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EDITORIAL

This issue sees a remarkable event in the annals of astronomy: Paper 250 in the series by Professor Roger Griffin on *Spectroscopic Binary Orbits from Photoelectric Radial Velocities*. It is remarkable not only for the number of papers published and the number of stars treated to a rigorous examination, but also for the fact that the whole approach — now used routinely for research at the forefront of astronomy, such as exoplanet discovery — was pioneered by the author and has been pursued relentlessly by him for over 40 years. And if the series in these pages was not enough, Roger has been prolific with papers on the same topic in several other journals, particularly the Indian *Journal of Astrophysics and Astronomy*. The dedication he has shown to observing with a modest telescope — and thus one of little interest to 'the thundering herd' — at Cambridge, with its less-than-ideal climate, is heroic indeed and amazingly shows little sign of abatement in spite of his 80 years. Roger's impact on astronomy has been impressive and this issue collects a number of tributes as letters from colleagues who have benefitted from his work.

SPECTROSCOPIC BINARY ORBITS FROM PHOTOELECTRIC RADIAL VELOCITIES

PAPER 250: THE CEPHEID BINARY AW PERSEI (HD 30282)

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AW Persei is a late-F star of about magnitude 7·5, close to the border between Perseus and Auriga. In 1928 it was discovered to be a variable star, and shortly afterwards was recognized as a Cepheid, with a pulsation period of 6·46 days; it was assigned the variable-star designation AW Per. A preliminary velocity curve, related to the Cepheid variation, was given by Joy in 1937. Duplicity of the object was recognized in 1960 from the smallness of the photometric amplitude in the near-ultraviolet, where the light of the Cepheid is significantly diluted by that of a B-type companion, which has repeatedly been suspected of being itself a double star. Fresh radial-velocity observations then showed a substantial change in the mean velocity since the epoch of Joy's observations, no doubt arising from orbital motion. Four publications have given orbits for the system, but none of the authors concerned had seen the system round a complete revolution of its orbit.

The star was placed on the Cambridge radial-velocity programme at the beginning of 1976 and has been observed systematically ever since. The author's 359 radial velocities, covering slightly more than a complete cycle, lead to a reasonably reliable orbit with a period of nearly 14 000 days (38 years), and give the ~6½-day pulsation period (which is, however, already well determined from photometry) to an accuracy of two-fifths of a second. Although there are more than 100 radial-velocity measurements of AW Per in the literature, they are a motley collection and quite fragmentary in their coverage of the orbit, so the present author's more systematic observations have alone been utilized in the discussion here. The Cepheid's pulsational radial-velocity variation mimics fairly closely the variation in the nearest-matching Keplerian orbit, which has been adopted as a first approximation to the pulsational velocity curve, so the ensemble of radial velocities has been treated as if it stemmed from a triple system with an outer and an inner orbit.

Introduction and Observational History

AW Persei is a 7^{m} star in a south-following corner of Perseus, where the dividing line between that constellation and Auriga to its east takes a small (~2°) 'jog' in RA in its otherwise N–S course. It is about 1° preceding the $4^{m}\cdot 8$ K star 2 Aur, and makes with that star and HR 1533, which is nearly a degree to their north, very nearly an equilateral triangle. The star first received an individual designation in the *BD*[1], as 36° 937. It was further designated HD 30282 in the second volume, published in 1918, of the *Henry Draper Catalogue**. A decade later, attention was drawn to it by Guthnick, who included it in a list[3] of newly discovered variable stars, in which it was designated "424·1928 Aur" and attributed a total amplitude of variation of $0^{m}\cdot 9$. It was in the official fixing of constellation boundaries[4] in 1935 that the relevant area of sky was transferred

*The first volume of that 9-volume work[2], belatedly honouring Dr. Draper, who died at the age of only 45 in 1882 from pleurisy that seems to have originated on a hunting trip, was published earlier in the same year; it bore a frontispiece illustrating examples of the spectra upon which it was based, whereas the corresponding place in the volume that includes HD 30282 has a portrait of Dr. Draper.

from Auriga to Perseus; until then, the star referred to above as HR 1533 was 1 Aurigae, and actually is still so labelled in the *Cambridge Star Atlas 2000·0* [4a].

Guthnick's evidence of photometric variations consisted of nine observations that were reported only qualitatively, in terms of the variable being brighter than, equal to, or fainter than, the comparison star. Subsequent photometric observations identified the variations as being of Cepheid character, with a period of 6·46 days. A visual light-curve was given in 1930 by Jacchia[5]; the light elements were listed by Kukarkin[6] in the same year and the variable-star designation AW Per was assigned. The spectral type had already been classified in the *Henry Draper Catalogue* as F8, quite appropriate to the star's Cepheid character.

Radial velocities of AW Per were first obtained by Joy[7] in 1932 and 1933, in the course of a major investigation, made with the Mount Wilson reflectors and a small prism spectrograph giving, in the case of interest, a reciprocal dispersion of 75 Å mm^{-1}, of the radial velocities of Cepheid variables. He listed nine measurements of AW Per. Since the period was already known from photometry, even that small number of measurements could be plotted against their known phases to form a preliminary velocity curve. When plotted on the orbital solution found here, two of them have very bad residuals of about −14 and −17 km s^{-1}, whereas the largest of the other seven is less than 5. The two discrepant measurements both fall at phases near the maximum velocity of the Cepheid pulsation, and could be brought more into line with the others, near the steep declining 'branch' of the velocity curve, by shifting their phases by about half a day, involving a decrease of about 9 seconds in the period attributed to the pulsation. That does not by any means find support from the rest of the data set, but Joy's measurements are isolated in time at an epoch about twice as long ago as the start of the quasi-systematic observations. Not caring to base a proposal of such a change in period on such a slender observational base, the writer has not tried to incorporate Joy's velocities in the solution of the orbit; in fact, he has not utilized *any* of the published velocities but has preferred to stick with just his own, which are tolerably systematic over the whole orbital period and are several times more numerous than the total of all the previously published ones.

