

THE OBSERVATORY

Vol. 137

2017 FEBRUARY

No. 1256

SECOND THOUGHTS BEYOND KEPLER:
THE EQUAL-AREA RULE OF COMETARY ORBITS
BY THOMAS WRIGHT OF DURHAM (1711–1786)

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In a remarkable 1750 publication, Thomas Wright of Durham speculated that all cometary orbits enclose the same physical area. Here we investigate Wright's intriguing claim, and while it is easily shown that no such universal area exists, we do find that there is some utility in exploring the relationship between orbital period and orbital area for periodic cometary bodies. Indeed, by considering orbital areas, a useful diagram can be constructed in which the distinction between Jupiter-family, Halley-type, and Centaur/Chiron-type objects is made clear to the eye.

Introduction

Thomas Wright of Durham typically enters into the history of astronomy dialogue *via* his musings in 1742 concerning the spatial distribution of stars and the structure of the Milky Way^{1–3}. Those thoughts, contained within the text, *Clavis Cælestis, being the explication of a diagram entitled Synopsis of the Universe or, the Visible World Epitomized*, would probably be less memorable today if it were not for a mis-reading of its content by Emmanuel Kant. Indeed, it was Kant who converted Wright's ideas into the philosophically more useful nebular hypothesis for the formation of planetary systems. A fascinating character^{1,2}, Wright became well known in his lifetime as a skilled draughtsman, dial-maker, mathematician, astronomer, philosopher, architect, and landscape gardener; he published a large number of works, on many topics, but it is one particular suggestion, in his 1750 work *The Universe and The Stars, being an Original theory on the visible Creation founded on the laws of Nature*, that recently caught my attention³. Concerning the properties of cometary orbits, Wright comments, "I am strongly of the opinion, that the Comets in general, through all their respective orbits, describe one common area, that is to say, all their

orbits with regard to the magnitude of their proper [that is orbital] planes, are mathematically equal to one another". This is an extraordinary claim, which from a modern perspective is easily negated: the orbital area, for example, of comet 1P/Halley is equal to 253.6 AU^2 , while those of 2P/Encke and 3D/Biela are 8.1 and 25.6 AU^2 , respectively. To step back to the 18th Century, however, we find that the reasoning behind Wright's (erroneous) idea builds upon a reasonable-enough solution to a practical geometrical dilemma.

The story begins in 1742. In that year Wright published an extraordinary map of the heavens. Impressive in both physical size and scale, the map displays multiple panels and insets and was printed on four 3-feet by 2-feet panels; the complete map, when assembled, was 6-feet (1.83 m) long and 4-feet (1.22 m) wide. The map revealed, to scale, the orbits of the planets, and it additionally displayed the orbits associated with three comets: C/1661 C1, C/1680 V1 and 1P/1682 Q1. Those comets were originally highlighted by Edmund Halley, in his 1705 *Synopsis of the Astronomy of Comets*, as being periodic in nature. The comet of 1682 is Halley's Comet, while the other two are now catalogued as being long-period comets with parabolic orbital elements only. The problem faced by Wright in the construction of his map, however, was how to determine the greatest distances by which the three 'periodic' comets strayed from the Sun.

As a detailed textual companion to his scale map of the Solar System, Wright additionally produced, in 1742, *Clavis Cælestis*, and in that work he reviews the contemporary knowledge of those "surprising bodies in the system call'd comets". Indeed, at that time Wright appears to have been particularly interested in comets, specifically observing and reducing the orbital elements for the comets^{4,5} of 1742 (C/1742 C1) and 1744 (C/1743 X1). While those latter two comets appeared at a time too late for representation in his map of the Solar System, he did depict the full orbits of Halley's three 'periodic' comets. To place those comets in his diagram, Wright determined their aphelion distances from their deduced orbital periods and perihelion distances. Taking Halley's Comet, for example, Wright had derived an orbital period (P) of 75 years, and that yields *via* Kepler's 3rd law an orbital semi-major axis $a = 17.78 \text{ AU}$. Taking the *Orbis Magnus* of the Earth (the modern-day astronomical unit) to be 81 million (English) miles, Wright then calculates the greatest distance of the comet from the Sun as $Q = (2a - q) \times 8.1 \times 10^7$ miles, where the perihelion distance q is taken from Halley's 1705 *Synopsis*. Of the three comets considered by Wright, that of 1680 had the greatest deduced heliocentric distance, being some 1.12×10^{10} miles (based upon an adopted orbital period of 575 years and using from Halley's 1705 *Synopsis*, $q = (612.5/100\,000) \times 8.1 \times 10^7$ miles). With that straightforward methodology in place Wright was able to complete his scheme and thereby reveal in his map the full extent of the known Solar System, showing that the comets roamed the depths of space out to distances at least 14 times further from the Sun than the then outermost known planet Saturn.

The suggestion that all comets might have the same orbital area appears as a singular idea in Wright's *The Universe and The Stars*, there being no mention of such a rule within *Clavis Cælestis*, nor in his analysis of the comets of 1742 and/or 1744. Likewise, no similar such claim or statement has been found in the writings of any of Wright's contemporaries. There is no precedent for the idea to be found in Halley's 1705 *Synopsis*, nor in William Whiston's *Astronomical Principles of Religion, Natural and Revel'd: in nine parts* (first published in 1717; 2nd edition, 1725). A survey through Roger Long's *Astronomy in Five Books*, published in two volumes between 1742 and 1764, reveals but short notice being given to comets, and no mention of an equal-area relationship. Likewise,

Richard Turner in his *A View of the Heavens* (published in 1783), while clearly setting down the characteristics of cometary orbits, makes no mention of any common-area rule. Certainly, there is no theoretical requirement for such an equal-area rule to exist — a conclusion that can, in fact, be drawn directly from Isaac Newton's *Principia*, published in 1687, where it was shown that a centrally acting force (gravity) and the conservation of angular momentum suffice to explain all planetary dynamics and specifically Kepler's three laws of planetary motion. The rule of equal area, which no other philosopher appears to have endorsed, seems to build upon the idea that comets are somehow different from the planets³, their orbital motion being constrained not only by Kepler's laws but by an additional rule, presumably creator-ordained and built-in *ab initio* to the planetary system. Certainly, the physical make-up of comets was entirely unknown at the time that Wright was developing his ideas, and it was then generally thought that comets were similar to planets in both size and structure³. For all that, however, Wright's justification for the equal-area rule is hardly convincing (as we shall see below), and it requires the reader to accept the equality of areas deduced for the comets of 1680 and 1682. In modern terms the area of each comet's orbit, in units of AU², will be $A = \pi a(qQ)^{1/2}$ where q is the perihelion distance (as deduced from the observations), and where, appropriate to an elliptical orbit, the aphelion distance is $Q = 2a - q$. Although he does not state his methods directly, Wright correctly found that the ratio of their orbital areas was $A_{1682}/A_{1680} \approx 17/13$. With that ratio in place, Wright then notes that if the perihelion distance to the comet of 1680 was just 1.6 times larger than that given by Halley in his 1705 *Synopsis*, an equality of the areas could be realized. That factor of 1.6 change in the perihelion distance, Wright argues, is a mere 35 000th of the comet's major axis, "which is an error every Astronomer will readily grant is very easily made". While clearly working on less-than-secure ground, Wright none-the-less argues, "if we can with any show of reason, and a probability on our side, bring the areas of these two extreme comets, as I may call them, to an equality, sure we may conclude it is a subject highly worthy to be more considered and enquired into".

We hear no more of the equal-area rule for cometary orbits after Wright's 1750 speculations, and it is completely done away with in his unpublished manuscript⁶ *Second or Singular Thoughts upon the Theory of the Universe* written some time circa 1771. Indeed, in that latter work Wright essentially abandons all of the ideas espoused in his (1742) *Clavis Cœlestis* and in his (1750) *An Original Theory, or New Hypothesis of the Universe*. The Sun and Solar System are now deemed to be contained within a solid spherical shell; the stars are linked to light emanations from volcano-like structures embedded within the inner surface of the shell, and comets are identified with the material ejected from those same starlight-volcanoes. Further, in his *Second or Singular Thoughts*, Wright argues that there is no such object as a periodic comet: "they have no common connection with our system so as to be looked upon as regular parts of it but as all of them totally independent and subject to other laws". What those "other laws" might be Wright leaves as an unarticulated blank. There is nothing wrong, of course, with an author changing his mind with respect to an earlier argument, and Wright is indeed struggling with a topic, essentially that of cosmology and the large-scale distribution of matter, that continues to occupy the minds of astronomers to this very day. Intriguingly, however, for all of Wright's vacillation there is, it transpires, some small value in taking his original idea concerning the area of cometary orbits a little further and, indeed, reacting to his 1750 suggestion that the topic is worthy of further enquiry.

In the eye of the beholder

The area of an ellipse is given by the product of its semi-major (a) and semi-minor axis (b) such that $A = \pi ab$. The semi-minor axis is further related to the semi-major axis and the eccentricity (e) as $b = a(1 - e^2)^{1/2}$, giving $A = \pi a^2(1 - e^2)^{1/2}$, and this, as seen earlier, can be related to the perihelion and aphelion distances: $A = \pi a(qQ)^{1/2}$. To take that result a little further algebraically, however, we introduce the Tisserand constant⁷:

$$T = (a_j/a) + 2 [(a_j/a)(1 - e^2)]^{1/2} \cos(i),$$

where a_j is the semi-major axis of Jupiter's orbit and i is the orbital inclination. Using that relationship and Kepler's 3rd law we now find:

$$\left[\frac{P(\text{yr})}{A} \right] = \frac{0.28 \cos(i)}{T - (a_j/a)}, \quad (1)$$

where the right-hand side of (1) may be taken as a (near) constant and parameterized term according to the values chosen for T , (a_j/a) , and $\cos(i)$ — at this stage we note that we still have the semi-major axis term a on the RHS of (1), but in what follows we take the ratio (a_j/a) to be either unity or zero, corresponding to the situations where $a \sim a_j$ or $a \gg a_j$. Additionally, we introduce at this stage the approximation that the orbits are predominantly confined to the ecliptic plane and take $\cos(i) = 1.0$. The construction of equation (1) builds upon a number of idealizations: the Tisserand constant is only strictly constant in the case of the restricted 3-body problem under the constraint of circular orbits^{7,8}; likewise Kepler's 3rd law is only strictly true for the 2-body problem. In the 2-body situation, such as that exhibited (approximately) by the individual planets, we have $P(\text{yr}) = (A/\pi)^{3/4}$. Introducing the Tisserand constant, equation 1, just like Kepler's 2nd and 3rd laws, generates a relationship between the geometrical characteristics of an orbit (through the orbital area) and the orbital dynamics (through the orbital period and the Tisserand constant). Additionally, by using the Tisserand constant an allowance is made for orbital evolution *via* gravitational interactions, and this, of course, is of great importance with respect to regulating the characteristics of cometary reservoirs and families⁹.

Figs. 1 and 2 show plots of orbital period P versus orbital area A for the known periodic comets¹⁰ (compiled through to the end of 2014 and the recovery of 316P/LONEOS–Christensen), and through these diagrams the existence of several distinct cometary groups is revealed. Indeed, the orbital-area *versus* orbital-period diagram brings out the existence of the Jupiter-family of comets (Fig. 1), the Halley-type comets, and the Centaur/Chiron-type objects (Fig. 2). In Fig. 1 there are a great number of comets, having orbital periods between ~ 3 and ~ 10 years with orbital areas numerically set between those corresponding to the planets Mars and Jupiter. Indeed, those comets are otherwise described as having Tisserand parameters between 2 and 3, and an orbital semi-major axis comparable to that of Jupiter ($a_j/a \approx 1$) — that is, they are the Jupiter-family of comets. For those comets with $5 < P(\text{yr}) < 10$ we find, from data in Fig. 1, to a reasonably good order, that $P(\text{yr}) \approx 3.0 + 0.1A$. For comets with $10 < P(\text{yr}) < 20$, there is a large spread in the associated period–orbital-area data points, although the trend is for the data points to fall towards the line parameterized by $T = 3$ and $a_j/a = 1$, giving $P(\text{yr}) \approx 0.14 A$. In Fig. 2 two additional groups of periodic objects are revealed: those which have $T = 2$ with $a_j/a = 1$ and those having $T = 3$ and $a_j/a = 0$. The former of those groups corresponds to the Halley-type

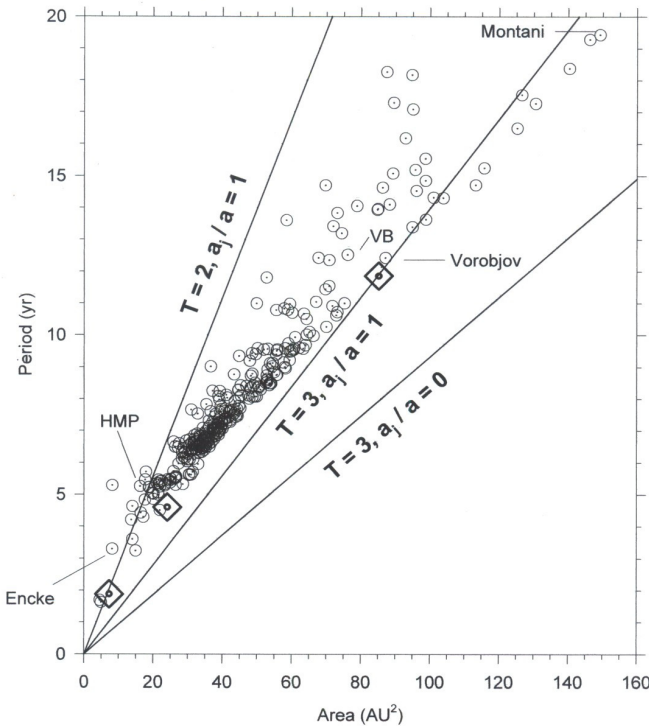


FIG. 1

Orbital period ($P < 20$ years) versus orbital area for the known periodic comets. The three labelled lines correspond to various parameter combinations for equation (1), and the three dotted-diamond points indicate the orbital period and orbital area of Mars, Ceres, and Jupiter. Several data points are identified for reference purposes only and correspond to comets 2P/Encke, 46P/Honda-Mrkos-Pajdušáková (HMP), 276P/Vorobjov, 314P/Montani, and 53P/van Biesbroeck (VB).

comets, while the latter corresponds to Centaur/Chiron-type objects. For the Halley-type objects we find for $20 < P(\text{yr}) < 200$, that $P(\text{yr}) \approx 0.28 A$, while for the Centaur/Chiron-type objects, $P(\text{yr}) \approx 0.09 A$.

Discussion

Rising to the challenge of a ‘considered enquiry’ some 266 years after Thomas Wright speculated, in his 1750 work *The Universe and The Stars*, that all cometary orbits have the same area, we find, to no modern-day surprise, that his ‘opinion’ was entirely wrong. That, of course, is no indictment on Wright’s other contributions to astronomy. What we do find as a result of this analysis, however, is that the orbital-area versus orbital-period diagram for the periodic comets usefully reveals, in visual form, the existence of three distinct cometary groups or families. This visual clarity stands apart, it is suggested, in contrast to alternative diagrams in which orbital eccentricity is plotted against semi-major axis, or the Tisserand constant is plotted against the inverse semi-major axis. While these latter diagrams contain the very same information as the orbital-area versus orbital-period diagram, the comet families are less readily evident to the eye.

