for its nomenclature, for one would like to have seen the most famous observers of the planet commemorated by named formations. We do find an Antoniadi Dorsum and a Schiaparelli Dorsum, but Lowell is not present and neither are Jarry-Desloges' resident observers G. and V. Fournier who did such important visual work, nor others who either mapped the planet or analyzed drawings and photographs, such as I. Sormano, L. Rudaux, B. Lyot, H. McEwen, A. Dollfus, *et al.* But at least the Dorsae are reserved for astronomers.

I hope that ultimately there may be a second edition of this book to complete the naming process for the few percent of the planet's surface mapped since publication; and no doubt for that tiny fraction there will be space for a few more names. If so, let's have some more astronomers, please!

In summary, this new Gazetteer of Mercury is very comprehensive and represents a really excellent publication. I strongly recommend it. — RICHARD MCKIM.

The Asteroid Threat: Defending our Planet from Deadly Near-Earth Objects, by William E. Burrows (Prometheus, Amherst), 2014, Pp. 275, 20·5 × 13·5 cm. Price $19·95 (about £12) (paperback; ISBN 978 1 61614 913 0).

Chicken Little is a famous folk-tale hero who rushes about generating mass hysteria, and shouting "the sky is falling", this clearly being an indicator that disaster is imminent. This little bird pecks away relentlessly throughout the book under review. Words like 'doomed', 'threat', 'armageddon', 'the ultimate catastrophe', and 'planet buster' leap from every page. The reader worryingly sits and envisages the four horses of the apocalypse thundering across the sky, their labels, 'pestilence', 'war', 'famine', and 'death', waving in the wind. But now these horses have a companion: a new horse — number five — labelled 'asteroid'.

The general thesis of *The Asteroid Threat* is simple. Asteroids (and comets too) are an impending danger to Earth's civilization and we are going to have to do something about it. Burrows, a journalist and emeritus professor of journalism, engagingly, in a very news-papery way, reminds us of the evidence. The window-smashing meteorite explosion over the Russian city of Chelyabinsk in 2013 February is described in detail. We then return to the tree-flattening Siberian Tunguska impact of 1908 June. Next we scurry back 50 000 years to marvel at the 1·5-km-wide Barringer meteor crater in Arizona. Also we mourn the death of the dinosaurs 65 million years ago, when the Mexican Chicxulub crater was produced. And we wonder at the recent collision between comet Shoemaker–Levy 9 and Jupiter. The message is unequivocal. Killer asteroids and comets are out there, and they are coming to get us. It is not a matter of 'if', it is a matter of 'when'.

Burrows then considers the solution. Step one is to find out what is wandering around the near Solar System. Luckily technology is on our side here. Modern telescopes coupled with large, sensitive charge-coupled devices and dedicated computers have enabled astronomers to discover asteroids and comets at an amazing rate. It does not cost too much. Well over 90% of the 1-km-and-larger potentially hazardous asteroids and comets have been found. We know when they are going to get uncomfortably close.

Step two is more problematic, and is dealt with in much less detail. We can easily write down statements like 'push them to one side' or 'blow them to pieces'. But the efficacy of letting off nuclear bombs attached to asteroids and comets is an unknown. Also we know what a few asteroids and comets look like on the surface but their interiors, strengths, and cohesiveness are unknowns. And finding out is very expensive, as is preparing space defence systems. We just do not know, at the moment, how to break up or deflect these bodies.

Step three is the big stumbling block and there Burrows is rather quiet. We are obviously confronted with a threat, but we have absolutely no idea when the problem will arise. We can convince our political friends to pay lip service, set up a committee, produce a report, fund a telescope or two for a few years, but what happens in the long term? Politicians are extremely mindful of the problems affecting society between now and their next election. Some might even have an attention span that encompasses the period up to the election after that. But try and get them to do something about a problem that might not occur in the next century, or millennium, or even longer. Forget it. Burrows does not look into this. Some time, we know not when, the big one will come hurtling in past the Moon. We might be lucky enough to have seen it coming, we might have the engineering and industrial potential to do something about it. But whether the world politicians will have done anything about it is extremely doubtful. All we can do is sit back, wait to be amazed, and become toast. — DAVID W. HUGHES.