The duplicity of AW Per was first suggested in 1960 by Oosterhoff[8], who noted the smallness of the photometric amplitude of the Cepheid in the near-ultraviolet in comparison with that in visual light. He was discussing the photometry that he obtained on many Cepheid variables during a visit in the preceding summer to the Palomar Observatory*. He wrote, "In the case of AW Persei the observations could be explained if the variable had a companion about two magnitudes fainter than the cepheid in visual light and about half a magnitude fainter in the ultraviolet.". He went on to report that at his request Dr. G. W. Preston had taken an 80-Å mm^{-1} spectrogram of the star, at a time when it was near minimum light, with the 'X spectrograph'[9] on the Mount Wilson 60-inch reflector, and that in the near-ultraviolet the spectrogram duly exhibited the proposed composite nature of the spectrum.

Preston himself, in collaboration with Miller, subsequently enlarged on that finding. They[10] obtained 17 spectrograms at a dispersion of 16 Å mm^{-1} at the Lick 120-inch coudé. The spectra verified the existence of a hot companion, for which they proposed a type of B6 or B7 V, whose light fills in the Ca II *K* line to

* He was remarkably lucky *and* diligent: he reported that he had made a 10-week visit to the Mt. Wilson & Palomar Observatories, where he observed with the P20-inch [*sic*] photometric reflector on 54 nights!

a considerable extent, making it appear a good deal shallower than the nearby *H*–Hε blend. The implied difference in *V* magnitude between the components was put at $2^{m}\cdot 8$, the Cepheid (at its mean magnitude) being that much brighter than its B-type companion. The *K* and *H* lines in the spectrum both showed sharp cores, whose radial velocities were constant within observational uncertainty, indicating an interstellar origin. The stellar lines upon which they were superimposed, however, exhibited conspicuous velocity changes that were phased with the photometric variation. Miller & Preston particularly noted that, over the 850-day span of their spectroscopic observations (1960 October to early 1963) there were no additional velocity changes that could represent orbital motion. The mean velocity was, however, about 20 km s^{-1} lower than the one that Joy[7] found*. In addition to their 'technical' paper on AW Per summarized in this paragraph, Miller & Preston published a brief description of their conclusions on that and two other stars in another paper[11] published in another journal at the same time.

It was Lloyd Evans[12] who in 1968 first pointed out the discordance between the mean velocities found by Joy[7] and by Miller & Preston[10] for AW Per. He noted the discrepancy to be as much as 20 km s^{-1}, and commented that it was too much to be ascribed to observational error; he also remarked that "This is the first known example of a Cepheid in a spectroscopic binary system where the spectrum of the companion is also visible." Lloyd Evans further indicated a number of ways in which the spectral type of the companion star might be estimated; he found that they pointed to a type of B6 or B7V. He also noted a lower limit to the orbital period, of 1200 days, which seems a bit conservative in view of the fact that Miller & Preston had seen no change at all in the mean velocity in 850 days, but major changes had been seen over much longer intervals.

In the first of several bites that she took of the AW Per cherry, Nancy Evans[13] published *UBV* photometry taken on four nights, and three radial velocities all obtained within about a week of one another, from spectra (two of them noted as 'weak') taken with the David Dunlap Observatory's 74-inch reflector at a dispersion of 12 Å mm^{-1}.

Madore[14] investigated the photometric effects that B-type secondaries of Cepheids might be expected to have upon the loops that could be plotted in the $(B-V)$–$(U-B)$ plane to represent the colour changes associated with the Cepheid variations. The effects proved to be quite conspicuous, and allowed Madore to postulate the existence of secondary stars associated with as many as 38 Cepheids (few of which were known at the time to be in binary systems) and even to estimate the spectral types of the secondaries from the characters of the photometric loops. By that procedure he found a B7 type for the secondary of AW Per.

In 1977 McNamara & Chapman[15] published a *Note on the radial velocity of AW Per*, in which they offered just two new velocities of the star, obtained at 20 Å mm^{-1} at the coudé focus of the Mount Wilson 100-inch reflector, and found them to fall quite near the velocity curve obtained by Joy from observations made about 16 000 days previously, and certainly not near the level found by Miller & Preston about one-third as long ago. They recognized the orbital period to be more than 20 years.

*If it were not for the two bad residuals in Joy's results, noted in the paragraph next but one above, the discrepancy would have been more like 23 km s^{-1}; but Miller & Preston seem not to have been aware of Joy's work — at least, it is not referred to in their paper.

Szabados[16], in a paper entitled *Photoelectric UBV Photometry of northern Cepheids, II*, found a total of 16 times of maximum light to have been published for AW Per altogether, by no fewer than ten authors apart from himself; he plotted the deviations of those times, from a constant-period baseline, as a function of time. He noted that "it is interesting that a simple eye inspection can reveal a sinusoidal wave in the $(O-C)$ diagram which is a direct result of the orbital motion of AW Per around the centre of mass of the binary system." He deduced a period of 10300 ± 800 days (about 28 ± 2 years). Evans[17] confirmed the phase shifts noted by Szabados between photometric data sets spanning a little over 20 years, and made a corresponding plot (with time as the abscissa) of the much more limited data on radial velocities (averaged in each case over the pulsational cycle). There were only four points, of which the first (Joy's[7]) more than doubled the time base; the others were from the works noted above from Miller & Preston[10] in 1960–63, McNamara & Chapman[15] in 1968/9, and Evans[13] herself in 1971; she also presented seven new velocities representing the years 1978, 1981, and 1982. By explicitly supposing Joy's measurements to have been made two cycles before the then comparatively recent ones (whereas in fact they represented the immediately-previous cycle), Evans concluded that "the orbital period must be between 19 and 23 years". The wrong choice of period naturally compromised some aspects of her ensuing discussion.