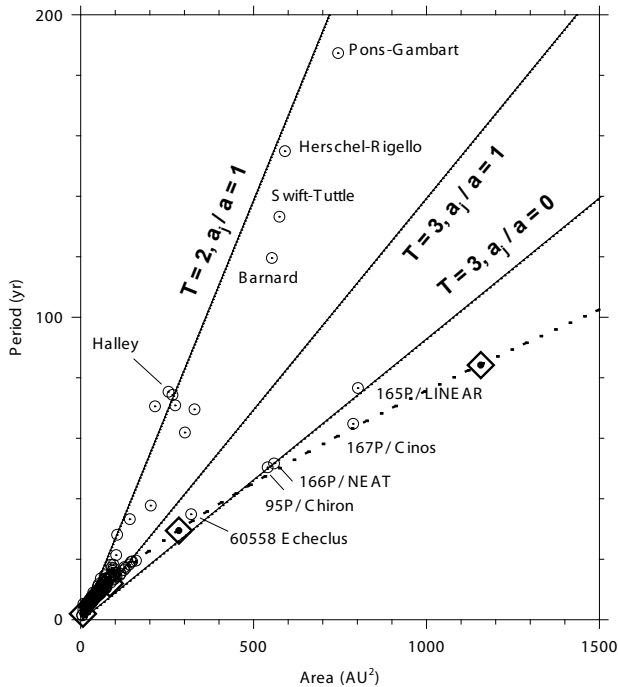


FIG. 2

Orbital period ($P < 200$ years) versus orbital area for the known periodic comets. The three labelled lines correspond to various parameter combinations for equation (1), and the four dotted-diamond points indicate the orbital period and orbital area of the planets Mars, Jupiter, Saturn, and Uranus. The dotted line corresponds to the period-area relationship in the restricted 2-body, circular-orbit situation: $P(\text{yr}) = 0.424 A^{3/4}$. Various data points are labelled, for reference purposes only, along the Halley-family branch and the Chiron/Centaur branch.

The classification of cometary families has long been a topic of great discussion, and various schemes have been proposed over the years, some related to orbital period only, others invoking various dynamical parameters. Figs. 1 and 2 here essentially provide a graphical representation of the taxonomic schemes outlined by Levison¹¹ in 1996 and by Horner *et al.*⁹ in 2003. The classification scheme proposed by Levison uses the Tisserand constant as the major discriminant, and indeed, the Tisserand constant is a measure of Jupiter's gravitational influence upon a comet's orbital evolution. Accordingly, the Jupiter family of comets is defined as those bodies constrained to move in the ecliptic with $2 < T < 3$, and such bodies will typically have $a_i/a \approx 1$ (see Fig. 1). Those objects with $T < 2$ constitute the Halley-type group of comets. Those bodies with $T > 3$ and with $a_i/a < 1$ fall into the Centaur/Chiron-type family of objects. For that latter group, as emphasized in the taxonomic scheme of Horner *et al.*, the orbital evolution is determined not only by the gravitational influence of Jupiter, but by their closeness of approach to the planets Saturn and Uranus (see Fig. 2). Main-belt asteroids, in contrast, are wholly confined interior to the orbit of Jupiter and have $T > 3$ and $a_i/a > 1$ — see Fig. 1 for the location

of Ceres. We find that the active asteroids (or main-belt comets)¹², defined as having $T > 3.08$ with $a_1/a > 1$ and which show evidence for mass loss in the form of a coma or tail(s), are not specifically distinguished in Fig. 1, but rather join smoothly into the small-area ($A < 32$), small-orbital-period ($P(\text{yr}) < 6$) domain of the Jupiter-family comets.

The simple period–orbital-area expressions derived from Figs. 1 and 2 do not provide any new and/or specifically profound description of cometary orbits, but they do bring out a clear and easily observed distinction between the Halley-type objects and the Chiron/Centaur-type objects. Indeed, the distinction between the Halley-type objects and the Chiron/Centaur objects in the period–orbital-area diagram is reflective of the fact that the former objects tend to have a relatively large semi-major axis (and hence, by Kepler’s 3rd law, a long orbital period) and a high eccentricity (which for a given value of the semi-major axis tends to reduce the associated orbital area). The latter objects, in contrast, have a restricted range in semi-major axis and allow for only a relatively small variation in orbital eccentricity — the eccentricity constraint in the case of the Chiron/Centaur objects is that, if it becomes too large, then a close gravitational encounter with either Saturn or Uranus must come about, and accordingly a dramatic orbital change is likely to occur. Likewise, the Jupiter-family comets are also restricted to a limited range in semi-major axis and eccentricity, requiring that the aphelion distance be close, but not too close, to the orbit of Jupiter, and that the perihelion distance be interior to the orbit of Mars.

Wright’s equal-area rule for cometary orbits is perhaps an aesthetically pleasing idea, but it has no anchor in reality. At times of new innovation and speculation, however, the appearance of such (over-)simplified rules is not uncommon in the history of science: they make difficult problems tractable and they impose (typically naïve) human sensibility. As a parallel example to Wright’s equal-area rule, one finds, for example, Johannes Kepler, in his *Mysterium Cosmographicum* (published in 1597), and later Jeremiah Horrocks, in his *Venus in Sole Viva* (published in 1662), arguing that the planets should obey an equal-angular-diameter rule if viewed from the Sun¹³. Such rules often have some apparent basis in the available observational data (a false positive in modern parlance), and while ultimately shown to be mistaken in reality, they can, and indeed quite often do, provide a continued stimulus to the development of new ideas and the development of un-anticipated results.

Acknowledgements

Many thanks are extended to the referee, Professor David Hughes, for his thoughtful comments on the first draft of this paper.

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SPECTROSCOPIC BINARY ORBITS FROM PHOTOELECTRIC RADIAL VELOCITIES

PAPER 252: HD 102687, HD 110987, HD 114604, AND HD 114882

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The four stars whose orbits are presented in this paper are all to be seen in the part of the sky that is within 15° of the North Galactic Pole, and were initially observed in the course of the writer's comprehensive radial-velocity survey of all the (~ 900) late-type stars in the *Henry Draper Catalogue* whose sky positions are within that area.

HD 102687 is a particularly faint *HD* star, and because its spectral type of F8V is actually much earlier than the Ko given in the *HD* it is not easy to get good radial velocities of it. On the other hand it has, by the standards of this series of papers, quite a short period (128 days) and a fair amplitude (13 km s^{-1}). The observations extend over more than 100 revolutions of the orbit (although they are only systematic over the last 18 cycles, starting in 2010), so the orbit is quite well determined; it has an eccentricity of 0.4.

HD 110987 is another late-F star that is classified as Ko in the *HD*; it is of ninth magnitude, and again it is quite a difficult object to observe because it is double-lined. The components are equal within the uncertainty of the observations, so the 'dip' in radial-velocity traces is often split into two, very shallow, ones — and when it is not, the difficulty of obtaining the twin velocities from the blend are even greater. The system has, however, an unusually short period of 5.66 days, watched for about 600 cycles since systematic observations started in 2007 and determined here to a precision of 12 seconds. The velocity amplitudes of both components are nearly 40 km s^{-1} , and their measured rotational velocities of about 5 km s^{-1} indicate synchronization with the orbit.

HD 114604 is a multiple system, first recorded as a visual double star by Struve in 1830, with components of magnitudes $8\frac{1}{2}$ and 10, $8''$ apart. In 1906 Aitken resolved the primary, seeing it as an unequal pair with a separation of only $0''.3$. Both components of the close pair register in radial-velocity traces; the fainter one, already known to be itself a single-lined binary, is confirmed to have an orbit with a period of only 3.35 days, that is found here to be circular within its uncertainty and is determined to $2\frac{1}{2}$ seconds.

HD 114882, which at $9^m.8$ is faint for a *Henry Draper Catalogue* star, has proved to be a somewhat unequal double-lined object in an orbit having an eccentricity of 0.4 and a period of 25 years that is determined to within two months. The system is reasonably well resolved in radial-velocity traces only in the vicinity of the more favourable node, which has recently been observed for the second time.

Introduction

The writer's interest in the stars treated in this paper arose from their inclusion in the project to survey the radial velocities of all the late-type *Henry Draper Catalogue* stars whose sky positions are within 15° of the North Galactic Pole (NGP). The project was begun 50 years ago when the radial-velocity spectrometer¹ was first developed, and its main results were published² by the writer, in collaboration with Dr. K. M. Yoss who undertook photometry of all the same stars, in 1997. There is evidence of the utility of the survey in the *Simbad* listings for all four of the stars treated in this present paper: the *V* and *B* magnitudes, spectral types, and radial velocities of all of them are quoted from it.

As a by-product of the survey, about 100 of the stars were found to be spectroscopic binaries; in the course of time many of them have been seen round their cycles (in some cases many times), and in about 70 instances their orbits have been written up in papers such as this one, which adds four more.

HD 102687

HD 102687 is at the extreme western margin of the NGP field as defined by the 15° -radius criterion; it is actually in the constellation Leo, rather than Coma or Canes Venatici like the great majority of NGP stars. It makes quite closely an equilateral triangle with the fifth-magnitude stars 92 and 93 Leo (the latter is a well-known composite-spectrum binary whose spectra have been disentangled³ by the Griffins). HD 102687 is a particularly faint object to be included in the *Henry Draper Catalogue*, where it is admitted to be $9^m.6$ and is accorded a spectral type of Ko. The *V* (actually 'photovisual') magnitudes of most *HD* stars were not actually measured for the entries in the *Catalogue* but were taken from the *BD*⁴ and are subject to systematic adjustments to bring them more nearly onto the *HD* scale, which is not so far from *V*. Like all the entries in the *HD*, however, the star was classified by Miss Cannon, who attributed to it a spectral type of Ko. Perhaps owing to its faintness, she was unusually inaccurate in the case of HD 102687, whose modern type (inferred from photometry², however, rather than properly classified from its spectrum) is F7V. The misclassification in the *HD*, together with the use there of tabular colour indices based on spectral

TABLE I
Radial-velocity observations of HD 102687

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

Date (UT)	MJD	Velocity km s ⁻¹	Phase	(O-C) km s ⁻¹
1973 Mar. 30·92*†	41771·92	+19·2	106·561	+0·9
1984 Jan. 9·13*	45708·13	+20·9	75·406	-0·1
2007 Apr. 10·98	54200·98	-4·6	9·957	+0·1
11·91	201·91	-4·7	·964	+0·1
2010 Apr. 14·89	55300·89	+17·7	0·576	-0·2
May 9·95	325·95	+9·9	·773	+0·1
11·89	327·89	+7·8	·788	-1·0
12·91	328·91	+7·9	·796	-0·4
15·98	331·98	+6·0	·820	-0·5
16·91	332·91	+6·6	·827	+0·7
17·89	333·89	+5·7	·835	+0·4
21·91	337·91	+3·2	·866	+0·6
24·00	340·00	+1·0	·883	-0·1
25·96	341·96	+0·2	·898	+0·6
27·90	343·90	-3·1	·913	-1·3
June 2·91	349·91	-4·9	·960	-0·1
4·93	351·93	-4·7	·976	0·0
11·93	358·93	+1·9	1·031	+0·5
14·92	361·92	+5·0	·054	-0·5
16·92	363·92	+8·4	·070	+0·3
17·91	364·91	+9·1	·078	-0·2
21·93	368·93	+12·5	·109	-0·9
22·92	369·92	+15·3	·117	+1·1
2011 Jan. 19·19	55580·19	+9·5	2·765	-0·7
Apr. 9·00	660·00	+21·8	3·390	+0·7
May 9·93	690·93	+16·2	·633	0·0
2012 Jan. 4·21	55930·21	+19·4	5·508	-0·1
17·20	943·20	+18·0	·609	+1·1
Feb. 2·13	959·13	+12·2	·734	+0·3
Apr. 10·96	56027·96	+20·5	6·274	-0·6
17·97	034·97	+22·4	·329	+1·0
29·94	046·94	+20·0	·422	-0·8
2013 Feb. 15·08	56338·08	+13·2	8·704	-0·2
Apr. 2·04	384·04	+8·1	9·064	+1·0
20·94	402·94	+19·6	·212	-0·3
May 2·91	414·91	+21·5	·306	+0·2
Dec. 28·21	654·21	+19·3	11·181	+0·6
2014 Jan. 5·19	56662·19	+21·1	11·244	+0·4
Feb. 26·10	714·10	+15·8	·650	+0·2
28·08	716·08	+15·3	·666	+0·3
Mar. 10·05	726·05	+10·9	·744	-0·5
23·09	739·09	+4·7	·846	+0·3
Apr. 15·03	762·03	-0·1	12·026	-0·7
15·97	762·97	+1·6	·033	-0·2
16·96	763·96	+2·8	·041	-0·4
18·94	765·94	+6·1	·057	+0·2
26·96	773·96	+14·3	·119	-0·1
May 2·98	779·98	+17·3	·167	-0·7
25·91	802·91	+20·5	·346	-0·9

TABLE I (concluded)

Date (UT)	MJD	Velocity km s ⁻¹	Phase	(O-C) km s ⁻¹
2015 Feb. 18.16	57071.16	+19.9	14.448	-0.6
Apr. 29.93	141.93	-2.7	15.003	0.0
2016 Apr. 30.94	57508.94	+1.8	17.879	+0.4
May 4.92	512.92	-1.5	.910	0.0
14.93	522.93	-3.7	.988	+0.4

*Observed with original Cambridge spectrometer
†Observed by G. A. Radford

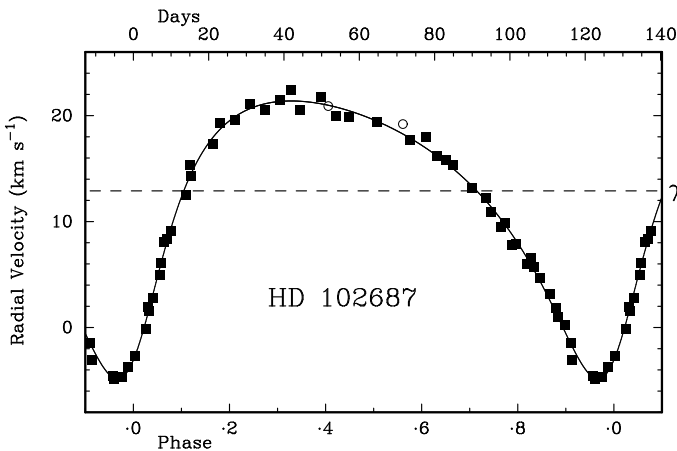


FIG. 1

The observed radial velocities of HD 102687 plotted as a function of phase, with the velocity curve corresponding to the adopted orbital elements drawn through them. All but two of the observations were obtained with the Cambridge *Coravel* and are plotted as filled squares; the two that were by far the earliest came from the original radial-velocity spectrometer and appear as open circles.

type (I^{m.0} for type Ko) led to a rather pessimistic ‘photographic’ magnitude of 10^{m.6}. The measured *V* and *B* magnitudes² are 9^{m.72} and 10^{m.21}, respectively, and it is the implied colour index of 0^{m.49} that led to the putative type of F7V. Many years previously, narrow-band photometry in the Copenhagen system⁵ had been obtained by Hansen & Radford⁶ (the latter being at the time a graduate student under RFG’s supervision); it led to a *V* magnitude of 9.71 and a value of the duplicity parameter *res(k)* large enough (> 0^{m.04}) to imply duplicity of the object and to falsify estimates (which were therefore not presented) from the photometry of [Fe/H] and *M_V*.

The radial velocity of HD 102687 was first measured by Radford in 1973 with the original photoelectric spectrometer⁷ at Cambridge. A decade later, another measurement, accordant with the first, was made by the present writer with the same instrument. There the matter rested for more than 20 years, until a third measurement was made, with the Cambridge *Coravel*, in 2007; it gave a result differing by about 25 km s⁻¹ from the two previous ones. A repetition of the

observation on the very next night confirmed the new velocity, so the star was transferred to the Cambridge binary programme. Intensive observations with the Cambridge *Coravel* in the 2010 observing season (18 in two months in May and June) then led to the recognition of the orbital period of about 128 days. There are now 54 measurements altogether; they are listed in Table I and define the period within an uncertainty of less than half an hour. The mass function of little more than $0.02 M_{\odot}$ is quite small, and it is not surprising that no evidence of the companion star has been seen in the radial-velocity traces. The full set of elements is given in Table V towards the end of this paper, where it is accompanied by those of the other stars treated below; the orbit is illustrated in Fig. 1.