From Dust to Life: The Origin and Evolution of our Solar System, by John Chambers & Jacqueline Mitton (Princeton University Press, Woodstock), 2013. Pp. 299, 24 × 16·5 cm. Price £19·95/$29·95 (hardbound; ISBN 978 0 691 14522 8).

Cosmogony is the word: the study of the origin and evolution of planetary systems. This is not to be confused with cosmology: the study of the origin and evolution of the Universe as a whole. As a life-long astronomer I have always been amazed by the cosmogony/cosmology ratio. Wandering around the astronomy and astrophysics departments of the world's universities you find that this ratio is typically around 1/100. Why? Maybe it is because cosmogony is much more difficult. The cosmogonist doesn't just sit back and wait for something to go 'bang', and then have everything created out of nothing. Maybe it is because cosmogony is much more relevant. We live on a planet. How planets evolve is important to humanity. And we are ever wondering how life on our planet is related to life elsewhere. Maybe it is because the cosmogonist has so much more data to deal with. Our Solar System has eight completely different planets with a wide range of satellite and ring systems, together with asteroids, comets, and trans-Neptunian objects, not to mention the fact that to date 1693 planets have been discovered around 1024 other stars, all of which need explaining.

Anyway, I would love to see the 1/100 ratio improve, and thanks to the hard work of skilful authors like Chambers & Mitton, I have hope. *From Dust to Life* is an exciting, enthusiastic, and encouraging book. The reader is captivated by the pace of advance and the feeling that the planetary physicist, geophysicist, and computer-aided dynamicists are getting close to an answer as to why the bodies in the Solar System have their specific physical and chemical properties and ages and orbits. The book also stresses that we live in very exciting cosmogonic times. It was only about two decades ago that astronomers both confirmed the existence of the first exoplanet, and discovered the first Edgeworth–Kuiper Belt object. And in the next year one spacecraft will fly by Pluto and Charon and others will orbit a comet and land on its surface. Chambers & Mitton also underline how the power of today's computers has revolutionized the subject. The movement of planets, the variability of their orbital eccentricities and semi-major axes, the way in which they fall into and out of resonances can now be investigated and modelled in detail.

Cosmogony is a superb subject and there are a host of problems for everyone to tackle. Why has Uranus been tipped on its side, why is Saturn's ring so much more massive than the rings of the other outer planets? Why are Mercury and Mars so much less massive than Earth and Venus? How can you actually proceed in the time available from the ubiquitous micron-sized dust particles to the typical planet which is 10^{40} times bigger? Why does the Sun only have 2% of the angular momentum whereas it has 99·8% of the mass?

This book is up-to date, thorough, and authoritative. It revels in the latest discussions and controversies. It sensibly balances what meteorites and planetary samples tells us about planetary chronology with what we learn from dynamics. It also provides a critical review of our early attempts to understand how planets might have formed. It is a joy to read and is accessible to any student with a scientific background. It underlines the fact that the study of the origin of planets is one of astronomy's really 'hot topics'. Read this book. Join the cosmogonists and help change the cosmogony/cosmology ratio. — DAVID W. HUGHES.

Cosmic Electrodynamics, by G. D. Fleishman & I. N. Toptygin (Springer, New York), 2013. Pp. 712, 24 × 16 cm. Price £153/$229/€181·85 (hardbound; ISBN 978 1 4614 5781 7).

The vast majority of astrophysical environs are sufficiently ionized to require attention to their electromagnetic properties and thus to treat them as plasmas. This 'textbook' is written by two experts who bring to bear both considerable theoretical expertise and applications to everything from the solar interior to active galactic nuclei. The book is self-contained, developing the necessary plasma physics, from particle motion to turbulence theories, from first principles. Each chapter contains numerous, often quite challenging problems together with their solutions. The overall production of the book is excellent, with clear text, consistent notation and equations, and just about enough figures to illustrate the essential concepts, applications, and observational results. The emphasis is distinctly theoretical; it would not be possible to include the full range of applications. Equally, the book doesn't shy away from complex detailed derivations, some of which follow non-conventional routes to their destinations.