Barnes, Moffett & Slovak[18] observed AW Per, among other Cepheid variables, at the 82-inch McDonald reflector, with a radial-velocity spectrometer that operated on the principle established by the present writer[19] some 50 years ago but gave velocities with typical uncertainties of as much as 4 km s^{-1}. They listed 31 observations*, but they are quite scattered and would need to be attributed a rather small weight, about 1/20, if they were to be included in the solution of the orbit. Wilson *et al.*[20] subsequently gave five more velocities obtained with the same equipment; four of them related to consecutive nights.

Beavers & Eitter[21] reported two observations of AW Per, taken within a few minutes of one another with the Fick Observatory radial-velocity spectrometer[22].

In a short abstract of a contribution on the AW Per system at an AAS conference in 1987, Welch & Evans[23] concluded that the secondary star, whose temperature had been deduced from *IUE* observations, could not have the mass demanded by the mass function unless it were itself a binary or else were an evolved (as distinct from a main-sequence) star. They gave for the system the first complete set of orbital elements, which are recorded in the first numerical column of Table I. Evans & Welch also presented a paper[24] to an *IUE Symposium* in 1988, saying that they, together with Scarfe, had derived an orbit for AW Per. The forward reference that they gave for it ("preprint") was inaccurate, and I am indebted to Professor C. D. Scarfe for the information that the intended paper was in fact published, but under the names of Welch & Evans[25] alone. The report of the *Symposium* presentation itself gave some of the elements; they were not identical with those that the same authors had proposed[23] the previous year. The slightly revised elements, like the 1987 ones, are set out in Table I; they include a period of 13100 ± 1000 days. (It will be noticed that the standard errors assigned to the elements have rather surprisingly *increased* in the later publication.) The authors again proposed that the companion star must itself be double, and said "This is to be investigated with a high-dispersion IUE

*Two of them are attributed dates that are identical to three decimal places, though the velocities differ by more than 5 km s^{-1}. Some error seems probable, but if one exists it cannot be corrected here. Dr. Barnes has kindly informed me that the original records cannot now be located.

TABLE I

Published orbital elements for AW Persei

Element	*Welch & Evans*[23]	*Welch & Evans*[25]	*Vinko*[27]	*Evans et al.*[29]
P (days)	12700 ± 600	13100 ± 1000	12913 ± 194	14594 ± 324
T (MJD)	25450 ± 500	25150 ± 900	25367 ± 279	38682 ± 197
γ (km s^{-1})	+6·9 ± 0·6	+6·9 ± 0·9	+6·89 ± 0·59	+5·5 ± 0·4
K_1 (km s^{-1})	11·3 ± 0·4	11·4 ± 0·6	—	11·6 ± 0·3
e	0·535 ± 0·055	0·55 ± 0·08	0·52 ± 0·07	0·45 ± 0·03
ω (degrees)	226 ± 6	229 ± 10	232·2 ± 5·8	245·9 ± 4·6
$a_1 \sin i$ (Gm)	—	1·71 ± 0·19*	1720 ± 113	2070 ± 80
$a_1 \sin i$ (AU)	11·1 ± 0·7	—	11·4 ± 1·3	13·8 ± 0·5
$f(m)$ ($M_\odot$)	1·15 ± 0·14	1·17 ± 0·30	1·21 ± 0·25	1·66 ± 0·16
R.m.s. residual (wt. 1) (km s^{-1})	—	1·8	—	1·7

*Correctly copied here, but evidently the units given in the original publication should have been Tm and not Gm

spectrum by Böhm-Vitense, Evans, and Welch"; the present writer has not been able to retrieve any such publication, but another paper by Evans[26] alone seems to answer to the description of its intention. That paper's main results are that the companion star is certainly chemically peculiar and probably double.

Another determination of the orbit of AW Per was made in 1993 by Vinko[27]; he contributed some photometry, but the radial velocities that he discussed were those already to be found in the literature. His method appears to have been to fit a standard pulsational radial-velocity curve to observations made over ranges of time small compared with the orbital period, and thereby to derive for the radial velocities at different epochs what might be termed 'normal points', from which the orbit, which has been added to Table I, was obtained. He remarked upon the fact that the radial velocities then available did not cover a complete cycle, and that there was accordingly considerable scope for error. Some years later, in collaboration with Kiss[28], he published five radial velocities of AW Per obtained with an échelle spectrometer on the David Dunlap Observatory 74-inch reflector, all taken within a 20-day interval. The observations were reduced in two different ways — by cross-correlation and by bisection of the line profiles. There were differences typically of half a km s^{-1} between the two methods, not always in the same sense, but in one case the discrepancy was as much as 2·5 km s^{-1}.

Evans, Vinko & Wahlgren[29] collaborated in another determination of the orbit of AW Per, in the year 2000. They used the David Dunlap reflector again, with a normal grating spectrograph which gave a reciprocal dispersion of 10·7 Å mm^{-1}, and a CCD detector. They listed 37 velocities, but one of the entries in their table appears to be duplicated, with identical times and velocities. Their orbit is noted in the final column of Table I.

Evans next collaborated with Massa, who was at the *NASA* headquarters at Greenbelt, in a project[30] to obtain a *Space Telescope* observation of AW Per to measure the apparent angular separation of the binary, which was found to be 13·74 ± 0·26 milliseconds of arc at a position angle of 184°·16 ± 1°·94*. A second measurement of the separation on the sky between the Cepheid and

*Not revealed in the *abstract* of the paper, although the whole purpose of the paper, reflected in its title, was to determine that quantity.

its companion was made[31] in 2012 by a syndicate that might be designated the 'CANDID Collaboration' (after the acronym for the mathematical method whereby they retrieved angular-separation data from multi-aperture interferometry). The collaboration involved no fewer than 18 authors from twelve different institutions. In the case of interest, they used the *CHARA* array[32] of six 1-m telescopes with the *MIRC* image-plane combiner[33], and found a separation of 32 milliseconds at p.a. 67°. Evidently there had been major changes, as expected, in the relative position of the components, but additional measurements will be necessary before the principal objective of the project — to determine the angular size and inclination of the orbit and the absolute masses — can be realized.