HD 110987

HD 110987 is near the north-preceding margin of the 15° -radius ‘NGP field’; it is to be found just over 2° preceding, and at almost identical declination to, the wide $2^{\text{m}}.9$ – $5^{\text{m}}.6$ double star α CVn (Cor Caroli); it is also 1° south of, and slightly following, the 6^{m} solar-type star ι CVn. The *Henry Draper Catalogue* lists for it the very optimistic ‘photovisual’ magnitude of $8^{\text{m}}.0$, but the fact that it lists it to only one decimal place indicates that that magnitude was simply adopted from the *BD* (whose magnitudes are Argelander’s ‘instant visual estimates’) with a tabular correction that is intended to offset the systematic discrepancy between Argelander’s personal scale and *V*. The ‘photographic’ magnitude given in the *Henry Draper Catalogue* is $9^{\text{m}}.0$, and was merely derived from the ‘photovisual’ one by adding the colour index of $1^{\text{m}}.0$ assigned to all stars classified in that work as type Ko. All of the quantities just cited are some way from what we may now be inclined to accept: the *V* and *B* magnitudes determined by actual measurement by Yoss & Griffin² are $9^{\text{m}}.05$ and $9^{\text{m}}.57$. The colour index of $0^{\text{m}}.52$ implies, in the light of other photometry presented in the same paper², a spectral type of F8 V. The luminosity is determined also geometrically by the *Hipparcos* parallax of 7.23 ± 1.23 milliseconds, corresponding to a distance of 138 ± 20 pc (not 138.310 pc, as listed by McDonald *et al.*⁸), and to a distance modulus of about $5^{\text{m}}.7 \pm 0^{\text{m}}.4$. The implied absolute magnitude is therefore about $3^{\text{m}}.3$, with the same uncertainty; that is about $0^{\text{m}}.7$ brighter than a main-sequence star of its measured colour index is supposed⁹ to be — almost twice as bright. So far from being a bit anomalous, that is in fact very satisfactory, because HD 110987 proves to be a double-lined binary system with practically equal components, and so *ought* to be twice as bright as a normal single star of the same colour index or spectral type.

The first effort at measuring the radial velocity of HD 110987 was made by the present writer with the original radial-velocity spectrometer on 1971 February 27 and was none too successful: in the record for that date, instead of a velocity there is a note, “Very uncertain whether I can see the place; possibly $\sim +40$ ”. Several other stars in the North Galactic Pole field also failed to give reasonably measureable traces with the radial-velocity spectrometer, and eventually (1974 March) I managed to arrange that Radford and I should have an observing run on the *Isaac Newton Telescope* (then still at Herstmonceux) on purpose to take classification-dispersion ($60\text{-}\text{\AA} \text{ mm}^{-1}$) spectrograms of the offending stars. Most of them, including HD 110987, proved simply to be misclassified objects of substantially earlier spectral types than those attributed to them by the *HD*. Subsequent efforts to observe the star with the original radial-velocity spectrometer were made in 1980 and 1984, and gave measureable results of $+4.0$ and $+3.1 \text{ km s}^{-1}$; notes against those results say, in the first case, “vfd” [shorthand for ‘very feeble dip’], and in the second case “More like 9^{m} than

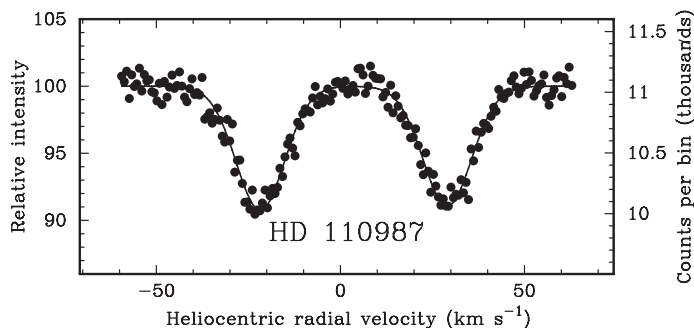


FIG. 2

Radial-velocity trace of HD 110987, obtained with the Cambridge *Coravel* on 2013 May 7 and illustrating the nature of the system, with its equal double lines.

8^m". Both notes were quite true! We can see, in retrospect, that both of those observations were obtained near single-lined phases of the orbit; it is significant that the early spectral type meant that, even when the two 'dips' in the trace were superimposed, their combination was still regarded as "very feeble".

Owing to the difficulty of observation and the apparent agreement of those two measurements (the 1971 effort was too uncertain to be considered significant, although now that the orbit is known it does prove to be somewhere near the truth), no further interest was taken in HD 110987 for a long time, until on 2007 May 6 the star was re-observed at Cambridge with the *Coravel* spectrometer, which was considerably more powerful than the original one, especially in its application to difficult objects. The star was immediately discovered to be double-lined, with sensibly equal components; an observation the very next night showed a significant change, so from then on the object was observed from time to time as opportunity arose. A double-lined trace is reproduced here as Fig. 2; of course when a star of comparatively early type (as F types are regarded in connection with the radial-velocity spectrometer) is observed, the 'dip' in the trace is quite shallow, and when through duplicity of the object observed it is split into two the individual components are inevitably *very* shallow. Even so, the r.m.s. radial-velocity residuals are only 0.7 km s⁻¹ (less than 2% of the velocity amplitudes), so the orbit is quite well determined.

There are now 34 double-lined observations available, which are listed in Table II and define the orbit which is plotted in Fig. 3 and whose elements are included in Table V below. The stellar masses are found to be equal within an uncertainty of less than 1%. The period is only about 5.66 days, and is determined with a standard error of only 12 seconds; its shortness guarantees that the stars are main-sequence objects. We can see now how the two observations that were successfully made with the original spectrometer were actually blends in which the two dips were largely superimposed; they thereby became more measureable than that in the original 1971 observation, which was taken at a double-lined phase, though only one of the dips was recognized then.

The mass functions for both components are small, 0.135 M_{\odot} , whereas the actual masses must be about ten times that quantity. The orbital inclination is thereby estimated with tolerable accuracy as $\arcsin(\sqrt[3]{1/10})$, or nearly 28°.

TABLE II
Radial-velocity observations of HD 110987

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

Date (UT)	MJD	Velocity		Phase	(O - C)	
		Prim. km s ⁻¹	Sec. km s ⁻¹		Prim. km s ⁻¹	Sec. km s ⁻¹
1971 Feb. 27.15*	41009.15	+40.0	—	2336.091	+3.8	—
1980 Jan. 2.23*	44240.23	+4.0	—	1765.225	—	—
1984 Apr. 25.97*	45815.97	+3.1	—	1487.756	—	—
2007 May 6.01	54226.01	-15.2	+24.6	0.335	+0.5	+1.1
7.98	227.98	-11.0	+19.7	.683	+0.8	+0.1
15.02	235.02	+38.4	-32.0	1.928	0.0	-1.1
18.96	238.96	-23.5	+31.0	2.624	0.0	-0.4
23.00	243.00	-16.1	+25.4	3.338	+0.3	+1.2
24.97	244.97	-11.3	+18.9	.686	-0.2	0.0
30.95	250.95	+3.5	—	4.743	—	—
2008 May 19.96	54605.96	-35.2	+42.1	67.496	-0.6	-0.4
20.93	606.93	-14.7	+23.1	.667	+0.5	+0.1
21.94	607.94	+25.6	-17.9	.846	0.0	+0.2
2009 Jan. 21.23	54852.23	+41.2	-35.7	111.027	-0.5	-1.4
Mar. 30.01	920.01	+42.1	-34.8	123.008	-0.1	0.0
2010 May 13.01	55329.01	-8.3	+17.0	195.304	+0.6	+0.3
20.05	336.05	-33.1	+40.2	196.548	-0.3	-0.6
June 3.98	350.98	+18.0	-11.3	199.187	-0.6	-0.3
5.01	352.01	-21.9	+30.5	.370	+0.5	+0.3
2012 Apr. 6.02	56023.02	+42.0	-34.7	317.979	+0.1	-0.2
17.99	034.99	+36.5	-28.3	320.095	+0.8	-0.1
July 24.91	132.91	-27.5	+35.2	337.403	+0.2	-0.4
2013 Mar. 27.06	56378.06	-1.2	+8.8	380.737	-1.8	+1.7
31.10	382.10	-33.0	+40.7	381.451	-0.2	0.0
Apr. 2.09	384.09	+15.5	-8.8	.802	-0.8	-0.1
27.04	409.04	+14.0	-5.7	386.213	+1.2	-0.6
May 7.91	419.91	+29.5	-21.4	388.134	+0.1	+0.5
2014 Feb. 2.25	56690.25	+37.1	-29.2	435.920	-0.4	+0.9
6.19	694.19	-25.2	+33.2	436.616	-0.4	+0.6
26.16	714.16	+27.1	-19.6	440.146	0.0	0.0
Mar. 12.06	728.06	-26.5	+34.7	442.603	+0.3	0.0
23.13	739.13	-32.1	+40.4	444.560	-0.2	+0.6
2015 Apr. 7.04	57119.04	-4.9	+12.2	511.714	-0.1	-0.3
June 10.95	183.95	+17.6	-11.3	523.188	-0.9	-0.4
11.95	184.95	-22.5	+30.1	.364	-1.0	+0.8
July 2.93	205.93	+38.8	-29.1	527.073	+0.5	+1.8
2016 Apr. 17.07	57495.07	+18.8	-11.0	578.182	-1.0	+1.2
July 18.91	587.91	-28.5	+34.5	594.593	-0.2	-1.7

*Observed with original Cambridge spectrometer; not used in orbit

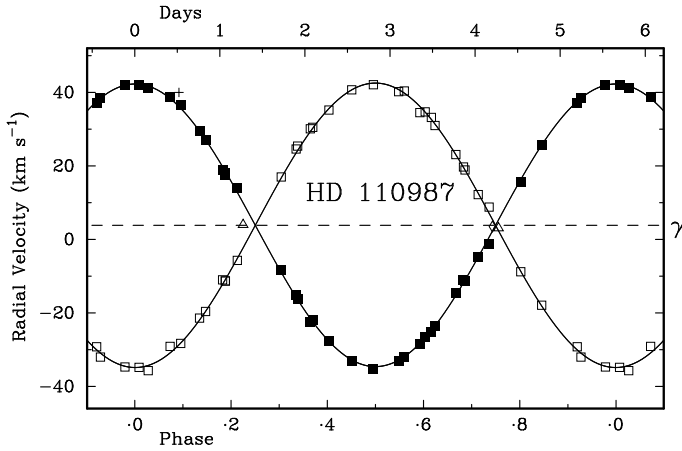


FIG. 3

The observed radial velocities of HD 110987 plotted as a function of phase, with the velocity curve corresponding to the adopted orbital elements drawn through them. Most of the observations were made with the Cambridge *Coravel* and are plotted as squares, filled for the primary and open for the secondary; the velocities of the two components were given equal weight in the solution of the orbit. Just one observation was measured as a single-lined blend (not useable in the solution of the orbit) and is plotted as an open diamond. The three observations that were by far the earliest were made with the original Cambridge spectrometer. Two were taken at times when the system appeared single-lined and are plotted as open triangles. The earliest one of all is shown as a plus; it was a very uncertain measurement (and gives a large residual), and has not been included in the calculation of the orbit.

The projected rotational velocities of the stars are determinable from the individual *Coravel* radial-velocity traces. Of course, when the rotational velocities are small, and/or the ‘dips’ in the traces are shallow (both of which hindrances exist in the present case) the results are none too accurate individually, but the means of a good number of observations may be expected to be tolerably realistic. Of the 34 double-lined traces available for HD 110987, 27 are sufficiently well resolved to permit the estimation of rotational velocities. The mean values are $5.5 \pm 0.6 \text{ km s}^{-1}$ for the component here designated as the primary* and $4.2 \pm 0.7 \text{ km s}^{-1}$ for the other component. Recalling that the Sun rotates with an equatorial velocity of just about 2 km s^{-1} in a period of about 25 days, we could expect HD 110987, if its components rotate in synchronism with the 5.66-day orbital period, to be correspondingly faster, and by a further factor of about 1.2 since F8 stars have radii of about $1.2 R_{\odot}$; thus the equatorial rotational velocities corresponding to synchronism would be about 10.6 km s^{-1} . It is part and parcel of the concept of synchronization of orbital and rotational periods that the rotational axis is perpendicular to the orbital plane, so in this case, where we believe the orbital inclination to be about 28° (as shown above from $\sin i \sim \sqrt[3]{1/10}$, giving $\sin i \sim 0.47$), synchronism would require the observed $v \sin i$ values to be about 0.47×10.6 , or 5.0 km s^{-1} . The values determined for the

*The difference in masses is less than its standard error, so we cannot actually tell which star is the primary.

two components (admittedly not very accurately, owing to the shallow nature of the ‘dips’ in the radial-velocity traces), lie about one standard deviation on either side of that calculated value, so we can well conclude that the system is synchronized.

HD 114604

HD 114604 is an obvious visual double star, with components of about $9\frac{1}{2}$ and $10\frac{1}{2}$ magnitude, to be found about $2^{\circ}.4$ directly following the fifth-magnitude late-type star 37 Com. It was first listed as a double star by Struve in 1830, and features in his great *Mensurae Micrometricae*¹⁰, as Σ 1729, with magnitudes 8.5 and 10.0 and a separation of $8''.05$ at position angle $274^{\circ}.9$; the relative positions have remained sensibly the same ever since. In 1906 Aitken¹¹ found the principal star to be itself a close double, with components that he estimated at $8^m.9$ and $10^m.3$ only $0''.29$ apart. Twelve years later he found that there had been a modest (12°) change in position angle; the star features in the *ADS*¹² as no. 8811, with just those two measurements and Aitken’s estimated magnitudes. Subsequent measurements in 1967 and 1997 make it appear that the close pair has an eccentric orbit with a period of the order of 100 years.

In the course of his interest in the radial velocities of *HD* stars in the NGP field, the present writer observed the apparent primary star of HD 114604* in 1984 with the original radial-velocity spectrometer. He also observed it with the Haute-Provence *Coravel* in 1986, 1987, and 1989. On each occasion he found the radial velocity to be close to zero. A new chapter opened when, 21 years after the previous effort, he observed the star again in 2010 May with the *Coravel* spectrometer at Cambridge. The initial radial-velocity trace exhibited a nasty slope, suggesting that the object might be double-lined. Another observation, taken the very next night, confirmed that that was so: a weak secondary dip had materialized some 30 km s^{-1} away from the usual component whose velocity had always been near zero. The following night the system was single-lined, but the zero-velocity dip was significantly deeper than it was in the SB2 trace; and the night after that the weak secondary had re-appeared, but was then 30 km s^{-1} away on the opposite side from where it had been only two nights previously.

As may be imagined, the object was then attentively followed, and the component that gave the weak dip soon had its orbital period established at close to 3.35 days. All the measurements of HD 114604 are set out in Table III; there are 40 of them, if the three blends are included in the count. The other 37 were obtained at times when the observed trace was sufficiently resolved for velocities to be determined for the components separately. Fig. 4 illustrates a radial-velocity trace taken near a node of the orbit, when the two ‘dips’ are practically separate. The principal dip shows little rotational broadening, but the weak one, whose area has been quantified as being 0.35 of that of the primary† shows significant broadening. The weakness of that dip means that individual estimates of its width are not in very good agreement, and after a time a $v \sin i$ value of 10 km s^{-1} was adopted and was imposed uniformly on the reductions of all the radial-velocity traces. The orbital elements of the binary are included in Table V below, while Fig. 5 illustrates the orbit graphically.

In addition to plotting the velocities given by the weak component seen in the radial-velocity traces, Fig. 5 includes the velocities measured for the primary star.

*He did not see it as double at the eyepiece of the 36-inch Cambridge telescope, which has about the minimum magnification (approximately $\times 120$) to allow light from the whole of the telescope aperture to enter the observer’s eye, and is intended for *finding* objects, not resolving close double stars.

†A quantity that is needed in order to obtain the twin velocities from unresolved blends.