Even given its considerable length, the authors are only able to develop each concept and application to a limited extent. For example, nonlinear three-wave interactions are treated in a single page, and then used 100 pages later without specific cross-referencing. Most of the chapters are fairly self-contained, however, so that they can be read independently. In this way, Fleishman & Toptygin provide a comprehensive encyclopaedia of astrophysical plasma processes. Someone new to plasma instabilities and turbulence could thus grasp the key elements and compare most if not all the competing formalisms by reading one 60-page chapter.

There are numerous places where some familiarity with the basics of plasma physics, or with the structure of the Sun, the interstellar medium, *etc.*, seem to be required. Additionally, there are also places where formulae or simplifications are parachuted into the text. To use the book either as a textbook or as a research reference will thus require some effort and some external reading. This, together with the price, may make the text a daunting prospect for many. However, for the not-so-faint-hearted, this book will serve as a solid springboard into the electrodynamic oceans of the cosmos. — STEVE SCHWARTZ.

Physikalische Mythen auf dem Prüfstand, by Wolfgang Kundt & Ole Marggraf (Springer Spektrum, Berlin) 2014. Pp. 445, 23 × 15 cm. Price £67·99/$109/€79·99 (paperback; ISBN 978 3 642 37705 1).

Yes, it's in German, from the *Vorwort* to the *Stichwortverzeichnis* (index, which has the names of people italicized). The first thing to be said about the book is that it covers an enormous amount of territory: geophysics; our Solar System; single and binary stars; neutron stars; supernovae, gamma-ray bursts, and cosmic rays; the Milky Way; astrophysical jets; cosmology; biophysics; and fundamental (particle) physics. The second is that Kundt & Marggraf have something unusual to say about every one of them, as is clear from their subtitle, *Eine Sammlung begründeter Alternativtheorien von Geophysik über Kosmologie bis Teilchenphysik*. There is something to surprise on nearly every page, from a map showing plate boundaries that, for once, doesn't put a gap in the middle of the Pacific ring of fire, to a smiling whale and an H–R diagram in landscape rather than portrait orientation.

The list of people whom the senior author knows or knew and was inspired by is an imposing one, including Pauli, Dirac, Feynman, Penrose, Hawking, Bondi, Ambartsumian, Wheeler, Rees, Morrison, Zeldovich, Layzer, Carter, and above all Thomas Gold. He missed meeting Landau and Einstein by only a few months, and yours truly appears for work on the Crab Nebula.

I can think of at least a small group of people who might benefit a great deal from the book: those who already know a fair amount of science, and are curious about weaknesses in conventional views of everything, and who would also like to teach themselves German. My own 'baptism of fire' was Otto Heckmann's *Theorien der Kosmologie*, which had not, at the time I tackled it (summer 1965), ever been translated. It still hasn't been, as far as I know, and it would be sad if Kundt & Marggraf met the same fate. — VIRGINIA TRIMBLE.

Astronomy for Young and Old: A Beginner's Guide to the Visible Sky, by Walter Kraul; translated from German and edited by Christian Maclean (Floris Books, Edinburgh), 2014. Pp. 164, 22·5 × 21 cm. Price £14·99/$24·95 (paperback, ISBN 978 178250 046 9).

The sub-title is perhaps more descriptive of the contents; this is essentially a book on naked-eye spherical astronomy. (The original German title is *Erscheinungen am Sternenhimmel*, for which not the most literal but perhaps the best translation is "(visual) phenomena on the celestial sphere".) However, the title itself is also apt: although essentially no knowledge of astronomy and little of mathematics is assumed, the text is equally suitable for the curious schoolchild and someone much older. The back cover mentions that the author taught at the Rudolf Steiner school in Munich, which put me on guard. Fortunately, one notices little anthroposophic influence on the text, which is very good and obviously written by someone who understands thoroughly what he is describing. Although there are many books at roughly the same level, this one covers essentially all that the amateur astronomer needs to know about naked-eye astronomy.