The radial velocities in the literature, and the orbits that they offer

An attempt has been made above to summarize the considerable literature that has accumulated regarding AW Per, more particularly as it refers to radial velocities and the long-period orbit. Four determinations of the orbit have been mentioned and are set out in Table I, where it will be apparent that there must have been optimism in at least some quarters over the reliability of the elements, because different determinations differ by more than is consonant with the listed standard deviations of the individual values.

References have been given to no fewer than 11 papers that collectively present more than 100 radial-velocity measurements. Unfortunately most of them refer only to intervals of time (from a single observation up to a duration of a year or even a few years) that are short in comparison with the orbital period. Thus each series is restricted to a small range in orbital phase. Although they can be concatenated to form the basis of a solution of the orbit, they cannot be regarded as other than a motley collection, opening the possibility (probability, even) that an orbital solution based upon them will be subject to uncertainties that may not be correctly represented by the standard deviations found for the elements. Such uncertainties may arise from differences in the effective zero-points of the velocity scales pertaining to the various sources of the velocities, as well as from the use of data of very disparate accuracies in different ranges of phase.

New radial velocities, and the pulsation curve and orbit derived from them

The present writer has attempted to improve on that situation to some extent, by observing AW Per throughout an orbital period. Ideally, the orbit should be seen round a complete cycle by an observer using the same instrumentation throughout, but since the cycle concerned occupies nearly 40 years it is almost inescapable that there will be changes of instrumentation (if not indeed of personnel too) in the course of that interval. It is hard to maintain an instrument in the same form and state over such a time (and the same is at least equally true of an observer!). All the same, an orbit based solely on the writer's own observations seems likely to be more reliable than one based on, or even one incorporating, the many relatively small data sets that are to be found in the literature and are enumerated above.

AW Persei was kindly drawn to the writer's attention by Dr. T. Lloyd Evans at the end of 1975 (the year in which no. 1 of this series of papers, that is now at no. 250, stood up). The object was duly placed on the radial-velocity observing programme of the prototype spectrometer that operated by cross-correlation, and the first observation of it was made early in the following year. The star has

TABLE II

Radial-velocity observations of AW Per (HD 30282)

Except as noted, the sources of the observations are as follows:
Up till 1986 – original spectrometer (weighted ⅓ in orbital solution);
1987–1997 — Haute-Provence Coravel (weight ½);
1999 onwards — Cambridge Coravel (weight 1)

Date (UT)			*MJD*	*Velocity*	*Long-period orbit*		*Pulsation 'orbit'*		*(O – C)*
					Phase	*Velocity*	*Phase*	*Velocity*	
				km s⁻¹		*km s⁻¹*		*km s⁻¹*	*km s⁻¹*
1976	Jan.	29·89	42806·83	+3·9	0·299	+14·5	0·340	−9·8	−0·8
	Mar.	1·88	838·82	+2·3	·302	14·4	5·290	−12·0	−0·1
		5·84	842·78	+38·8	·302	14·4	·902	+21·6	+2·8
	Apr.	7·85	875·79	+20·1:	·304	14·4	11·009	+4·0	+1·7
	Nov.	29·10	43111·04	+9·2	·321	14·0	47·404	−7·0	+2·2
1977	Mar.	1·16*	43203·09	+18·4	0·328	13·9	61·647	+4·7	−0·1
	Apr.	4·83	237·76	+19·4	·330	13·8	67·011	+3·4	+2·1
	Nov.	1·09	448·02	+14·5	·345	13·5	99·540	−0·8	+1·8
		4·06	450·99	+21·8	·346	13·5	·999	+8·1	+0·2
		18·04	464·97	−5·9:	·347	13·4	102·162	−16·7	−2·6
1978	Jan.	22·91	43530·84	+4·0	0·351	13·3	112·353	−9·3	−0·1
		30·90	538·83	+14·4	·352	13·3	113·589	+1·6	−0·6
	Mar.	27·89	594·82	−0·9	·356	13·2	122·251	−13·6	−0·5
	Apr.	14·84	612·77	+12·9	·357	13·2	125·028	−3·3	+3·0
	Aug.	19·12	739·04	+14·3	·366	13·0	144·565	+0·4	+0·9
	Oct.	12·14	793·06	+35·2:	·370	12·9	152·922	+22·2	+0·1
1979	Jan.	14·01	43886·93	+6·7	0·377	12·8	167·445	−5·2	−0·9
	Mar.	21·84	953·76	+26·8	·382	12·7	177·784	+13·2	+1·0
	Sept.	29·01	44144·93	+2·8	·395	12·3	207·360	−9·0	−0·6
1980	Jan.	1 ·94	44239·86	+4·0	0·402	12·2	222·046	−9·0	+0·8
	Sept.	17·18	499·09	−5·2	·421	11·8	262·153	−16·9	−0·1
	Oct.	2·19	514·10	+6·6	·422	11·7	264·475	−3·8	−1·4
		8·08	519·99	+2·5	·422	11·7	265·387	−7·8	−1·5
		10·10	522·01	+19·9	·422	11·7	·699	+7·7	+0·5
	Dec.	8·03	580·94	+26·8	·427	11·6	274·816	+15·6	−0·4
		19·02	591·93	+9·5	·427	11·6	276·516	−1·9	−0·2
1981	Jan.	30·87	44634·78	−7·2	0·430	11·5	283·146	−17·0	−1·7
	Feb.	1·88	636·79	+8·2	·431	11·5	·457	−4·6	+1·3
		4·95	639·86	+34·4	·431	11·5	·932	+22·1	+0·8
	Apr.	17·84	711·75	−0·3:	·436	11·4	295·054	−10·8	−0·9
		18·84	712·75	−3·3	·436	11·4	·208	−15·3	+0·6
		20·85	714·76	+12·0	·436	11·4	295·519	−1·7	+2·3
	Sept.	23·06	869·97	+8·6	·447	11·1	319·532	−1·1	−1·4
		29·16	876·07	+8·5	·448	11·1	320·476	−3·8	+1·1
	Oct.	7·15	884·06	+16·9	·448	11·1	321·712	+8·4	−2·6
		13·13	890·04	+13·5	·449	11·1	322·637	+4·2	−1·7
	Dec.	13·00	950·91	+2·4	·453	11·0	332·054	−10·9	+2·3
		18·97	956·88	+26·4	·454	11·0	·978	+15·6	−0·2
1982	Jan.	10·92	44979·83	+11·1	0·455	10·9	336·528	−1·3	+1·5
		18·88	987·79	+23·5	·456	10·9	337·760	+11·5	+1·0
	Sept.	12·17	45224·08	−1·8	·473	10·5	374·316	−10·8	−1·5
		27·14	239·05	+13·7	·474	10·5	376·632	+3·9	−0·7
1983	Feb.	4·35†	45369·26	+23·1	0·483	10·3	396·777	+12·7	+0·1
		22·89	387·80	+15·4	·484	10·2	399·646	+4·6	+0·5
	Mar.	4·89	397·80	−6·1	·485	10·2	401·193	−15·8	−0·5
		15·84	408·75	+30·4	·486	+10·2	402·887	+20·7	−0·5