TABLE III
Radial-velocity observations of HD 114604
All the observations were made with the Cambridge Coravel

Date (UT)		MJD	Velocity (km s^{-1})		Phase	(O - C) km s^{-1}
			A	B		
2010 May	17:031	55333.031	-0.9		0.681	—
	18:037	334.037	+0.5	+32.5	.981	+1.5
	19:003	335.003	-1.5		1.271	—
	19:957	335.957	+0.7	-33.9	.556	+1.7
	21:958	337.958	+0.3	+16.0	2.154	-0.3
	22:946	338.946	+0.3	-35.9	.450	+0.1
	23:954	339.954	+0.1		.750	—
	25:979	341.979	+0.5	-23.4	3.356	+1.0
	27:921	343.921	-0.1	+29.1	.936	+0.7
	June	3:994	+0.3	+29.8	6.050	+0.3
		4:960	+0.2	-22.2	.339	-0.7
		11:937	-0.1	-33.6	8.424	+0.2
		16:946	+0.4	+27.4	9.921	+0.3
		21:918	+0.5	-30.6	11.407	+1.4
		22:936	0.0	-12.5	.711	-1.0
		23:947	+0.1	+31.3	12.014	+0.2
2011 May	15:031	55696.031	+0.1	+10.3	109.176	-1.9
2012 Apr.	16:043	56033.043	-0.2	+26.2	209.903	+1.2
	26:019	073.019	-0.5	+14.3*	221.852	-3.0
2013 Apr.	2:076	56384.076	0.0	+10.5	314.821	-1.2
	6:050	388.050	+0.1	+31.2	316.009	+0.1
	7:104	389.104	0.0	-18.0	.324	+0.7
	18:105	400.105	-0.1	-30.7	319.612	-1.2
	21:074	403.074	-0.1	-41.2	320.500	-3.5
	May	1:045	-0.2	-38.7	323.480	-1.3
		8:981	+0.1	+14.8	325.852	-2.5
	June	3:996	+0.1	-27.1	333.627	+0.1
2014 Feb.	6:241	56694.241	-0.1	-36.7	407.525	+0.6
	26:188	714.188	-0.2	-37.3	413.487	+0.3
	Mar.	5:203	-0.2	-31.5	415.583	+1.6
		10:091	+0.1	+29.6	417.044	-0.3
		12:099	+0.4	-23.5	.644	+1.0
	Apr.	16:996	+0.6	-29.9	428.373	-2.5
		27:087	0.0	-29.3	431.389	+0.4
	May	16:020	-0.5	+29.2	437.048	-0.4
	June	13:002	+0.1	-31.2	445.412	+1.3
2015 Apr.	12:041	57124.041	+0.4	+29.5	535.985	-1.5
	June	10:992	+0.4	+25.3	553.903	+0.2
2016 Feb.	16:214	57434.214	+0.9	-14.4	628.691	+1.4
	Apr.	1:070	+0.2	+27.2	642.098	+2.3

*Rejected

It is not surprising that there is a distinct offset between them and the γ -velocity of the companion system, an offset that represents the relative radial velocities of the close visual components in the ~ 100 -year orbit. The system has not been observed for long enough for a systematic long-term variation to have become apparent, either in the velocity of the primary star or in the γ -velocity of the sub-system.

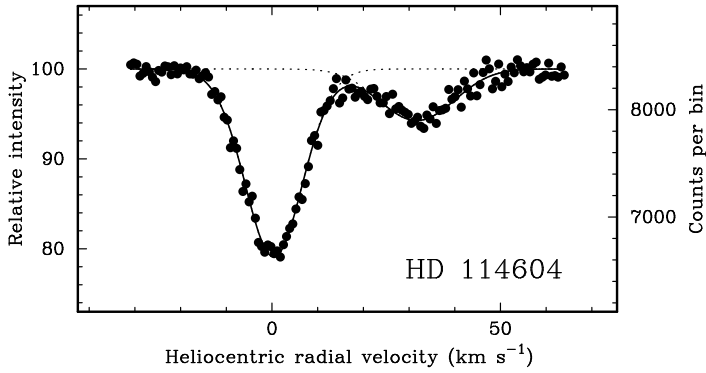


FIG. 4

Radial-velocity trace of HD 114604, obtained with the Cambridge *Coravel* on 2013 April 6 and illustrating the very unequal double lines at practically their maximum separation.

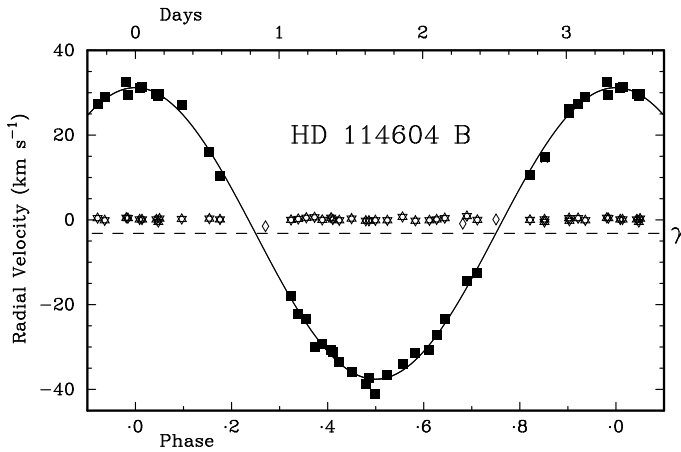


FIG. 5

The observed radial velocities of HD 114604 plotted as a function of phase, with the velocity curve corresponding to the adopted orbital elements drawn through them. The observations of the star that corresponds to the weak 'dip' in the trace shown in Fig. 4 are plotted as filled squares, while those of the principal star (which clearly does not share the orbit) are shown as open stars. Three blends (not used in the solution of the orbit) appear as open diamonds. The discrepancy in velocity between the γ -velocity of the binary sub-system and the quasi-constant velocity of the primary star represents the velocity difference between those components in their long-period (~ 100 -year) mutual orbit. There seems, however, to have been little change during the interval of observation, and nothing else of interest can yet be determined concerning that orbit.

What the writer (reprehensibly enough) did not know while he was busy elucidating the orbit of the secondary star of the close visual binary was that the nature of HD 114604 had already been divined by Mazeh & Latham¹³ and their collaborators¹⁴, and its orbital period and γ -velocity had already been published¹³. Those authors referred to the star exclusively by the name W 11450, deriving from a 1972 paper by Weistrop¹⁵. The writer's ignorance would have been alleviated had there not been an analogous failing on the part of *Simbad*, whose bibliographical listing for HD 114604 retrieves neither Mazeh & Latham nor Weistrop.

The $(B - V)$ colour index found by Yoss & Griffin² for the binary is $0^m.69$, so the primary star must be a little bluer than that and the secondary a good deal redder. The magnitude difference, in the B photometric band that roughly matches the spectral region utilized by the *Coravel*, must be considerably greater than the $1^m.14$ that corresponds to the relative dip areas, because the secondary star, being cooler and matching the (K2-inspired) mask in the *Coravel* instrument better than the primary, will give a better dip in relation to its brightness. Just from those photometric considerations, we might estimate that the primary star is of early-G type and the secondary early K. Using absolute magnitudes and colour indices from AQ^9 , we find that a combination of G2 + K0 main-sequence stars produces the correct colour index, and the difference in B magnitudes is $1^m.46$, suitably greater than the ratio of dip areas in radial-velocity traces.

HD 114882

This star is unusually faint for a northern-hemisphere *HD* star, being listed as $9^m.7$ in the *HD* and measured at $V = 9^m.80$ (and $(B - V) = 0^m.67$) by Yoss & Griffin². It is too faint to be plotted on the *Uranometria 2000.0* chart, but is to be found 4.3 south-following HD 114841, a 9^m F8 star that is plotted there at epoch-2000 position $13^h 13^m 06^s$, $+16^\circ 24' 55''$. The *Simbad* bibliography of HD 114882 consists solely of the paper² to which reference has just been made above.

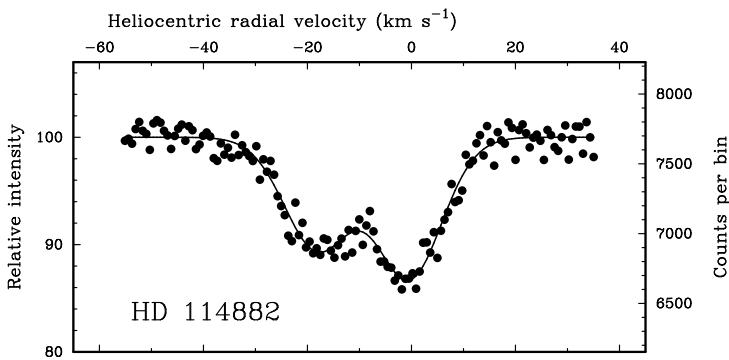


FIG. 6

Radial-velocity trace of HD 114882, obtained with the Cambridge *Coravel* on 2014 May 26 and illustrating the double lines at practically their maximum separation.

TABLE IV
Radial-velocity observations of HD 114882

Except as noted, the sources of the observations are as follows:
1987–1998 — OHP Coravel (wt. ¼); 2000–2016 — Cambridge Coravel (wt. 1)

Date (UT)	MJD	Velocity		Phase	(O – C)	
		Prim. km s ⁻¹	Sec. km s ⁻¹		Prim. km s ⁻¹	Sec. km s ⁻¹
1984 May 13·95*	45833·95	–7·0		0·789	—	—
1987 Mar. 4·12	46858·12	–1·1	–14·7	0·899	–0·2	–1·0
1988 Jan. 31·55†	47191·55	+0·4	–16·2	0·935	–0·2	–0·8
Mar. 12·08	232·08	–1·7	–17·0	·939	–2·4	–1·5
17·02	237·02	+0·8	–15·3	·940	0·0	+0·3
1989 Feb. 23·28‡	47580·28	+0·9	–16·8	0·977	–0·4	–0·7
Mar. 25·97	610·97	+1·8	–15·4	·980	+0·6	+0·7
31·04	616·04	+0·9	–16·7	·981	–0·3	–0·7
Apr. 29·02	645·02	+1·1	–17·2	·984	0·0	–1·2
May 2·98	648·98	+1·9	–14·4	·984	+0·8	+1·6
1990 Jan. 31·17	47922·17	–1·6	–16·9	1·014	–1·5	–2·3
Feb. 12·37‡	934·37	–1·5	–14·5	·015	–1·3	0·0
1991 Jan. 30·11	48286·11	–3·0	–12·1	1·053	0·0	–0·7
1992 Jan. 18·19	48639·19	–7·1		1·091	—	—
Apr. 27·11	739·11	–6·3		·102	—	—
1993 Feb. 14·16	49032·16	–7·4		1·133	—	—
1994 Feb. 21·13	49404·13	–7·1		1·173	—	—
May 1·06	473·06	–7·1		·181	—	—
1995 Jan. 8·21	49725·21	–7·0		1·208	—	—
June 6·97	874·97	–7·3		·224	—	—
1996 Apr. 1·07	50174·07	–7·6		1·256	—	—
1997 Mar. 6·19 [§]	50513·19	–11·0	–2·0	1·293	–0·1	+0·9
May 10·03 [§]	578·03	–11·5	–2·8	·300	–0·6	0·0
1998 May 2·06	50935·06	–7·5		1·338	—	—
July 24·90	51018·90	–7·7		·348	—	—
2000 Apr. 7·08	51641·08	–11·2	–3·1	1·415	–0·3	–0·2
2002 Mar. 2·16	52335·16	–7·9		1·489	—	—
May 30·95	424·95	–9·4	–3·7	·499	+0·9	–0·2
2003 Feb. 21·13	52691·13	–10·2	–3·8	1·528	–0·1	–0·1
July 12·91	832·91	–9·8	–4·6	·543	+0·1	–0·7
2004 Apr. 16·99	53111·99	–10·0	–3·2	1·573	–0·4	+1·1
May 24·97	149·97	–10·7	–3·9	·577	–1·2	+0·4
2005 Jan. 13·23	53383·23	–8·8	–4·8	1·602	+0·4	–0·1
Apr. 19·07	479·07	–8·9	–3·7	·613	+0·2	+1·1
2006 Mar. 23·09	53817·09	–7·7		1·649	—	—
June 27·94	913·94	–6·8		·660	—	—

TABLE IV (concluded)

Date (UT)		MJD	Velocity		Phase	(O-C)	
			Prim. km s ⁻¹	Sec. km s ⁻¹		Prim. km s ⁻¹	Sec. km s ⁻¹
2007 Mar.	2:15	54161.15		-7.2	1.686	—	—
	May 8:00	228.00		-7.6	.693	—	—
2009 Mar.	27:14	54917.14		-6.8	1.768	—	—
	May 28:94	979.94		-7.0	.774	—	—
2010 Apr.	9:02	55295.02		-6.7	1.808	—	—
2012 Apr.	11:05	56028.05	-1.9	-14.4	1.887	-0.4	-1.3
	May 12:99	059.99	-0.8	-13.4	.891	+0.5	-0.1
	June 15:97	093.97	-1.3	-12.6	.895	-0.2	+0.9
2013 Mar.	14:14	56365.14	-0.7	-15.2	1.924	-0.9	-0.3
	Apr. 6:08	388.08	+0.1	-14.9	.926	-0.2	+0.1
	18:09	400.09	0.0	-14.6	.928	-0.3	+0.5
	June 6:97	449.97	+0.5	-14.4	.933	0.0	+0.9
	July 6:93	479.93	+1.2	-14.6	.936	+0.6	+0.8
2014 Jan.	13:28	56670.28	+1.1	-15.9	1.957	-0.1	+0.1
	Mar. 10:13	726.13	+1.6	-16.2	.963	+0.3	-0.1
	May 26:02	803.02	+1.1	-16.6	.971	-0.2	-0.5
	June 30:94	838.94	+2.5	-16.1	.975	+1.2	0.0
2015 Jan.	17:24	57039.24	+1.2	-15.0	1.996	+0.4	+0.6
	23:26	045.26	+1.1	-14.9	.997	+0.4	+0.6
	Apr. 12:08	124.08	+0.4	-14.9	2.006	+0.1	+0.2
2016 Feb.	19:19	57437.19	-2.6	-12.3	2.039	-0.6	+0.3

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

The writer's first radial-velocity observation of HD 114882 was made with the original Cambridge spectrometer in 1984 and appeared just like that of a normal single-lined object of a spectral type too early to give a good deep dip in the trace. The next observation was made in 1987, with the Haute-Provence *Coravel*, when the trace was seen to consist of a pair of almost equal, overlapping, dips. That has proved to be the normal situation with HD 114882. The star has continued under observation, and has exhibited a leisurely orbit with a period of some 25 years. The components are nearly equal, and their radial velocities never differ by more than about 17 km s⁻¹, so even at best there is substantial mutual blending. A trace taken with the Cambridge *Coravel* near the better-resolved node in the eccentric orbit appears here as Fig. 6. That phase has been observed twice, first in 1989 and then again recently in 2014/15. Altogether 57 observations have been accumulated on the binary, of which 19 are so closely blended that they have been reduced as single-lined; they are all set out in Table IV. Of the resolved traces, 26 have been made with the Cambridge *Coravel*, nine at Haute-Provence, two at ESO, and one at the DAO; all have been made by the writer. The small disparity in the dip signatures of the two components has warranted, in the solution of the orbit, a weighting of ¾ for the secondary's velocities in comparison with those of the primary. The orbital elements appear in the final column of Table V, and the orbit is illustrated by Fig. 7.

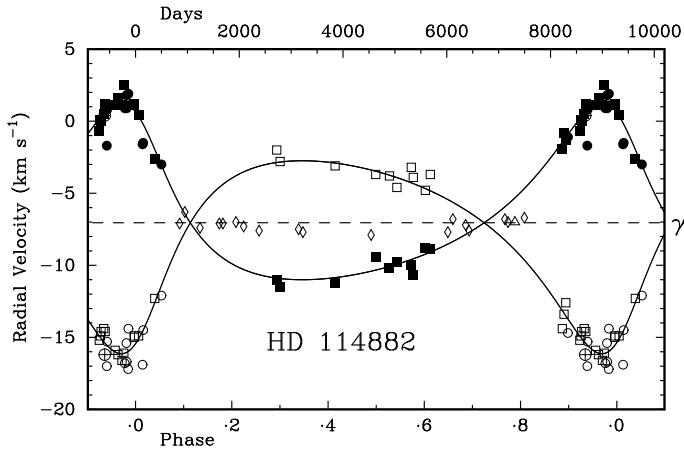


FIG. 7

The observed radial velocities of HD 114882 plotted as a function of phase, with the velocity curve corresponding to the adopted orbital elements drawn through them. The same plotting conventions are used as in Fig. 3, but here there are also measurements made with the OHP *Coravel* and plotted with filled and open circles (one ESO observation is plotted as if it were an ‘honorary OHP’ one). There is in addition one pair of measurements obtained with the DAO spectrometer and plotted as open circles with plusses in them.