The book is divided into four parts (and, unusually for a book of this length but quite usefully, has three more levels of division): the stars; the Sun; the Moon; planets, comets, and meteors. The emphasis is on what can be seen with the naked eye; binoculars and telescopes are mentioned only a few times in passing, as are Uranus and Neptune. For the same reason, there is little on the physical composition of celestial bodies. (In general this is fine, though mentioning Thomson–Widmannstätten structures in meteorites without any explanation of their origin is a bit puzzling.) Descriptions are followed by physical explanations; for example, the phenomenon of retrograde motion is explained with diagrams showing how it comes about. (This is done in the context of the heliocentric model; epicycles and so on are not mentioned. In general, there is little historical background, with a couple of exceptions mentioned below.)

The book begins by discussing the daily rotation of the Earth, constellations (including the zodiac in its own chapter), and asterisms, and introduces important concepts such as sidereal time. The discussion of the movement of the Sun includes most of the concepts of orbital kinematics, including the precession of the equinoxes; aurorae and rainbows (both of course caused by the Sun) are also discussed in this part of the book. The third part, about the Moon, continues the discussion of orbital kinematics, including a good discussion of nodes and their precession. Only in the final part, on planets, comets, and meteors, is there more than a brief mention of historical topics. In particular, Kepler's attempt to relate the relative distances of the planets to the Platonic solids and the Titius–Bode law are presented. It seems a bit strange to choose those two from the many historical topics which would fit into a book like this, should one want to mention any at all. These were perhaps chosen because the author sees them as 'remarkable', though he does note that neither is quite accurate.

The production, appearance, and layout of the book are superb. Stand-alone boxes on various topics complement the main narrative and most chapters have an additional summary box. There are 129 figures, of which only 17 are photographs (three of them are of historical works of art), and the remaining 112 are sketches. All but some of the line drawings and two historical engravings are in colour. The sketches, by exaggerating important aspects, show the subject more clearly than photographs could, without being too unrealistic. A list of books for further reading is provided, many from the same publisher (Floris Books). They are all in English, though a couple are by authors with German names (I don't know if they are translations or books written in English). I haven't read the original so I don't know whether this list is different from that in the original, though presumably it is. (The original was published in 2002; the fact that the book mentions the Chelyabinsk meteor shows that this is not a direct translation, but that the book has indeed been edited as well.) Well-known names such as Ian Ridpath and Dava Sobel appear alongside unfamiliar (to me) ones, many of them on books from the same publisher. The index is only two-and-one-half pages, but that is sufficient.

There are relatively few typographical errors and only a few minor factual mistakes: although correct in the text, Fig. 22 shows the Small Magellanic Cloud in Hydrus rather than Tucana; there are more cases of half-hour time zones than mentioned and no mention is made of quarter-hour time zones; the author suggests that the value of the AU was not known at all before modern times, when in fact even the Ancient Greeks had at least a rough idea; his explanation for the source of meteor light is at best incomplete.

More troubling are some references to pseudo-science. Astrologers are described, with no further qualification, as "those who study the influence of stars on human life" during a discussion of the precession of the equinoxes. While it might be appropriate to mention that this is the reason for the discrepancy between zodiacal constellations and astrological signs, it should at least be mentioned that astrology is no longer considered scientific (especially since outdated concepts are rarely mentioned otherwise). If this were the only such reference, it could be excused as perhaps just unclear, but later in the text it is mentioned that the Moon is "said to influence plant growth, animals and even human behaviour". While the "said to" might suggest that the author is merely noting that some people believe this, the fact that he mentions it at all, then goes on to say that further discussion "would go far beyond the scope of this book" indicates otherwise. Later there is a box on astrological aspects, which seems somewhat gratuitous. Mentioning that the planets were associated with days and metals is something one often finds in similar books; adding colours, trees, grains, and (human) organs goes too far, especially since the nearby text mentions that "[t]hese were not random connections but showed an insight into the nature and character of each planet and its counterpart". Finally, a biodynamic calendar is mentioned in the further-reading list and the last page is a full-page advert for the same.