TABLE II (*continued*)

Date (UT)			*MJD*	*Velocity*	*Long-period orbit*		*Pulsation 'orbit'*		*(O – C)*
					Phase	*Velocity*	*Phase*	*Velocity*	
				km s⁻¹		*km s⁻¹*		*km s⁻¹*	*km s⁻¹*
1983	Sept.	19·17	45596·07	+31·5	0·499	+9·9	431·869	+19·5	+2·1
		20·18	597·08	+7·0	·499	9·9	432·025	−2·3	−0·6
		22·17	599·07	−2·8	·500	9·9	·333	−10·1	−2·5
	Oct.	31·44[†]	638·34	+3·7	·502	9·8	438·408	−6·8	+0·7
	Nov.	21·03	658·93	+11·2	·504	9·8	441·594	+1·9	−0·5
		23·04	660·94	+30·3	·504	9·8	·905	+21·7	−1·2
		24·03	661·93	−2·5	·504	9·7	442·058	−11·7	−0·6
	Dec.	1·01	668·91	−8·5	·505	9·7	443·138	−17·1	−1·2
		3·03	670·93	+4·5	·505	9·7	·450	−4·9	−0·3
		11·01	678·91	+13·7	·505	9·7	444·685	+6·8	−2·9
		22·07	689·97	+2·5	·506	9·7	446·396	−7·3	+0·1
1984	Jan.	4·91	45703·81	+7·0	0·507	9·7	448·537	−0·9	−1·8
		17·87	716·77	+7·9	·508	9·7	450·542	−0·6	−1·1
		18·87	717·77	+11·2	·508	9·6	·697	+7·6	−6·0
	Feb.	8·85	738·75	+29·9	·510	9·6	453·943	+21·6	−1·4
	Sept.	2·17	945·07	+29·0	·524	9·2	485·863	+19·1	+0·7
	Dec.	11·93[‡]	46045·83	+4·4	·532	9·1	501·452	−4·9	+0·2
1985	Jan.	28·93	46093·83	+31·1	0·535	9·0	508·878	+20·1	+2·0
	Mar.	12·85	136·75	+7·8	·538	8·9	515·518	−1·8	+0·7
	Oct.	5·15	343·05	+2·7	·553	8·5	547·435	−5·6	−0·2
		14·19	352·09	+24·1	·554	8·5	548·833	+16·9	−1·2
		20·12	358·02	+17·3	·554	8·5	549·751	+10·9	−2·1
1986	Jan.	24·88	46454·78	+14·9	0·561	8·3	564·721	+9·0	−2·4
		25·87	455·77	+27·8	·561	8·3	·874	+19·9	−0·4
		26·96	456·86	+1·9	·561	8·3	565·043	−8·0	+1·6
	Oct.	16·15	719·05	+10·7	·580	7·8	605·606	+2·5	+0·4
		17·17	720·07	+18·3	·580	7·8	·764	+11·8	−1·3
		24·11	727·01	+23·7	·580	7·8	606·838	+17·2	−1·3
	Dec.	7·06	770·96	+10·2	·584	7·7	613·638	+4·2	−1·7
		12·01	775·91	+1·4	·584	7·7	614·403	−7·0	+0·7
		13·97	777·87	+13·0	·584	7·7	·707	+8·1	−2·8
1987	Jan.	30·86[§]	46825·76	−9·4	0·588	7·6	622·116	−16·9	−0·1
		31·92[§]	826·82	−4·8	·588	7·6	·280	−12·4	0·0
	Feb.	28·81	854·71	+12·8	·590	7·5	626·595	+1·9	+3·3
	Mar.	1·86	855·76	+21·8	·590	7·5	·757	+11·3	+2·9
		3·85	857·75	−5·7	·590	7·5	627·065	−12·9	−0·3
		5·84	859·74	−2·5	·590	7·5	·373	−8·4	−1·6
		21·85[§]	875·75	+25·4	·591	7·5	629·850	+8·1	−0·2
	Oct.	13·08	47080·98	+10·0	·606	7·1	661·601	+2·3	+0·6
		17·19	085·09	−8·9	·606	7·1	662·237	−14·2	−1·8
		18·18	086·08	+0·3	·606	7·1	·390	−7·6	+0·8
		19·18	087·08	+7·9	·606	7·1	·545	−0·5	+1·3
		23·06[§]	090·96	−9·8	·607	7·1	663·145	−17·0	+0·1
		25·05[§]	092·95	+2·9	·607	7·0	·453	−4·8	+0·6
		29·09[§]	096·99	−7·6	·607	7·0	664·078	−14·7	+0·1
	Dec.	8·09[§]	136·99	−6·8	·610	7·0	670·267	−13·0	−0·8
1988	Jan.	24·34[†]	47184·24	+9·1	0·613	6·9	677·577	+1·1	+1·2
		26·31[†]	186·21	+28·4	·613	6·9	·882	+20·4	+1·1
		31·32[†]	191·22	+10·2	·614	6·8	678·657	+5·2	−1·9
	Feb.	1·30[†]	192·20	+22·2	·614	6·8	·808	+5·0	+0·4
	Mar.	10·90	230·80	+20·2	·617	6·8	684·780	+2·9	+0·5
		11·87	231·77	+31·5	·617	6·8	·930	+2·2	+2·6
		12·87	232·77	−9·0	·617	6·8	685·085	−15·4	−0·4
		13·91	233·81	−7·4	·617	6·8	·246	−13·8	−0·3
		14·87	234·77	−0·2	·617	+6·8	·395	−7·4	+0·5