TABLE V

Orbital elements for HD 102687, HD 110987, HD 114604, and HD 114882

Element	HD 102687	HD 110987	HD 114604 B	HD 114882
P (days)	127.613 ± 0.018	5.657312 ± 0.000014	3.345781 ± 0.000029	9278 ± 52
T or T_0 (MJD)	55737.82 ± 0.36	55819.4764 ± 0.0029	56180.581 ± 0.006	57073 ± 60
γ (km s ⁻¹)	$+12.90 \pm 0.09$	$+3.85 \pm 0.09$	-3.24 ± 0.24	-7.05 ± 0.09
K_1 (km s ⁻¹)	13.11 ± 0.13	38.44 ± 0.18	34.44 ± 0.29	6.15 ± 0.12
K_2 (km s ⁻¹)	—	38.69 ± 0.26	—	6.70 ± 0.14
e	0.408 ± 0.008	0	0	0.401 ± 0.017
ω (degrees)	210.2 ± 1.4	—	—	27 ± 4
$a_1 \sin i$ (Gm)	21.00 ± 0.22	2.990 ± 0.014	1.585 ± 0.013	718 ± 16
$a_2 \sin i$ (Gm)	—	3.010 ± 0.020	—	783 ± 18
$f(m)$ (M_\odot)	0.0227 ± 0.0007	—	0.0142 ± 0.0004	—
$m_1 \sin^3 i$ (M_\odot)	—	0.1352 ± 0.0021	—	0.82 ± 0.05
$m_2 \sin^3 i$ (M_\odot)	—	0.1344 ± 0.0017	—	0.75 ± 0.04
R.m.s. residual (wt. 1) (km s ⁻¹)	0.39	0.69	1.31	0.51

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CORRESPONDENCE

To the Editors of 'The Observatory'

GAIA SHOWS THAT MESSIER 40 IS DEFINITELY NOT A BINARY STAR

Messier 40 has always been something of an oddity in the Messier Catalogue, since it is just a pair of stars rather than a nebulous object¹. It seems to have ended up in the list because Charles Messier was following up on an observation by Hevelius² of a nebulous binary star in its vicinity. Although Messier identified no nebulosity (and, in fact, had found a different pair of stars from those seen by Hevelius), he added the pairing to his catalogue for completeness. Surprisingly, the identification was then lost until 1966, when the pair of stars were noted as almost certainly HD 238107 and HD 238108³.

Little was known about that pair of stars, but a thorough analysis in 2002 noted that the proper motions derived from the *Tycho-2 Catalogue* and earlier observations indicated that those stars were likely to be unrelated objects passing one another on the sky⁴. Support for that interpretation came from the spectroscopic parallaxes estimated for those objects of 590 ± 230 pc and 170 ± 70 pc, respectively⁴. However, the error bars were uncomfortably large, and the distances sufficiently great that *Hipparcos* data placed no significant constraint on their astrometric parallax distances, so the possibility still remained that the stars could form a wide physical binary⁴.

The first data release from the *Gaia* satellite⁵ definitively puts paid to that interpretation. The combined *Hipparcos/Gaia* astrometric solution gives parallaxes of 2.87 ± 0.24 milliarcseconds and 7.13 ± 0.24 milliarcseconds, translating to distance estimates of 350 ± 30 pc and 140 ± 5 pc for the two objects. Messier 40 consists of a pair of entirely unrelated stars.

Yours faithfully,
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2016 October 3

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REVIEWS

Surveying the Skies: How Astronomers Map the Universe, by G. Wynn-Williams (Springer, Heidelberg), 2016. Pp. 187, 23.5 × 15.5 cm. Price £19.99/\$34.99 (paperback; ISBN 978 3 319 28508 5).

This book is all about the history of sky surveys. It begins with the cuneiform tablets made by temple scribes in Babylonia and ends with crowd-sourced big data in the cloud. That's quite a voyage: the narrative uses two dimensions, time and wavelength, to organize the itinerary in an accessible manner. On the time axis the ports of call are: the naked-eye era from prehistory until the 17th Century; the telescope era from Galileo to the introduction of photography; then the photographic era from around 1880; that is followed by the electromagnetic era, from the end of World War II to the space age; and finally Wynn-Williams introduces the CCD era in which telescopes have come back to ground and yet are discovering sources in the billions thanks to digital technology. On the wavelength axis, the author starts where his own career began, radio surveys, and by turns we encounter infrared, the cosmic microwave background, ultraviolet, and X-ray surveys, then concluding on a gamma-ray high.

This book is published in Springer's *Astronomers' Universe* series, which delivers an armchair experience to active amateur astronomers. Fair enough. However, it is suitable, and deserves a much wider readership, because it is such a handy history of how the heavens have been harvested. The story of invention in instrumentation, the influence of innovation, is compelling. As an historian of astronomy, I will be using the review copy as a *vade mecum* for following the various time-lines involved in opening up the invisible universe, as well as a quick look-up for all of the acronyms: 2MASS, *Pan-STARRS*, SDSS, *Uhuru*, and so forth. There are 11 Appendices, along with a brief introduction on how to access astronomy surveys. It is a good introduction for graduates who are considering doctoral research in observational astronomy, and an essential reference book for libraries. — SIMON MITTON.

Cartography of the Sun and the Stars, edited by J.-P. Rozelot & C. Neiner (Springer, Heidelberg), 2016. Pp. 206, 23.5 × 15.5 cm. Price £40.99/\$59.99 (paperback; ISBN 978 3 319 24149 4).

The word “cartography” in the title of this book is a bit hyperbolic when applied to stars other than the Sun, and yet the prospects for mapping the surfaces of stars have never been more promising. Advances in observational techniques and instruments along with new algorithms for processing their data have already produced a modest collection of resolved photospheres of rapid rotators that show oblateness and the resulting gravity darkening. Images of the close binaries β Lyrae and Algol not only dramatically show their orbital motions but also resolve the Roche-Lobe-filling components. Most recently, spotted stars are being mapped to explore the nature of the features that punctuate their surfaces as a result of sub-surface physics. These results are attributable to the handful of interferometers developed over the last few decades, culminating in the south with the *VLT Interferometer* and in the north with the *CHARA Array*. Not only do these instruments complement one another geographically, they also separately capitalize on sensitivity and resolution. Significantly, interferometers are few and far between, but they have succeeded in attracting a new generation of bright young scientists with great ideas for exploiting the inherent capabilities of those facilities.

This book originated with a workshop held at l’Observatoire de Besançon, France, in 2014 May, following which a subset of presenters prepared review articles. US participation was modest, so there is a resulting Eurocentric tilt to the book. This volume of Springer’s *Lecture Notes in Physics* begins with an overview of image reconstruction (C. Theys & C. Aime) and then continues with three solar-imaging chapters on sub-surface imaging by local helioseismology (A. G. Kosovichev & J. Zhao), space-borne photometric imaging of spots (A. F. Lanza), and helioseismic imaging of sub-surface thermal and magnetic-field structures (K. M. Hiremath). The next four chapters discuss the physics of rotation with surface manifestations (M. Rieutord), interferometric imaging of the rapid rotator Achernar (separate chapters by P. Kervella and A. Domiciano de Souza), and imaging of starspots (G. Perrin). The final chapter considers stellar Doppler and Zeeman–Doppler imaging (O. Kochukhov).

The book’s strengths are in the juxtaposition of stellar and solar imaging and the quality of its nine chapters. Its primary weakness devolves from the near absence of the contributions from US interferometry. *Cartography of the Sun and the Stars* is a fine resource for graduate students and postdocs or for anyone interested in this important developing field for which the best is yet to come.
— HAROLD A. MCALISTER.

Ground-Based Solar Observations in the Space Instrumentation Era (ASP Conference Series, Vol. 504), edited by I. Dorotović, C.E. Fischer & M. Temmer (Astronomical Society of the Pacific, San Francisco), 2016. Pp. 341, 23.5 × 15.5 cm. Price \$88 (about £58) (hardbound; ISBN 978 1 58381 892 3).

This volume contains the Proceedings of a conference held in 2015 October in Coimbra (Portugal), on the west coast of the Iberian Peninsula, which is a place with a long tradition in astronomy and, in particular, solar observations. In fact, the meeting was organized around the 90th anniversary of the performance of the first spectroheliographic observations in Coimbra by Prof. Francisco Costa

Lobo (1864–1945) and the 150th anniversary of the creation of the Geophysical Institute of the University of Coimbra.

This book covers several aspects of solar physics since it is based on observations carried out over the entire electromagnetic spectrum from ground and space. Interesting contributions on instrumentation, solar observing and image-processing techniques, theory and modelling, existing facilities and future perspectives in the field of solar observation appear in this volume, as well as a part devoted to long-term variations of the Sun.

I particularly enjoyed some chapters of this book. For example, A. A. Pevtsov wrote an interesting chapter on the need for synoptic solar observations from the ground in our space-instrumentation era. L. Bertello *et al.* review the long-term synoptic observations of Ca II K and magnetic flux. A. M. Veroning and W. Pötzi briefly review the ground-based observations of the solar sources of space weather and present as an example the system of real-time detection of H α flares and filaments established at Kanzelhöhe Observatory.

In conclusion, I think that this book provides a useful summary of the current research in an important field of knowledge and I recommend it to researchers interested in ground and space solar observations. — JOSÉ M. VAQUERO.

The Solar System in Close-Up, by J. Wilkinson (Springer, Heidelberg), 2016.

Pp. 291, 23.5 × 15.5 cm. Price £19.99/\$34.99 (paperback; ISBN 978 3 319 27627 4).

I regret that I cannot really recommend this book. It is a poorly written collection of sometimes ill-chosen information, which the author occasionally seems to have misunderstood.

The cover blurb promises a “complete guide” for amateur astronomers, students, science educators, and interested members of the public. Sadly, all of those would be misled by incorrect information that keeps cropping up. The drawings of ellipses to illustrate differing eccentricity (Fig. 1.5) show their foci displaced much too far from the centre, and the orbit of Eris in Fig. 13.8 is drawn so badly that the Sun is not on the major axis of the ellipse and so cannot be at one of the foci. Eccentricity is defined as “a measure of how far an orbit deviates from circularity”. That is correct, but an equation defining it in relation to the major and minor axes would have helped. We are, however, given an equation to quantify the property of clearing an orbital neighbourhood, which is a crucial aspect in the 2006 IAU definition of planethood. We are told (p. 7) that to be able to clear its neighbourhood, λ must be greater than 1, where $\lambda = kM^2T^{-3/2}$, where M is the body’s mass, T is its orbital period round the Sun, and $k = 0.0043$. This was new to me (it is known as the Stern–Levison parameter) and my first reaction was that it was useful, until I realized that k cannot be dimensionless as its quoted value implies, and that the whole thing is meaningless without being told what units are to be used for M and T (kg or Earth-masses? Seconds or years?). Furthermore, this seems to be the wrong equation: $T^{-3/2}$ should be replaced by $a^{-3/2}$ (where a is the orbital semimajor axis) or just T .

Misleading expressions abound. *Spitzer* is described as a “space probe” so a novice reader will attribute its ‘discovery’ of Makemake (which is incorrect anyway) to a flyby, whereas in fact *Spitzer* is an infrared telescope orbiting the Earth. Readers are twice (p. 69, p. 74) erroneously told that Mercury has a “far side”; this makes Mercury sound like the Moon, which does genuinely keep one face permanently turned away from the Earth. The cut-away view of Mercury’s interior in Fig. 4.4 shows the crust and a hypothetical layer of FeS

surrounding the liquid outer core, both far too thick, and omits the intervening mantle completely. The crustal thicknesses of Venus and Mars in the equivalent diagrams (Figs. 5.4 and 7.6) are similarly exaggerated, though at least their mantles are distinguished. Wilkinson gets the crust about right for the Earth (Fig. 6.2), but then shoots himself in the foot on p. 109 by telling his unfortunate readers that the Earth's tectonic plates are made of crust that moves around on top of the mantle (in fact the crust is only the top part of each plate, most of which is rigid mantle, the two forming the lithospheric plates that slide over the weaker part of the deeper mantle). — DAVID ROTHERY.

Dawn of Small Worlds: Dwarf Planets, Asteroids, Comets, by M. Moltenbrey (Springer, Heidelberg), 2016. Pp. 273, 23.5 × 15.5 cm. Price £23.99/\$31.99 (paperback; ISBN 978 3 319 23002 3).

In 2006, the IAU reclassified lesser bodies in our Solar System. For some, the change was a dramatic shift given their perspective of Pluto being demoted to the status of 'dwarf planet'. For others, it served to highlight the importance of the newly introduced class of 'small Solar System body' or SSSB, which encompasses both comets and asteroids. A decade on, much more has now been discovered about the variety of SSSBs out there, and several space probes have visited some of those objects: notably *Dawn* to the asteroids Vesta and Ceres, *Rosetta* to Comet 67P/Churyumov–Gerasimenko, and *New Horizons* to Pluto. It is timely therefore that a book be written in which those types of object are described and their place alongside the planets put into context.

Springer's *Astronomers' Universe Series* now comprises some 57 volumes in all, written in a style aimed primarily at active amateur astronomers, whilst also appealing to a wider readership of astronomically-informed readers one might term 'armchair astronomers'. This volume addresses the topic of small worlds in our Solar System with separate chapters on: 'Asteroids'; 'Comets'; 'Trans-Neptunian Objects (TNOs)'; and 'Dwarf Planets'; before rounding off with an account of the 'Exploration of Small Solar System Bodies'.

Following a short introductory chapter, pages 17–71 cover the discovery of asteroids and have separate sections on Near-Earth Asteroids, Trojan objects in gravitational resonance with various planets, and Centaurs. The chapter ends with more detailed accounts of the objects Vesta, (2060) Chiron, and Chariklo. A further 68 pages are dedicated to Chapter 3 on Comets, with the latter half comprising descriptions of comets Halley, Encke, the collision of Shoemaker–Levy 9 (SL9) with Jupiter in 1994, Hyakutake, Hale–Bopp, and the close encounter of Siding Spring with Mars in 2014. Pages 141–173 deal with TNOs and two specific examples by way of Sedna and Orcus. An account of each of the four dwarf planets is presented in Chapter 5, including preliminary results on Ceres from the *Dawn* spacecraft, although the text predates the 2015 July fly-by of Pluto by *New Horizons* and so the book contains none of its new findings but does include details of the mission in the final chapter dealing with exploration. Given limited space, the book has a necessarily light-touch approach but this reviewer would like to have seen more emphasis on observational studies of asteroids and comets (*e.g.*, with more information about their spectral properties, and by way of an appendix or two) since amateur astronomers are amongst the target readership.

Michael Moltenbrey works in Scientific Computing at the Technical University, Munich, and appears to have a limited command of written English given the poor standard manifested in the text (unless it was translated by someone else). There is little evidence that the manuscript has been properly

proof-read or edited and it is primarily in this aspect that the book falls short of its objectives. The book is peppered throughout with grammatical errors, and many expressions appear to have been directly translated word for word from the German, making much of it heavy going for the reader. Incorrect prepositions, tenses, swapping of adverbs and adjectives, poor use of punctuation, and misspelling do not help either. Spell checking would have missed the use of incorrect words (*e.g.*, ‘conduction’ for ‘conjunction’, ‘commentary’ for ‘cometary’, *etc.*). Sentence construction tends to be clumsy in places with some lacking the verb, and much repetition where a well-chosen pronoun would have done the job. Indeed, the text looks to be tautological at several levels, and several cases were spotted in different parts of the book where blocks of text are repeated almost word for word. Similar, or the same, concepts are repeated in different sections, which affects readability, as does inconsistent terminology (*e.g.*, with dates switching format on the same page, for instance between ‘July 17’ and ‘17.7’), and the rounding of numbers is variable. In some parts (*e.g.*, the collisions of the various SL9 fragments with Jupiter, or the different families of asteroids in the Main Belt), the author attempts to describe something entirely in words that would have been better represented in tabular form, thereby making it rather tedious to read.