I read several roughly similar books when my age in years was measured with a single digit. This book covers more than most such books, is well written and illustrated, and was enjoyable to read. I would like to recommend it, but cannot because of the uncritical mention of astrology and other pseudo-scientific topics. They take up a negligible portion of the book, but the impression is created that they are just as legitimate as the other topics. Since the author obviously has a good working knowledge of astronomy, it cannot have escaped his attention that essentially the entire astronomical community would find those topics at best out of place in such a book. Short of leaving them out entirely, it would have been more honest for the author at least to mention that his views in this area are not main-stream. I am left with the impression that an otherwise excellent book contains some fifth-column topics whose goal is to attract into pseudo-science those curious about astronomy. My experience is that astrology and biodynamic agriculture are often associated with other pseudo-scientific beliefs such as that vaccines are more harmful than the diseases they protect against, which in several cases has led to otherwise avoidable deaths in children, who have no say in the matter. I thus can't see even just a few brief references to pseudo-science as harmless. Many who could learn much from this book will probably have little scientific background in areas other than astronomy as well; it would be a shame if readers were led down the wrong road, but it is also a shame that an otherwise excellent book is thus tarnished. — PHILLIP HELBIG.

The Hunter, by G. Genta (Springer, Heidelberg), 2014. Pp. 130, 23·5 × 15·5 cm. Price £15/$19·99/€21·39 (paperback; ISBN 978 3 319 02059 4).

This short book is another offering from Springer's 'Science and Fiction' series, in which scientific ideas are explored by means of short science-fiction stories. The main theme explored in this book is humanity's encounter in the 24th Century with self-reproducing alien interstellar space probes (*i.e.*, interstellar von Neumann machines). Although apparently initially built by their unknown makers millions of years ago for peaceful purposes of galactic exploration, by the time humanity encounters them they have unfortunately evolved into lethal planet-destroying machines, and the story revolves around efforts to destroy them.

From a fictional point of view, the story bears some resemblance to a couple of 1960's *Star Trek* episodes (*The Doomsday Machine*, written by Norman Spinrad, and *The Changeling*, written by John Lucas), although no reference is made to those earlier stories and the author may be unaware of them. Outside of fiction, it has long been realized that the danger of self-replicating machines evolving through natural selection in unintended and possibly dangerous directions is a strong argument for never allowing them loose in the Galaxy. The non-fictional appendix, which is a standard part of the 'Science and Fiction' format, gives a good set of references to existing literature on that topic.

A second thread to the story involves the possibility that machines might be able to evolve intelligence and/or consciousness. Clearly, if the alien probes had evolved to be conscious, and were destroying planets of their own free will, then it might be possible to reason with them in a way that would not be possible if they were mere automata. The story also explores the possibility that one day humanity may have to grapple with this issue in the context of our own artificially intelligent machines. In his appendix the author sides with thinkers like Roger Penrose (*e.g.*, *The Emperor's New Mind*, OUP, 1989) who consider the evolution of machine consciousness to be unlikely, and against those like Ray Kurzweil (*e.g.*, *The Singularity is Near*, Duckworth Press, 2009) who think that it is all but inevitable. Indeed, Genta argues that the inability of machines to become truly conscious will prove to be a fundamental limitation of artificial intelligence, and a major reason why a human presence 'on the ground' will always be required in the exploration of space no matter how far artificial intelligence may progress. Only time will tell who is right on this one.

The story itself is a good yarn, packed with action and adventure, and, given its short length, achieves reasonable character development. However, it has to be said that, as a piece of sci-fi writing, it isn't all that deep, and would probably appeal more to a readership several decades younger than (I imagine!) most readers of book reviews in *The Observatory*. — IAN CRAWFORD.