TABLE II (*continued*)

Date (UT)			*MJD*	*Velocity*	*Long-period orbit*		*Pulsation 'orbit'*		*(O – C)*
					Phase	*Velocity*	*Phase*	*Velocity*	
				km s⁻¹		*km s⁻¹*		*km s⁻¹*	*km s⁻¹*
1988	Nov.	3·07	47467·97	+4·4	0·634	+6·3	721·473	−3·9	+2·0
		6·08	470·98	+29·1	·634	6·3	·939	+21·9	+1·0
		7·18	472·08	−11·4	·634	6·3	722·109	−16·8	−0·9
	Dec.	6·03[§]	500·93	+8·1	·636	6·2	726·573	+0·8	+1·0
		12·96[§]	507·86	+8·5	·636	6·2	727·645	+4·6	−2·3
		19·97[§]	514·87	+16·2	·637	6·2	728·730	+9·5	+0·5
1989	Mar.	25·84	47610·75	+7·3	0·644	6·0	743·562	+0·3	+1·0
		26·84	611·75	+13·5	·644	6·0	·717	+8·7	−1·2
		30·82	615·73	−3·5	·644	6·0	744·332	−10·2	+0·7
	Oct.	29·97	828·88	−4·7	·659	5·5	777·309	−11·2	+1·0
	Nov.	1·07	830·98	+9·3	·660	5·5	·634	+4·0	−0·2
		17·08[§]	846·99	−13·0	·661	5·5	780·111	−16·8	−1·7
		26·03[§]	855·94	+3·9	·661	5·4	781·496	−2·8	+1·3
1990	Jan.	26·85	47917·76	−7·5	0·666	5·3	791·060	−12·1	−0·7
		30·95	921·86	+11·8	·666	5·3	·695	+7·4	−0·9
	Oct.	7·17[§]	48171·08	−8·6	·684	4·7	830·252	−13·6	+0·3
		8·15[§]	172·06	−2·2	·684	4·7	·404	−7·0	+0·1
		13·14[§]	177·05	−11·5	·684	4·7	831·176	−16·4	+0·1
1991	Jan.	26·99	48282·90	+6·7	0·692	4·5	847·552	−0·2	+2·4
		28·00	283·91	+11·8	·692	4·5	·708	+8·2	−0·9
		29·95	285·86	+6·9	·692	4·5	848·010	+3·6	−1·2
		31·01	286·92	−12·7	·692	4·5	·174	−16·4	−0·8
	Feb.	1·01	287·92	−6·5	·692	4·5	·329	−10·3	−0·7
		3·00	289·91	+8·9	·692	4·5	·637	+4·1	+0·3
		3·94	290·85	+17·1	·693	4·5	·782	+13·1	−0·4
		4·98	291·89	+25·4	·693	4·5	·943	+21·6	−0·7
		5·91	292·82	−10·3	·693	4·4	849·087	−15·5	+0·8
	Oct.	29·08	558·00	−14·2	·712	3·8	890·112	−16·8	−1·2
	Nov.	1·02	560·94	+6·1	·712	3·8	·567	+0·6	+1·7
	Dec.	17·06	606·98	+9·8	·715	3·7	897·690	+7·1	−1·0
		18·87	608·79	+20·8	·715	3·7	·970	+17·6	−0·5
		21·00	610·92	−7·6	·715	3·7	898·300	−11·6	+0·3
1992	Jan.	13·96	48634·88	+8·0	0·717	3·6	902·007	+5·0	−0·6
		15·00	635·92	−13·0	·717	3·6	·168	−16·6	0·0
		16·00	636·92	−7·5	·717	3·6	·322	−10·6	−0·5
		16·96	637·88	−0·4	·717	3·6	·471	−4·0	0·0
		17·98	638·90	+6·7	·718	3·6	·629	+3·7	−0·6
		20·96	641·88	−13·5	·718	3·6	903·090	−15·8	−1·4
		22·96	643·88	−3·0	·718	3·6	·399	−7·2	+0·6
	Dec.	18·03	973·95	−1·2	·742	2·8	954·466	−4·2	+0·2
		19·07	974·99	+6·6	·742	2·8	·627	+3·6	+0·2
		21·07	976·99	+26·2	·742	2·8	·936	+22·0	+1·4
		21·98	977·90	−13·4	·742	2·8	955·077	−14·5	−1·6
1993	Feb.	10·91	49028·83	+23·1	0·745	2·6	962·956	+20·2	+0·2
		11·80	029·72	−14·0	·746	2·6	963·094	−16·1	−0·6
		12·91	030·83	−11·0	·746	2·6	·266	−13·0	−0·6
		13·96	031·88	−2·7	·746	2·6	·428	−5·9	+0·6
		14·97	032·89	+5·6	·746	2·6	·585	+1·4	+1·6
		15·89	033·81	+11·1	·746	2·6	·727	+9·4	−0·9
		17·81	035·73	+0·2	·746	2·6	964·024	−1·9	−0·6
		17·94	035·86	−6·6	·746	2·6	·044	−8·4	−0·8
		18·95	036·87	−12·4	·746	2·6	·200	−15·6	+0·6
	Dec.	25·99	346·92	−16·2	·768	1·8	1012·168	−16·6	−1·4
		26·93	347·86	−8·9	·768	1·8	·313	−11·0	+0·3
		28·00	348·93	−0·6	·768	1·8	·479	−3·6	+1·2
		28·88	349·81	+5·1	·768	1·8	·615	+3·0	+0·3
		30·07	351·00	+16·2	·769	+1·8	·799	14·3	+0·1