Scientific accuracy appears to be rather patchy, with much of the content having been extracted from *Wikipedia*, re-worded in part, and occasionally misinterpreted somewhat. For instance, the author falls into the trap of thinking that asteroid (2309) Mr. Spock is named directly after the character from *Star Trek*, whereas it was named after the discoverer’s, Jim Gibson’s, cat! But there are many other inaccuracies which mislead the reader, such as the different physical data quoted in different sections (*e.g.*, the table on p. 78 gives incorrect data for the size of the nucleus of comets 1P/Halley and 9P/Tempel, the correct ones appearing later on p. 113 and p. 261, respectively). It would have been good practice if the author had used a single source for physical data of minor bodies, such as the *JPL HORIZONS* website. On p. 91 the erroneous statement is made that “dust tails usually do not follow the comet’s orbit as *e.g.* the gas tails do”. Bizarrely, the incorrect term, ‘burst’, is used many times in place of ‘outburst’ when discussing active comets. Also, Halley-type comets are twice described as having orbital inclinations of up to 90°, even though Halley’s orbit has an inclination of 162°, *i.e.*, exhibits retrograde motion.

The publisher on its website affirms the need that these *Astronomers’ Universe* series have to be carefully written, structured, and edited given that they are aimed at scientifically-aware readers. Somehow, this particular book seems to have fallen through their net and this reviewer strongly recommends that a new edition be issued in which *Rosetta*, *Dawn*, and *New Horizons* findings can be brought up to date, whilst at the same time correcting the book’s many shortcomings. — RICHARD MILES.

Uncharted Constellations, by J. C. Barentine (Springer, Heidelberg), 2016. Pp. 222, 23.5 × 15.5 cm. Price £22.99/\$39.99 (paperback; ISBN 978 3 319 27618 2).

Last year I reviewed a book by the same author called *The Lost Constellations* (136, 144) which told the stories of nearly 30 constellations that for one reason or another never made it to the IAU’s canonical list of 88. Barentine’s sequel amounts to a mopping-up operation of figures even more obscure than those in the first volume, many of them mere asterisms rather than fully-fledged

constellations. Hence this follow-up is likely to appeal only to historians of the night sky and the compilers of astronomy-trivia quizzes.

The only figure that most are likely to have heard of is Caput Medusae, the head of Medusa the Gorgon. She stares balefully from the book's cover, held in the hand of Perseus who decapitated her. Ptolemy in the *Almagest* itemized four stars in Perseus as comprising the Gorgon's head, so it was understandable that a number of celestial cartographers in the 17th and 18th Centuries depicted the head as a sub-constellation within Perseus. Some even ventured to give it independent status, but to no lasting effect.

Several of Barentine's chapters deal with what he terms 'single-source' constellations, meaning those proposed by individual authors and ignored by all others, such as Leo Palatinus (the Palatine lion), Marmor Sculptile (the bust of Christopher Columbus), and Sciurus Volans (the flying squirrel).

A couple of others — Corona Firmiana (the Firmian Crown) and Sceptrum et Manus Iustitiae (the Sceptre and Hand of Justice) — he describes as 'rebrands', since they reworked the stars of existing constellations. Seen from this remove, their ridiculous pomposity is all too apparent. Francis Baily of the RAS needed no persuading of their unsuitability and left them all out of his influential *British Association Catalogue* of 1845 (the forerunner of the Yale *Bright Star Catalogue*), thereby ensuring their extinction.

Barentine ends with two Appendices, one discussing some unusual asterisms to be found on the star charts of the 16th-Century German astronomer Peter Apian, and a second on 15 constellations representing various unappealing creatures that were invented in the 1750s by the English naturalist John Hill, a noted provocateur and scourge of the Royal Society. Hill's figures, which included a leech, a worm, and a slug, were probably not meant seriously. No doubt he would be amused to find them still being discussed. — IAN RIDPATH.

Copernicus: A Very Short Introduction, by Owen Gingerich (Oxford University Press), 2016. Pp. 98, 17.5 × 11 cm. Price £7.99/\$11.95 (paperback; ISBN 978 0 19 933096 6).

Nicolas Copernicus (1473–1543) was one of those intriguing historical characters whom, if they had not existed, it would have been necessary to invent. He lived at a time when astronomy was about to be dragged kicking and screaming into the Renaissance. The planets were a mess, and planet Earth (earth also being the heaviest of the five elements, with water, air, fire, and aether) was stuck centrally, solid and stationary in the cosmic epicentre. Predicting future planetary positions, the mainstay of astrology at the time, was mathematically complicated and also inaccurate. For the previous 1300 years Ptolemy had ruled and it was time for a serious upgrade.

Copernicus' move from geocentrism to heliocentrism not only explained logically the retrograde motion of the outer planets, but also produced a revealing physical model of the whole Solar System. Copernicus was not only a celibate canon lawyer, medic, classicist, economist, and diplomat; he also had a passion for astronomy coupled, thankfully, with inventiveness, great mathematical competence, money, and time at work to do something useful.

The author of the book under review, Owen Gingerich, an emeritus professor specializing in the history of astronomy at Harvard University, has not only a profound knowledge of the life and times of Copernicus, he also has studied nearly every extant copy of Copernicus' masterpiece *De Revolutionibus Orbium Coelestium* (On the Revolutions of the Celestial Spheres). He has also specifically

investigated the way this revolutionary tome was accepted and appreciated by the astronomical community in the century following its publication in 1543.

This short book is a clear, erudite, and thought-provoking introduction to the astronomy and the life of Copernicus and the effect that Copernicus' work had on the following generations. It also provides a refreshingly understandable introduction to the mathematics and observational basis behind the Copernican approach to planetary-position prediction in a Sun-centred system. Gingerich puts Arthur Koestler in his place, explains in detail the attribution of the Osiander preface, describes the DNA evidence that led to the correct identification of the bones of Copernicus in Frauenburg Cathedral, and leaves the reader wanting more. Gingerich is clearly a great fan of Copernicus and this superb little book will make you a fan too. — DAVID W. HUGHES.

50 Astronomy Ideas You Really Need to Know, by Giles Sparrow (Quercus, London), 2016. Pp. 208, 20.5 × 17.5 cm. Price £11.99 (hardbound; ISBN 978 1 784296100).

One shouldn't judge a book by its cover or, as in this case, its title. One might be forgiven for thinking that this is merely a collection of recycled factoids of little use for anything but a pub quiz, but, far from it, this is a truly excellent introduction to astronomy. It covers about the same material as an undergraduate astronomy text, and despite the lack of equations nothing is dumbed down. Giles Sparrow, with degrees in astronomy (University College London) and science communication (Imperial College) and the author of about 30 books on astronomy, is more than sufficiently qualified to write such a book. (Not surprisingly, this is one in a series of similarly named books. The fact that three others in the series are written by Joanne Baker — whom I remember from cosmology conferences in the 1990s and who is now a senior editor at *Nature* — is evidence that not just this book but perhaps the whole series is of high quality.)

The chapters (of four pages each), after two introductory ones on our place in the Universe and telescopes, are divided into four parts (though not indicated as such): the Solar System (11 chapters), stars (20), galaxies (including the Milky Way) (5), and cosmology (12). Each consists of an abstract, a timeline, a quotation, the main text (divided into sections), a pithy one-sentence summary, and either a figure and a box of additional text (sometimes containing a figure) or two such boxes (apart from Chapter 6 with just one box — perhaps to confuse pedantic reviewers). A glossary and small-print index of two pages each round out the book. One might be surprised that such a general popular-astronomy book contains relatively little material on galaxies, but perhaps this is to avoid too much overlap with the *Universe* book by Joanne Baker (also author of the *Physics* and *Quantum Physics* members of the series). Despite the cut-and-dried format, the book is a coherent whole, with many references to other chapters or pages in the book.

Apart from my pet peeves of missing hyphens in two-word adjectives and misplaced “only”s¹, both of which abound, the text is fine, with essentially no typos. Somewhat confusing is that Samuel Heinrich Schwabe is referred to as “Samuel” in the timeline and “Heinrich” in the main text. Potentially more dangerous is the figure in Chapter 50 showing different possibilities for the expansion history of the Universe. Although probably meant only qualitatively, the reader could get the impression that the acceleration due to

the cosmological constant is kicking in just now, though in reality our Universe has been accelerating for about 5 billion years, more than a third of its present age. But these are mere details. My only real complaint concerns the legibility of the boxes and figures. The former are difficult to read with black text on a grey background, and most of the latter seem to be black-and-white versions of colour figures. These days, high-quality colour figures can be produced on normal paper (and thus within the main text), rather than on slick 'plates', resulting in only a marginal increase in the price of the book. Since this series of books appears to be doing well, hopefully this improvement will be considered for future editions.

The text is up to date, mentioning pebble accretion, the multiverse, the Nice model, ice giants, quark stars, and exoplanets. Subtle points often glossed over in works at a similar level, such as the difference between the Hubble sphere and the particle horizon (though neither term appears in the book), branes and higher dimensions, and possible instability of the vacuum, are explained clearly and correctly. Good popular-science books need to be clear without dumbing down while still providing enough detail to be more than just a superficial description. This book excels on both counts, and is an excellent introduction for those wanting a good but non-mathematical introduction to all of astronomy. — PHILLIP HELBIG.

Reference

- (1) L. Baldwin, *The Observatory*, **136**, 194, 2016.

Lettres à Franz Xavier von Zach (1792–1804) — Lalandiana III, by Jérôme Lalande. Texts edited, annotated, and commented by Simone Dumont and Jean-Claude Pecker (Eds. Observatoire de Paris & Vrin, Paris), 2016. Pp. 278, 13.5 × 20.5 cm. Price €27 (about £24) (paperback; ISBN Paris Obs.: 978 2 901057 71 0, ISBN Vrin: 978 2 7116 2666 3).

This book is the continuation of three volumes reviewed earlier in these pages: first (**129**, 35 & 288, 2009) *Un astronome des lumières — Jérôme Lalande*, by Simone Dumont (Vuibert, 2007), and *Lettres à Madame du Pierry et au Juge Honoré Flaugergues — Lalandiana I* (Vrin, 2007), followed by (**134**, 288, 2014) *Mission à Berlin — Lettres à Jean III Bernoulli et à Elert Bode — Lalandiana II* (Vrin, 2014).

The current volume has been conceived in the same spirit as the two earlier ones and gathers together the letters sent — between 1792 and 1804 — by Joseph Jérôme Lefrançois de Lalande (1732–1807) to Franz Xaver¹ von Zach. Considered by some as Hungarian, by others as Austro-German, von Zach was born in 1754 in Pest (nowadays a component of Budapest) and passed away in 1832 in Paris. His activities covered mainly astronomy, but also mathematics, geodesy, physics, and history of sciences. He served in the Austrian army and taught at the University of Lemberg (today Lviv in Ukraine).

He lived in Paris (1780–83) and London (1783–86) — where he was in touch with astronomers such as Lalande, Laplace, and Herschel — before being appointed by Ernest II, Duke of Saxe-Gotha & Altenburg, as Director of an observatory to be erected on the Seeberg². Following the Duke's death, von Zach accompanied his widow in her travels through Southern Europe, until 1815 when they established themselves in Genoa where von Zach set up another observatory³, the architecture of which was inspired by the Gotha one.

He returned to Paris in 1827 where he died a lustrum later.

Reporting in detail von Zach's life and activities is out of the scope of this review. Excellent books have been devoted to them, especially by Peter Brosche, and are highly recommended to readers mastering German⁴. We shall only remember here that, among many other things, von Zach is to be credited with a certain international organization of astronomy, especially for the search of the 'missing planet' between Mars and Jupiter (according to the Titius–Bode law⁵). The discovery of Ceres⁶ was a happy collateral accident at the start of the programme. An international symposium was also centred on von Zach's work and epoch⁷.

Von Zach maintained an extensive correspondence with many personalities (political and others) of his time, including with numerous colleagues such as (to name only a few) the mathematician Carl Friedrich Gauss (1777–1855), the astronomers Heinrich Wilhelm Olbers (1758–1840) and Johann Hieronymus Schröter (1745–1816), as well as Lalande, of course.

Those exchanges between von Zach and Lalande were sustained after 1792, if we exclude a period of 'coldness' between the two and a couple of revolutionary phases when the mail was beset with difficulties. If von Zach's letters to Lalande have been preserved at Paris Observatory, Lalande's letters received by von Zach exist only (except one still as an original) through their German versions as published by von Zach, possibly not always faithfully translated, nor certainly in full.

With such reservations, by re-translating Lalande's letters from German into French and by annotating and commenting on them, Dumont and Pecker have achieved a remarkable compilation. The letters have been grouped in three sections: *Éphémérides de Berlin*, *Allgemeine geographische Ephemeriden*, *Monatliche Correspondenz*.

But the book goes much beyond that. A brilliant historical introduction (*Naissance de l'Empire romain germanique et de la Principauté de Gotha* [Birth of the Roman Empire of the German Nation and of the Principality of Gotha]) would deserve to be published separately and to be distributed widely. It is followed by a section proper to the relationship between Lalande and von Zach.

Several complementary articles cover about a hundred pages at the end of the volume: *Remarques au sujet du courrier international pendant la Révolution* [Remarks about the international mail during the Revolution], technical appendices (tables of the Sun, metric system, small planets, compared chronology), as well as a substantial biographical section (75 pages) on the characters mentioned in the letters — as in the previous volume of the series — and a bibliography.

One can only praise highly such a publication while perhaps lamenting the omission of a detailed index; although appreciating how tedious such a work would be, for the benefit of future historians we would strongly recommend — in the framework of an announced further volume or as a conclusion to the whole series — the compilation of a general index allowing efficient navigation around the various territories of Lalandiana. — A. HECK.

Notes and References

- (1) Be careful with the spelling of his first name: Franz Xaver, in French François Xavier. It seems then that the editors have mixed the two forms.
- (2) Today a hotel–restaurant.

- (3) Contrary to what is said in some Wikipedia versions (including the English one, 2016 August), that observatory is not Capodimonte Observatory, which is in Naples, not in Genoa.
- (4) See mainly: *Der Astronom der Herzogin — Leben und Werk von Franz Xaver von Zach 1754–1832* (*Acta Historica Astronomiae*, **12**, 2001, Verlag Harri Deutsch, Frankfurt/Main) and *Zach-Spätlese* (*Acta Historica Astronomiae*, **54**, 2014, Akademische Verlagsanstalt, Leipzig).
- (5) A formula suggesting that, going out from the Sun, each planet would be approximately twice as distant as the previous one.
- (6) By Giuseppe Piazzi in Palermo, on 1801 January 1.
- (7) *The European Scientist — Symposium on the Era and Work of Franz Xaver von Zach (1754–1832) — Budapest, September 15–17, 2004*, eds. L. G. Balázs, P. Brosche, H. W. Duerbeck & E. Zsoldos (Verlag Harri Deutsch, Frankfurt/Main), 2004.

Astronomy Photographer of the Year: Collection 3, collated at the Royal Observatory, Greenwich (Collins, Glasgow), 2014. Pp. 198, 27 × 27 cm. Price £25 (hardbound; ISBN 978 0 00 759869 4). **Astronomy Photographer of the Year: Collection 4**, collated at the Royal Observatory, Greenwich (Collins, Glasgow), 2015. Pp. 192, 27 × 27 cm. Price £25 (hardbound; ISBN 978 0 00 814635 1).