Here and There

THE BIG COUNTRY

Formation and Evolution of Star Clusters in Chile — Title of workshop in Santiago, 2014 March 28.

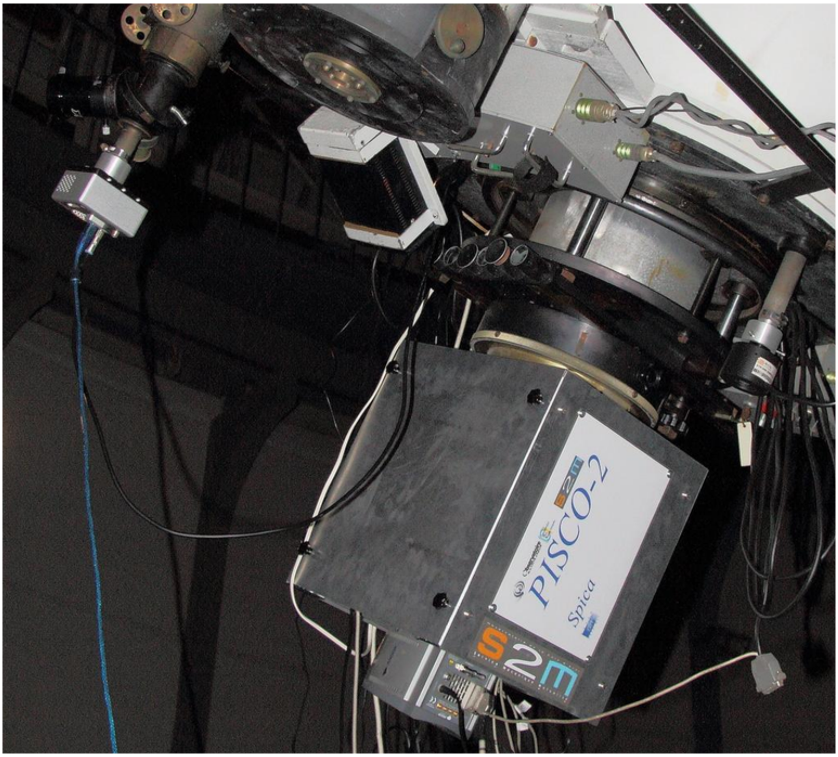
HOT PURSUIT

… Rosetta then chases Comet Churyumov-Gerasimenko through the inner Solar System at speeds of over 100,000 km/s. — *Popular Astronomy*, **61**, 26, 2014.

NOT RECOMMENDED

The system produces tack-shape stars across a 4°-wide field. — *Sky & Telescope*, 2014 January, p. 68.

Plate 1
PISCO2 on the Nice 76-cm refractor (L76)