TABLE II (*continued*)

Date (UT)			*MJD*	*Velocity*	*Long-period orbit*		*Pulsation 'orbit'*		*(O – C)*
					Phase	*Velocity*	*Phase*	*Velocity*	
				km s^{-1}		*km s*$^{-1}$		*km s*$^{-1}$	*km s*$^{-1}$
1994	Jan.	1·87	49353·80	−11·7	0·769	+1·8	1013·232	−14·4	+0·9
		5·05	356·98	+9·9	·769	1·7	·724	+9·2	−1·1
	Dec.	28·14	714·08	+18·6	·795	0·7	1068·972	+17·3	+0·6
		28·73	714·67	−9·3	·795	0·7	1069·063	−12·6	+2·5
		28·84	714·78	−14·5	·795	0·7	·080	−14·9	−0·3
		28·94	714·88	−15·5	·795	0·7	·095	−16·1	−0·1
		29·15	715·09	−17·4	·795	0·7	·128	−17·1	−1·1
1995	Jan.	1·89	49718·83	+7·9	0·795	0·7	1069·707	+8·1	−0·9
		2·99	719·93	+22·1	·795	0·7	·877	+20·1	+1·3
		3·14	720·08	+21·9	·795	0·7	·900	+21·5	−0·3
		3·71	720·65	+10·3	·795	0·7	·988	+12·3	−2·7
		3·82	720·76	+6·0	·795	0·7	1070·005	+5·7	−0·4
		3·95	720·89	−0·8	·795	0·7	·025	−2·4	+0·8
		4·07	721·01	−6·4	·795	0·7	·044	−8·3	+1·2
		4·19	721·13	−12·4	·795	0·7	·062	−12·5	−0·6
		5·02	721·96	−14·2	·795	0·7	·191	−15·9	+1·0
		7·04	723·98	0·0	·795	0·7	·503	−2·5	+1·8
		8·05	724·99	+6·5	·795	0·7	·660	+5·4	+0·4
		8·92	725·86	+7·5	·795	+0·7	·794	+13·9	+2·9
	Dec.	22·06	50073·01	−0·8	·820	−0·3	1124·502	−2·5	+2·1
		24·03	074·98	+15·4	·820	−0·3	·807	+14·9	+0·9
		26·88	077·83	−14·0	·821	−0·3	1125·248	−13·8	+0·1
		31·72	082·67	+7·9	·821	−0·4	·997	+9·0	−0·8
		31·85	082·80	+0·3	·821	−0·4	1126·017	+0·9	−0·2
		31·96	082·91	−5·2	·821	−0·4	·034	−5·4	+0·5
1996	Jan.	1·09	50083·04	−11·2	0·821	−0·4	1126·054	−10·8	0·0
	Dec.	15·00	431·96	−8·8	·846	−1·4	1180·036	−6·0	−1·3
		15·11	432·07	−12·9	·846	−1·4	·053	−10·6	−0·9
		16·04	433·00	−17·2	·846	−1·4	·197	−15·7	−0·1
		17·93	434·89	−3·8	·846	−1·4	·489	−3·1	+0·8
		22·01	438·97	−20·0	·847	−1·4	1181·121	−17·0	−1·6
1997	Jan.	22·92	50470·88	−13·6	0·849	−1·5	1186·058	−11·6	−0·5
		23·94	471·90	−16·6	·849	−1·5	·215	−15·0	0·0
		24·96	472·92	−9·6	·849	−1·6	·373	−8·4	+0·3
		26·90	474·86	+4·3	·849	−1·6	·673	+6·2	−0·3
	Feb.	10·82	489·78	+11·1	·850	−1·6	1188·982	+14·4	−1·7
	Dec.	20·95	802·92	−7·8	·873	−2·5	1237·428	−5·9	+0·6
		22·07	804·04	+0·6	·873	−2·5	·601	+2·3	+0·8
		22·90	804·87	+7·2	·873	−2·5	·730	+9·6	+0·2
		23·96	805·93	+20·9	·873	−2·5	·894	+21·2	+2·3
		25·02	806·99	−14·3	·873	−2·5	1238·058	−11·6	−0·1
		25·95	807·92	−19·7	·873	−2·5	·202	−15·5	−1·6
		26·79	808·76	−12·8	·873	−2·6	·332	−10·2	−0·1
1999	Dec.	20·07	51532·07	−17·9	0·925	−3·9	1350·236	−14·2	+0·3
		27·08	539·08	−15·0	·925	−3·9	·320	−10·7	−0·4
		28·97	540·97	−0·7	·926	−3·9	·613	+2·9	+0·4
		29·92	541·92	+6·6	·926	−3·9	·760	+11·5	−1·0
2000	Jan.	8·99	51551·99	−13·7	0·926	−4·0	1353·318	−10·8	+1·0
		9·89	552·89	−6·8	·926	−4·0	·457	−4·6	+1·8
		13·91	556·91	−17·0	·927	−4·0	1354·079	−14·8	+1·7
		15·88	558·88	−10·3	·927	−4·0	·384	−7·9	+1·5
		17·94	560·94	+1·7	·927	−4·0	·703	+7·9	−2·2
		19·99	562·99	−3·2	·927	−4·0	1355·020	−0·3	+1·0
	Nov.	17·09	865·10	+6·4	·949	−3·5	1401·760	+11·5	−1·6
		30·06	878·07	+8·1	·950	−3·5	1403·767	+12·0	−0·4