In earlier issues of this *Magazine* (**133**, 236, 2013 & **134**, 224, 2014) I reviewed previous editions of this work. These latest two editions cover images submitted for the sixth and seventh years (2014 & 2015) of the competition that is organized by the Royal Observatory Greenwich, the BBC's *Sky at Night* programme, and Flickr, the image-sharing website. *Collection 3* is based on seven categories, very similar to earlier competitions, but the number of categories was expanded to 14 for the latest competition, covered in *Collection 4*, with sponsorship from Insight Investments. The expanded categories primarily concerned sub-sections for topics such as images of the Moon, the Sun, and aurorae.

Apart from design considerations, my main concern with all these works has been with the accuracy — dare I say ‘the honesty’? — of the submissions, where the declared dates and locations, equipment, and methods are sometimes incompatible with the actual images. In general, however, the details accompanying each image are improved in these two collections, with a notable improvement in the notes added by the editors. There are still some problems and simplifications: in *Collection 3*, for example, the illustration on p. 49 is described as showing 16 Perseid meteors, whereas there are actually 13, plus three sporadics. There are a few silly errors, such as the statement on page 65 that the *ISS* is orbiting at 28 km per hour, when the actual velocity is about 27 500 km per hour, and that the image on p. 111 (which is entitled “Heart of the Scorpion” when it is of the Rho Oph region), is taken with a “12.5-inch mirror lens”. Perhaps the strangest image is that on p. 40, which shows elliptical star trails, with the major axis inclined to the horizon, suggesting that the aspect ratio has been altered in both X and Y coordinates. I have, unfortunately, encountered the problem where book designers have altered the aspect ratio of astronomical images, so this dreadful error may not be the fault of the original photographer.

Regrettably, some images that are (to me) obviously composites are not described as such, and several that consist of multiple exposures are listed with a single exposure duration, so we are forced to assume that time applied to each individual exposure. Some of the details of multi-frame images are rather odd. The image on p. 85, for example, is stated to be “An average of 9000 frames were stacked from the 14,000 captured for this image.” Presumably this should read ‘9000 frames were averaged’. Similarly, that on p. 125 must consist of multiple frames not just one as implied.

Some of the images do not actually show the details suggested by the captions. Search as I may, I cannot find Mercury in the image on p. 126, supposedly showing Venus, Jupiter, and Mercury. Nor can I see any signs of the ‘relativistic jet’, notionally shown in the image on p. 146. Assuming that these features were visible to the selectors, we can only assume that they have been lost in the printing process.

In *Collection 4*, we do, unfortunately, find some of the same problems. On p. 29, the photographer states that 30 Geminid meteors were recorded over three hours, but the technical details explicitly state “30-second exposure”. One of the images of star trails (that on p. 35) appears odd in that the trails do not appear to be portions of circles, and the image on pages 42–43 shows extraordinary trails, accentuated by their being complete ellipses around the southern polar region. Again, both the X and Y coordinates must have been altered, either by the photographer when combining images to obtain the trails, or by the book’s designer. Either the judges or the editors must have been at fault in not spotting these anomalies.

One thing that these collections reveal is how common it has become for photographers to stack multiple images (sometimes thousands) into a single final image in a search for perfection. Similarly, images are created by the use of multiple filters or even from different telescopes. Many images are stitched together to create panoramas. (Personally, I find I dislike those that show, for example, a strongly curved Milky Way that does not match the impression one gains when gazing at the sky with the naked eye.) Regrettably, all this reliance on computational ability sometimes results in rather ‘unnatural’ images.

As with previous editions, I remain concerned about the way in which many (and usually the best) images are printed across the gutter. Given the large page size of these books, a full page-width is, in my opinion, perfectly adequate. Similarly, there are still differing orientations of images of the same object. Images of the Moon are often subject to seemingly arbitrary rotations, usually of 90°, but sometimes by different amounts. (This is particularly evident in *Collection 4*.) The Orion Nebula is another object often affected, but several others suffer in the same way.

All these (relatively minor) problems suggest that there has been inadequate editorial control, with little or no interaction between the editors and the photographers to check details. I suspect also that the comments were generated during the judging process, and that there has been inadequate examination and correction by the editors at the books’ proof stage. — STORM DUNLOP.

Magnetic Reconnection: Concepts and Applications, edited by W. Gonzalez & E. Parker (Springer, Heidelberg), 2016. Pp. 542, 24 × 16 cm. Price £133.50/\$129.99 (hardbound; ISBN 978 3 319 26430 1).

When Jim Dungey first conceived of the magnetic reconnection process during his PhD studies in the late 1940s, developing his supervisor Fred Hoyle’s ‘neutral point’ theory of the Earth’s aurorae, he can little have imagined the international research industry that his idea would eventually generate, still going strong after more than 65 years with yet much unfinished business. Reading the present weighty collection of review chapters on the subject, the by-product of a workshop held in Brazil in 2014 March, was also of particular interest to me as a former PhD student of Jim’s who researched in this area for his PhD and subsequently in the 1970s and 1980s, before side-stepping into allied areas. Many of the themes I found still to be familiar, such as the strong

effects of plasma and flow asymmetry in the two in-flow regions, though here much more deeply developed and systematized, but some were new, such as the effects of the Hall physics in the vicinity of the X-line.

The main issue with reconnection which makes the process so teasingly problematical theoretically, and hence interesting, is that key elements of the process perform take place in thin layers in which the ions and in turn even the electrons become ‘demagnetized’, thus involving spatial scales down to that of the ion and then the electron gyroradius, while the consequences can have global impact upon the systems concerned, both with regard to rapid energy release from the magnetic field to the plasma, and to the connectivity of the field, allowing plasmas from differing sources to intermingle along field lines in a manner prohibited by ‘frozen-in flux’. While Dungey saw his ideas criticized and mainly ignored for about 20 years following their first publication in 1953 (though “reconnection” itself was not coined until a few years later), the chapters of this book well illustrate how mainstream they have now become throughout magnetospheric research, solar and stellar physics, and astrophysics. An excellent chapter on reconnection at the Earth’s magnetopause by Cassak & Fuselier considers that ‘driven’ reconnection is occurring at some point on the surface at all times, depending on interplanetary conditions, while following chapters by Petrukovich *et al.* and Walker & Jia consider the more impulsively-occurring reconnection occurring in the Earth’s tail during substorms, and the role of related reconnection in the mass-loss budget in giant planets’ magnetospheres, respectively. Shibata & Takasao are also of the view that all active phenomena in the solar atmosphere are related to reconnection, either directly or indirectly, from nanoflares to giant arcades. They also warn of the potential effects on techno-Earth of the occurrence of another reconnection-driven giant flare on the Sun, comparable to the first and most energetic ever observed (the Carrington event of 1859), while also pointing out that flares on similar-class stars have been observed by the *Kepler* spacecraft with energies yet a million times larger.

Chapters by Lazarian *et al.* and Uzdensky further discuss the ubiquity of reconnection in the astrophysical context, probably the causative process powering all manner of explosive flaring phenomena, up to and including gamma-ray bursts. Their contributions newly consider the effects on reconnection of the all-pervasive turbulence occurring in astrophysical plasmas, and of the dynamical effects of coupled radiation in environments of extreme energy density. On-going research is also discussed by Priest, who considers generalized concepts of reconnection in three-dimensional systems, a topic which he believes is still in its infancy. Overall, in those and other in-depth chapters of this well-produced book there is much to recommend to anyone with a serious interest in getting to grips with the present state of play, theoretical, computational, and experimental, in this important and on-going area of research. — STANLEY W. H. COWLEY.

The Birth of NASA, by Manfred ‘Dutch’ von Ehrenfried (Springer, Heidelberg), 2016. Pp. 358, 24 × 17 cm. Price £22.99/\$39.99 (paperback; ISBN 978 3 319 28426 2).

Author von Ehrenfried has provided a subtitle, *The Work of the Space Task Group, America’s First True Space Pioneers*, which is a better description of the contents than *The Birth of NASA*, although there are 33 pages covering what happened before the creation of the Space Task Group (STG), during the Eisenhower presidency.

The main time frame includes the creation of NASA (from NACA and other inputs), of Project Mercury, of a new word: 'astronaut', and of the STG to manage the programme from Langley Field, Virginia. There were seven Mercury astronauts*, all men because they had to have been military test pilots. But the numbers of men and women who contributed to the project (many of whom later moved on to Gemini and Apollo tasks) ran into the hundreds and more at various times. This is their story. The bulk of the volume has two roughly equal parts: what happened, when, how, where, how decisions were made, and who was involved; and capsule biographies of 60 'founding fathers' and members of STG core team (61 if you count Sam, the rhesus monkey who flew before any of the humans). Von Ehrenfried was one of the team (trained for flight control) and has chased down and talked with as many of the others, and some non-core people, as he could find. Many are, of course, now dead and others were simply lost from records. There are organization charts, team lists (contracts and scheduling included a Wanda, a Joyce, and a Margaret as well as 15 guys).

Is there astronomy here? Almost none, except the astronauts marvelling at the skies above them. Some planned scientific activities included weather observations (yes, NOAO was going to want to work from space!), behaviour of weightless fluids (including the interiors of the astronauts, who were measured and monitored extensively), and towing of a balloon to measure drag (never very successful). Several of the pilots took photographs of air glow, horizons, zodiacal light, and such, often with a Hasselblad camera. That one of these remains in space is a story from a different book.

I happily volunteered as reviewer for this book, hoping to find two things. One was there, the other not, but a third surprise came along. The missing person is Katherine Johnson, a 'computer' who bridged the era from Monroe calculators to vacuum tubes and beyond. She calculated the launch window for one of the Mercury missions and received a National Medal of Science in 2015 at the age of about 97. Glenn asked her to check the official orbit calculations before he would fly. She was, not surprisingly, the first black American woman to do many things.

Present, just barely, is White Sands Missile Range, from which many of the captured German V-2 rockets were fired. It was tasked with testing methods for tracking orbital objects, which is why my late father, Lyne Starling Trimble, had for some years a White Sands contract to develop an easy way to find sparse signals on miles of magnetic-tape records, beginning in 1959-60 (as I was finishing high school). *Mach junior* was a thin glass container of iron filings in moderately viscous fluid that you moved over the tape until the filings aligned on top of the tape bit with data on it. *Mach senior* was a coating on the tape that, when exposed to a magnetic field, would develop colour because the field expanded magnetostrictive particles coated with something brittle like antimony and thereby exposed the particles to the ambient chemicals with which they produced red, green, or blue pigments, depending on the field strength and so on which coatings were broken. I inherited the patents, which were evaluated with a worth of \$1 at father's death.

From the same paragraph on p. 52 comes the factoid that some 1600 German scientists, engineers, and technicians came to the US and joined missile and rocket programmes here. I had always thought of Wernher von Braun and a few buddies, hadn't you?

*At least some of the names will resonate: Alan Shepherd, Walter Schirra, John Glenn, Virgil Grissom, Scott Carpenter, Leroy Cooper, and Donald Slayton.

Finally the surprise. Von Ehrenfried includes his own capsule biography with the rest among “other STG members”. He stayed with NASA and during 1970 and 1971 was Chief of the Science Requirements and Operations Branch for Apollo, with responsibility for the definition, coordination, and documentation of science experiments for the ALSEP (Apollo Lunar Surface Experiments Package). *ALSEP 17* launched in 1972 December, included my husband’s *Lunar Surface Gravimeter*, so they must have met one another, perhaps each wearing his ‘bunny suit’ required for being in the facilities where space things were built. — VIRGINIA TRIMBLE.

Interkosmos: The Eastern Bloc’s Early Space Program, by C. Burgess & B. Vis (Springer, Heidelberg), 2016. Pp. 321, 23.5 × 15.5 cm. Price £22.99/\$39.99 (paperback; ISBN 978 3 319 24161 6).

This book harks back to the days of the Cold War, when competition between the United States and the Soviet Union dominated international affairs, including space activities. The Interkosmos programme began in the 1960s as a modest scientific endeavour, involving eight countries within the Soviet sphere of influence. The first space launch of the Interkosmos programme was *Kosmos-261*, a satellite dedicated to investigation of aurorae and the upper atmosphere. Thirty-nine launches later, after the break-up of the USSR, the programme was officially terminated following the launch of *Koronas-1* on 1994 March 2.

Very little coverage of the robotic Interkosmos flights is provided in this volume, with the authors concentrating on a series of short flights to Soviet space stations that involved ‘guest’ cosmonauts from eastern-bloc countries or nations that were within the area of Soviet influence. Interesting additions were India and France, which were also happy to take advantage of the offer of rides into space for their citizens. Altogether, 15 crewed flights are described, with an emphasis on the biographical details of the various prime and back-up crew members. Most of the missions took advantage of the requirement to replace Soyuz ferry craft within 90 days, so that Soviet cosmonauts could conduct extended missions on board the *Salyut 6*, *Salyut 7*, and *Mir* space stations.

Little science of significance was undertaken during these missions, and, apart from the propaganda bonus of regular flights for ‘friendly’ nations at a time when US astronauts were grounded after the end of the Apollo era, they were generally regarded as low priority — even by the Soviet leaders. Today, the Interkosmos programme is a largely forgotten episode in the saga of space rivalry between the two superpowers. — PETER BOND.

Dissent, Revolution and Liberty Beyond Earth, edited by Charles S. Cockell (Springer, Heidelberg), 2016. Pp. 240, 24 × 16 cm. Price £82/\$129 (hardbound; ISBN 978 3 319 29347 9).

Astronomy and politics are two words you do not usually see in the same sentence, and there was certainly no dual honours degree in those subjects at my university. But might that change in the future? When we really start building our space colonies on the Moon and beyond, politics in an astronomical environment will become highly relevant and will need to be studied.

In extremis down here on Earth, we can use revolution, violence, and sabotage to overthrow a despotic régime. But in a space station, or on a planetary colony, one can hardly blow the place up if you have a disagreement with ‘the management’. That would depressurize the whole system and kill everyone.

So space colonists are not free; they cannot effectively dissent; they have no real liberty. The words serf and vassal spring to mind.

Charles S. Cockell is a professor of astrobiology at the University of Edinburgh who is fascinated by political philosophy. This has resulted in his editing three books, the first two being *The Meaning of Liberty beyond Earth* (Springer, 2013) and *Human Governance beyond Earth* (Springer, 2014), and the third being the book under review. In the latest book, fourteen papers from a meeting held in 2015 June have been collected together. The authors are scientists, theologians, lawyers, philosophers, and politicians. The topics range from possible labour relations in lunar medical establishments; political dissent in space colonies; social order and policing in extra-terrestrial communities; discipline problems that have already arisen in the manned missions that have taken place so far; the potential for terrorism in space; is 'liberty' possible in space habitats?; do humans have rights when 'off-Earth'?; dare we take adolescent teenagers into space?; in a closed system will humans inevitably have mental breakdowns, or will space colonies advance culturally?; and how does the development of an economy in space fit in with the rate at which we are degrading life on Earth?

The standard of these papers is exceedingly high. There was never a dull moment. New ideas burst from every page and hypotheses abound. The English-American theoretical physicist Freeman Dyson once wrote "Space is huge enough, so that somewhere in its vastness there will always be a place for rebels and outlaws." (*Eros to Gaia*, Penguin, 1993). I wonder if he was right. And I wonder how long we will have to wait to find out. — DAVID W. HUGHES.

The Hubble Space Telescope: From Concept to Success, by D. J. Shayler & D. M. Harland (Springer, Heidelberg), 2016. Pp. 414, 23.5 × 15.5 cm. Price £22.99/\$39.99 (paperback: ISBN 978 1 4939 2826 2).

There are many ways of telling the story of the *Hubble Space Telescope*. The road to success was rocky, but the outcome has far surpassed the expectations of even the most optimistic astronomer. Behind the scientific success were huge battalions of expert engineers, technicians, designers, astronauts, project managers, and so on, who were the people who actually put the telescope and its support system together and made it work in space. This book is their story. The chapter titles give a good impression of the scope of the book: 'Deployment', 'The dream', 'From dream to reality', '*LST* becomes *ST* becomes *HST*', 'Simulating servicing', 'Tools of the trade', 'Behind the scenes', and 'Service mission 1'.