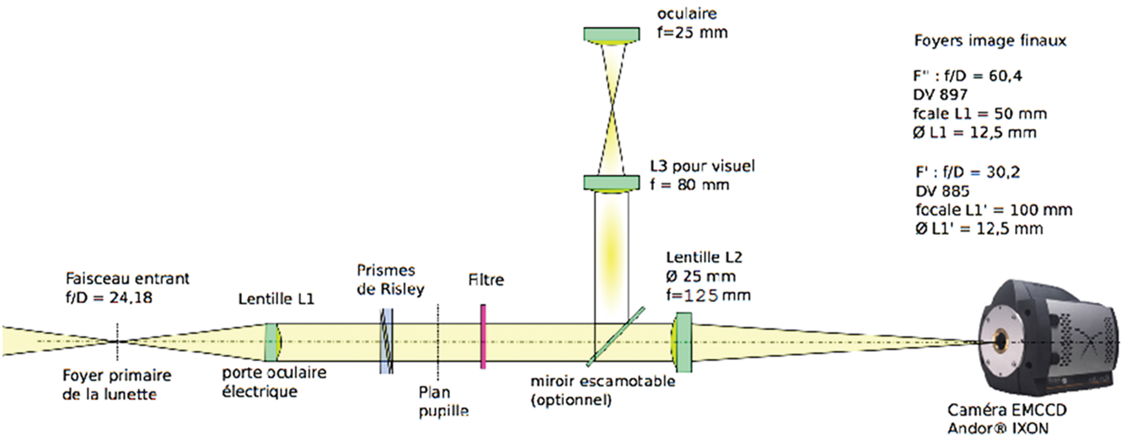
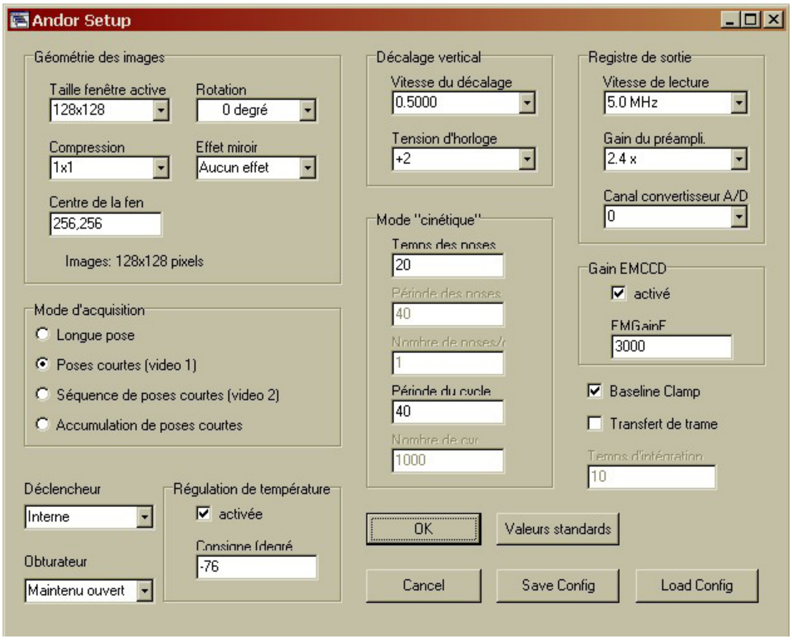


PLATE 2

PISCO2 with the ANDOR DV897 detector (top) and optical layout (bottom)



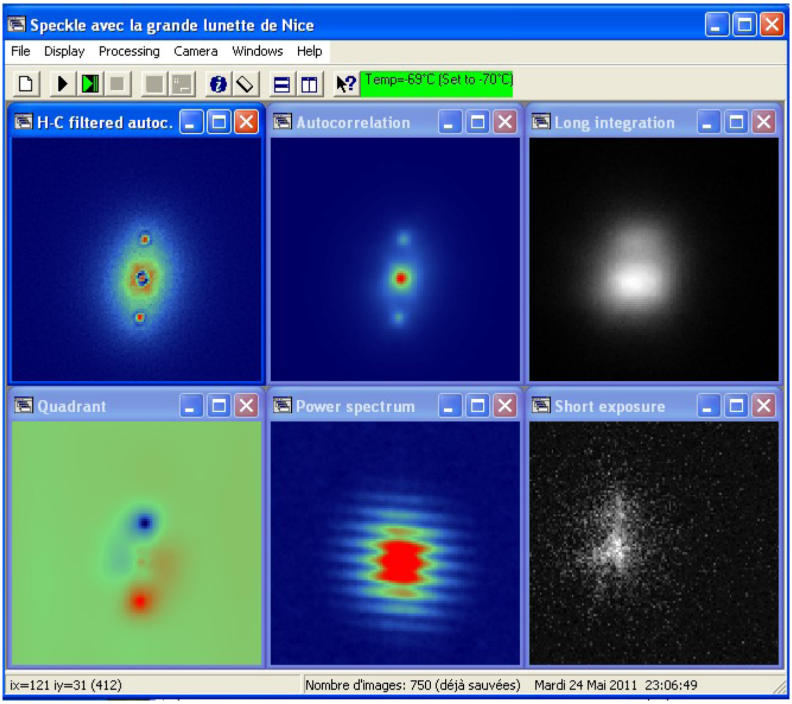


PLATE 3

Program BUILDSPECK1 used for the data acquisition with ANDOR cameras and real-time processing. Top: camera setup. Bottom: example of image processing of the binary star BU1273 ($\rho = 1''{\cdot}3$, $V = 9^{m}{\cdot}6$, $\Delta V = 1^{m}{\cdot}3$).

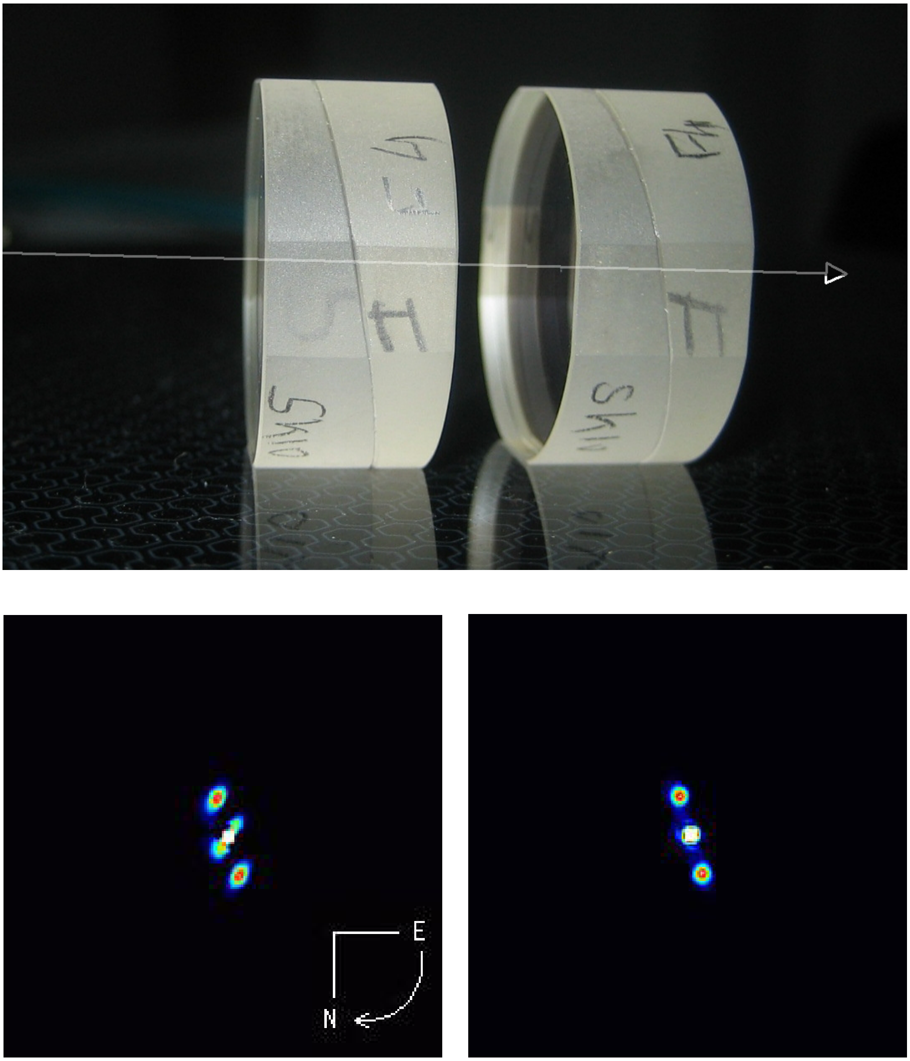


PLATE 4

Set of the Risley prisms used for correcting the atmospheric dispersion (top). Bottom left: uncorrected autocorrelation of the binary star A2724 ($\rho = 0''\cdot 8$, zenith distance: 42°). Bottom right: autocorrelation obtained with the good orientation of the Risley prisms (instrumental setup: L76, *PISCO2*, and the ANDOR DV897 camera).