The book is full of interest for those interested in knowing how NASA, ESA, and the industrial companies involved in the project actually pulled off the largest and most demanding project in the history of astronomy. The chapters are well provided with the details of what was involved at every stage of the development, construction, and launch processes. The lasting impression is the extent of the very demanding monitoring, simulation, and training involved throughout the whole programme, despite which the spherical-aberration problem surfaced immediately after launch.

The book gives a reasonably detailed account of the technical issues involved at each stage of the programme and how they were solved. The reader is not spared the plethora of acronyms, committees, technical tables, and job descriptions which were all part of the NASA culture. I remember only too well the need to learn a totally new vocabulary to understand exactly what was going on during the many meetings I attended during the development phases of the programme.

It is important to note what is *not* included. There is no discussion of the astronomical achievements of the project, nor is there a discussion of the complex political and managerial problems which beset the programme from the beginning. The fact that the programme was seriously under-funded from the beginning is not discussed. For those aspects of the story, David Smith's *The Space Telescope: A Study of Nasa, Science, Technology, and Politics* (CUP, 1993) is an authoritative account. The present book, however, covers many key aspects of the programme which were crucial to its success and which are normally invisible to the astronomer. Here the heroes are the engineers, managers, and particularly the astronauts who made the telescope work in space and saved the project as a result of the amazing first servicing mission. This book recounts exactly what was involved and what they did. — MALCOLM LONGAIR.

Calculating the Cosmos: How Mathematics Unveils the Universe, by Ian Stewart (Basic Books, New York), 2016. Pp. 320, 23 × 14.5 cm. Price \$27.99 (about £22) (hardbound; ISBN 978 0 465 09610 7).

More than 50 years ago, Physics Nobelist Eugene Wigner described “the unreasonable effectiveness of mathematics in the natural sciences” as a “miracle”. Stewart’s equivalent is “Nature has laws. They are mathematical. We can find them. We can use them.” This is the story he has to tell, from Galileo and Newton’s laws of gravity down to modern cosmologies and multiverses, in almost equation-free form. That choice does not mean that the book avoids difficult issues like star formation and why many galaxies, like our Milky Way, have spiral arms. For the latter, he champions a relatively recent picture, called ‘sticky chaos’, over the fifty-year-old density waves most current astronomers learned in school.

The author emphasizes repeatedly that even mathematically correct calculations can lead to nonsense if the underlying idea is wrong. Thus he does not require aliens to be carbon-based and would be perfectly happy with a Universe in which something other than hydrogen fusion provided sources of high-grade energy long enough for such aliens to come into existence. I fully agree, but we come to a parting of the ways on both historical and astronomical facts. A particularly depressing set of four pages gives Williamina Fleming credit for the work of Annie J. Cannon; calls helium the main fuel of fusion reactors; places the Kelvin–Helmholtz mechanism for stellar energy in the 1920s rather than the 1870s; provides one step of the hydrogen fusion reaction that does occur in stars with a typo that says $2 + 2 = 3$; and describes only the classes of stars whose spectra show weak hydrogen lines. This last also misses the opportunity for a fine bit of mathematical physics called the Saha equation, used by Cecilia Payne (later Gaposchkin) to show that stars consist mostly of hydrogen and helium rather than the Earth-like composition of silicon, oxygen, *etc.*, favoured by her predecessors. She gets no credit.

That our ‘best buy’ explanations of the world around us change, sometimes gradually, sometimes in revolutions, though in both cases with accompanying mathematics, is one of the author’s important points. One could wish, however, that when he writes that it may turn out that there was no Big Bang and there are no black holes he is not denying the existence of the 2.7-K microwave background and the observations of celestial objects with sizes very close to their Schwarzschild radii, but rather predictions about “before” and “inside”.

Books written for citizen-scientists rather than for us full-time harmless drudges should perhaps be reviewed by members of that community. Attempting to think from within that box rather than my own, I would probably

have noticed first that the ordering of the topics is closely that of an elementary astronomy textbook, that is, Solar System first, then stars and galaxies, then the Universe as a whole, with extraterrestrial life tucked in toward the end. In Stewart's case, however, the ordering is driven by the historical order in which the relevant mathematics was developed, automatically putting Newton and the Solar System at the beginning, Maxwell and electromagnetism in the middle, and Einstein and the Universe near the end. I would very much have liked to have a few more of the footnotes indicate sources of information and would have preferred not to read the sentence (about the discovery of dwarf planet Ceres) "Not wishing to start the search all over again, astronomers asked the scientific community to provide a more reliable prediction." Astronomers when cut may not bleed quite as many equations as physicists, but we still think we are scientists! On the other hand, much must be forgiven an author who describes the development of the scientific literature as "To every publication there is an equal and opposite retraction." — VIRGINIA TRIMBLE.

The Hunt for Vulcan ... And How Albert Einstein Destroyed a Planet, Discovered Relativity, and Deciphered the Universe, by T. Levenson (Random House, New York), 2016. Pp. 249, 20 × 13 cm. Price \$16.00 (about £12) (paperback; ISBN 978 0 8129 8830 7).

This book, by the director of the MIT Graduate Program in Science Writing, was short-listed for the Royal Society Insight Investment Science Book Prize, losing out to Andrea Wulf's highly praised book about the life and work of Alexander von Humboldt¹. Most readers of these pages have heard the story of Vulcan, but are probably not aware of the roles in its story played by a cigar factory, Texas Jack, and Thomas Edison as an embarrassed dude in the American West.

The twelve chapters are divided into three parts, the first setting the stage by reviewing Newtonian gravitation, its application to astronomy, and the discovery of Neptune. The second is about the actual hunt for Vulcan, both theoretical and observational, and the third concerns how General Relativity provided the correct explanation for the advancement of the perihelion of Mercury. There are no equations, but the descriptions of the problem, various blind alleys, and the ultimately right answer are correct and clear. The narrative is chronological, with personalities playing a prominent role, both the main actors, such as Newton, Herschel, Le Verrier, and Einstein, and extras such as Edison and Lescarbault.

With only a couple of typos, the book is not only well written but also well edited (though of course my pleasure was somewhat reduced by missing hyphens in two-word adjectives), and certainly deserves to be on the Royal Society's shortlist. There are a handful of black-and-white photographs and diagrams scattered throughout the text. Footnotes at the bottom of the page make for easier reading, and sources are listed in the twenty pages of notes following the main text, with a page number and short quotation identifying the corresponding part of the text. Ten pages of bibliography and an eleven-page index make the book very useful as a jumping-off point for further investigation of the story of the hunt for Vulcan.

Usually, the astronomical side of the story is told, with a postscript noting that Einstein provided the correct answer to the problem (in today's terminology, 'modified gravity' rather than 'dark matter'), or discussions of the work of Einstein note that his solution to the problem of Mercury's orbit was correct

and the idea of Vulcan a blind alley. This book combines the two in about equal parts. Among his other books, Levenson has also written a book on Newton² and one on Einstein³, and is equally at home whether telling an interesting story or explaining the science behind it. Explicitly mentioning *BICEP2*, there are of course parallels to other situations where confirmation bias has embarrassed otherwise good scientists. This is an excellent book. Those not familiar with the story of Vulcan will probably not find a better synopsis, and even those who are will probably learn something new. — PHILLIP HELBIG.

References

- (1) A. Wulf, *The Invention of Nature* (John Murray, London), 2015.
- (2) T. Levenson, *Newton and the Counterfeiter* (Houghton Mifflin Harcourt, Boston), 2009.
- (3) T. Levenson, *Einstein in Berlin* (Bantam Books, New York), 2004.

The Cosmic Web: Mysterious Architecture of the Universe, by J. R. Gott (Princeton University Press, Woodstock), 2016. Pp. 255, 24.5 × 16 cm. Price £22.95 (hardbound; ISBN 978 0 691 15726 9).

Cosmology is the most explicitly reductionist of the sciences, tracing everything we can see around us back to small initial density fluctuations that collapsed *via* their own gravitational attraction. Better still, those initial seeds are not some abstract unifying hypothesis, but they can be seen directly. Or, rather, it can be observed that cosmological space-time contains fluctuations on a range of scales — from billions of light-years to 100 000 light-years or smaller. The distribution of matter is crinkled like the surface of a pond by those long- and short-wavelength disturbances. It is pretty reasonable to assume that individual objects like galaxies arose from the ‘breaking’ of waves that are of such short wavelength that they no longer exist — but the larger-scale fluctuations remain, acting as a relic of the earliest stages of the evolution of the Universe.

The discovery of those astronomical fossils is one of the great scientific stories of our era. Today, the best information we have comes from the cosmic microwave background: radiation that last interacted at the time when the global temperature was hot enough to unbind matter into plasma. Since no complex structures then existed, the fluctuations at that time give the cleanest window into the deep past. But such observations only became clear and detailed in the present century (especially through NASA’s *WMAP* satellite), whereas the existence of primordial fluctuations was first deduced through the large-scale structure in the distribution of galaxies — starting in the 1930s and reaching maturity around 1990. Those are historic events, which deserve to be known and understood by a general readership; that is the aim of this new book, written by a cosmologist who made important early contributions to our understanding of galaxy clustering.

Gott tells the story pretty much in chronological order. He starts with the discovery of redshifts and the general expanding universe in the early decades of the 20th Century. Unlike many writers, he does manage to give at least some credit to Slipher’s pioneering role, although there is still a bit too much hero-worship of Hubble for my taste. In the early days, clusters of galaxies were the only evidence for large-scale structure, but already their internal dynamics revealed the existence of the dark matter that dominates the gravitational collapse of the cosmic web. The antithesis of a cluster is a cosmic void, and it may seem obvious that collecting matter together in some regions (clusters)

would leave a deficiency in others. But a strange fact of the history of this subject is that the existence of voids only became clearly established with new ‘redshift surveys’ in the early 1980s. Stranger still is that the accepted ‘inflation’ theory of the origin of structure *via* quantum fluctuations arose around the same time, very quickly leading to detailed computer simulations of the development of the web expected in inflationary models. Thus the observational discovery of large-scale structure went in parallel to the theory; in some ways this was positive, as it guided effective design of new galaxy surveys. But it also had a seriously malign influence: an inflationary prejudice towards a universe of critical density in dark matter, leading to excessive credence in observations consistent with such a model. Without that distraction, the true vacuum-dominated accelerating model might have been established much sooner. Gott discusses this matter in his final chapter, but he underplays the extent to which large-scale structure anticipated the Nobel-winning supernova results of 1998/99. The evidence was there, and it is an interesting question as to why the community was reluctant to accept the conclusion. Especially in a book for a general reader, it would have been good to expose the extent to which sociology shapes scientific progress.

Gott’s telling of this tale is in general well done, covering the main events and explaining their significance with well-chosen analogies. But some features will not be welcomed by all readers. One is that he does not shy away from equations or technicalities, especially in the long and detailed central chapter on the topology of the large-scale structure. This is beautiful stuff, but may put off less-mathematical readers. The other thing to say is that this is in large part a scientific autobiography, with the history related much as Gott himself experienced it. That has its advantages in giving potentially abstract material a human context. But it ends up distorting the history, giving rather too much emphasis to things that happened at Princeton. And in any case, the general reader will be more interested in the ideas than in a long list of who did what and when; fortunately, the excitement of this story of cosmic discovery still comes over. — JOHN PEACOCK.

Understanding the Epoch of Cosmic Reionization: Challenges and Progress, edited by A. Mesinger (Springer, Heidelberg), 2016. Pp. 280, 24 × 16 cm. Price £74.50/\$129 (hardbound; ISBN 978 3 319 21956 1).

This is an excellent introduction to the ‘Epoch of Reionization’. Andrei Mesinger has collected some of the experts in the field to cover the important theoretical, observational, computational, and analytical issues relevant to extracting information about the Universe from that important phase in its evolution. It is very timely, as it is a relatively new frontier in several senses, and one to which considerable resources are being directed. The chapters are refreshingly honest about the formidable challenges that lie ahead. This has none of the relative simplicity of the cosmic microwave background in its interpretation, and major hazards abound at every street corner. The articles are all excellent, and the authors have stuck to the brief of the title very well, starting with an excellent overview by Zoltan Haiman. There are discussions of the numerical challenges in modelling re-ionization, especially the wide range of physical scales that need to be modelled, and the dependence of the observed quantities on very small sources that have little hope of being directly observed. The discussion of the observational situation in the UV echoes those challenges. Even with a large investment in telescope time, we are left with some fairly basic unknowns that hamper the interpretation, involving a ‘Drake’s equation’ of re-

ionization, expressing our ignorance in terms of a number of relatively poorly known quantities. In some other areas we have a better understanding of the physics, but further challenges, such as in the limited number of high-redshift quasars that can be used as beacons to probe the intervening Universe. The promise of 21-cm cosmology is discussed in the final, excellent article by Steven Furlanetto, which sets out very clearly the physics and the uncertainties in this field for which the *Square Kilometre Array* is being built. Many of the drawbacks of other probes are avoided, but these are replaced by a host of new challenges, which are going to be difficult to meet. The ‘Epoch of Reionization’ has some very tempting fruit in it, but it is not low-lying by any stretch of the imagination.

In summary, this is an excellent collection of articles that give a balanced and comprehensive review of the state of the subject, and it is thoroughly recommended for students embarking on the topic, for the wider community of cosmologists, and for experts in the field, who will probably also learn something new as well. — ALAN HEAVENS.

THESIS ABSTRACT

PLANETARY ORBITS AND INTERACTIONS WITH DEBRIS

By Tim D. Pearce

Astronomical instrumentation is now sufficiently advanced that we can image planets orbiting other stars. We can also resolve extrasolar debris discs; this term describes regions of small bodies orbiting a star, akin to the Sun’s Asteroid and Kuiper Belts. The kinematics of many extrasolar planets and discs appears to be very different from their equivalents in the Solar System, and understanding the dynamics of those objects is critical for developing theories of planetary-system formation and evolution. However, such work is compounded by several issues. Firstly, planets can only be imaged far from their host stars, and hence their long orbital periods mean that we can observe them only for small fractions of their orbits. Uniquely solving their orbital parameters is therefore impossible. Secondly, despite advances in the field, the planets and debris discs of the Solar System would not currently be detectable were they located around other stars. Hence it is likely that planets and discs lie undetected in many systems, making it difficult to constrain the dynamical history of those systems. This thesis aims partly to address those two problems.

In the first part of the thesis I discuss the constraints that can be placed on the orbits of imaged companions. I first argue that orbital-characterization techniques commonly used in the literature, such as Markov Chain Monte Carlo analyses, do not always provide all the necessary information and can be significantly biased by the choice of priors. I therefore suggest alternative orbit-characterization methods, which can constrain orbital parameters in a prior-independent way. I then consider the potential effects of unseen masses on the derived orbits of long-period companions. In particular, I find that unseen bodies could make imaged companions appear more eccentric than they really

are. Many of the companions that have been imaged could be liable to that error when their orbital parameters are first estimated.

The second part of the thesis models the interaction between an eccentric planet and a debris disc. This analysis could be used to place dynamical constraints on planetary systems, and to infer the location of unseen planets from observed debris features. I first consider planets at least an order of magnitude more massive than the disc, and find that the interaction results in one of two outcomes. Which one occurs depends on the initial orientation of the planet's orbit relative to the disc mid-plane; planets roughly coplanar with the disc mid-plane clear the inner region of debris, and remaining particles form an eccentric disc apsidally aligned with the planet's orbit. In the highly inclined régime, surviving debris forms a hollow bell-shaped structure enveloping the planet's orbit. I then examine the case where the planet and disc are of equal mass. In this régime I find that planetary precession causes some debris close to the planet to align with the planet's orbit, whilst that farther away becomes anti-aligned. I show that the general outcome of that interaction is a double-ringed debris disc, in which the planet is located close to the inner edge of the disc. Finally, I apply those results to the disc of HD 107146, and show that an unseen eccentric planet could sculpt the debris into the observed structure and surface-brightness profile. — *University of Cambridge; accepted 2016 April.*

A full copy of this thesis can be requested from: tdpearce64@gmail.com

Here and There

MOST UNUSUAL

The geology around Svalbard and Spitsbergen is most unusual. ... It has fossil evidence of trees that lived some 300,000 million years ago. — Advertising brochure from 'Exodus' (polar expeditions).