TABLE II (*continued*)

Date (UT)			*MJD*	*Velocity*	*Long-period orbit*		*Pulsation 'orbit'*		*(O – C)*
					Phase	*Velocity*	*Phase*	*Velocity*	
				km s⁻¹		*km s⁻¹*		*km s⁻¹*	*km s⁻¹*
2000	Dec.	2·11	51880·12	–18·2	0·950	–3·4	1404·084	–15·3	+0·5
		3·03	881·04	–17·9	·950	–3·4	·226	–14·6	+0·2
		9·08	887·09	–19·5	·950	–3·4	1405·162	–16·7	+0·6
		9·98	887·99	–15·5	·950	–3·4	·302	–11·5	–0·6
		14·05	892·06	+19·1	·951	–3·4	·931	+22·1	+0·4
		28·97	906·98	–18·4	·952	–3·3	1408·240	–14·1	–1·0
		30·01	908·02	–10·1	·952	–3·3	·400	–7·1	+0·4
		30·87	908·88	–3·2	·952	–3·3	·534	–1·1	+1·2
2001	Jan.	6·96	51915·97	+0·4	0·952	–3·3	1409·631	+3·8	–0·1
		7·91	916·92	+8·9	·952	–3·3	·777	+12·7	–0·5
		8·93	917·94	+18·8	·953	–3·3	·935	+22·0	+0·1
		9·93	918·94	–20·0	·953	–3·3	1410·090	–15·8	–0·9
		10·97	919·98	–16·7	·953	–3·3	·251	–13·6	+0·2
		13·90	922·91	+2·7	·953	–3·3	·704	+8·0	–2·0
		15·93	924·94	–3·8	·953	–3·3	1411·018	+0·3	–0·9
	Oct.	7·14	52189·16	+20·0	·972	–1·6	1451·896	+21·3	+0·3
	Nov.	1·06	214·08	+8·0	·974	–1·4	1455·752	+11·0	–1·6
		2·08	215·10	+20·5	·974	–1·4	·910	+21·9	0·0
		3·13	216·15	–16·5	·974	–1·4	1456·072	–13·9	–1·2
	Dec.	15·09	258·11	–0·3	·977	–1·0	1462·564	+0·4	+0·3
		31·97	275·00	–16·6	·978	–0·8	1465·175	–16·4	+0·6
2002	Jan.	17·91	52291·94	+13·3	0·979	–0·6	1467·796	+14·1	–0·2
		24·92	298·95	+20·2	·980	–0·6	1468·881	+20·4	+0·4
		28·77	302·80	–3·8	·980	–0·5	1469·477	–3·7	+0·4
	Feb.	14·83	319·86	–16·6	·981	–0·3	1472·116	–16·9	+0·7
	Oct.	24·13	571·16	+11·9	·999	+2·8	1510·996	+9·3	–0·2
	Dec.	11·14	619·17	–2·3	1·003	3·5	1518·424	–6·1	+0·3
2003	Jan.	5·05	52644·08	–8·7	1·005	3·8	1522·278	–12·5	0·0
		6·00	645·03	–1·5	·005	3·8	·425	–6·1	+0·7
		7·10	646·13	+6·0	·005	3·9	·595	+2·0	+0·2
		10·04	649·07	–4·4	·005	3·9	1523·050	–9·9	+1·6
		15·97	655·00	+21·7	·005	4·0	·967	+18·3	–0·6
	Feb.	19·89	689·92	–3·7	·008	4·5	1529·370	–8·5	+0·3
		20·87	690·90	+4·3	·008	4·5	·521	–1·6	+1·4
		21·88	691·91	+9·2	·008	4·5	·678	+6·4	–1·7
	Mar.	16·87	714·90	–9·3	·010	4·8	1533·235	–14·3	+0·2
		27·84	725·87	+27·0	·010	5·0	1534·932	+22·1	–0·1
	Apr.	16·85	745·88	+1·3	·012	5·3	1538·028	–3·2	–0·8
	Sept.	24·18	906·22	+24·0	·023	7·6	1562·833	+16·8	–0·4
		29·15	911·19	+10·7	·024	7·6	1563·602	+2·3	+0·8
	Oct.	12·16	924·20	+11·2	·025	7·8	1565·614	+3·0	+0·4
	Nov.	13·11	956·15	+10·0	·027	8·2	1570·557	+0·1	+1·7
	Dec.	16·05	989·09	+12·9	·029	8·7	1575·654	+5·1	–0·8
2004	Jan.	17·03	53021·07	+11·2	1·032	9·1	1580·601	+2·3	–0·2
	Feb.	8·95	043·99	–8·4	·033	9·4	1584·147	–17·0	–0·8
	Mar.	29·86	093·90	+30·6	·037	10·0	1591·869	+19·5	+1·1
	Apr.	16·84	111·88	+13·9	·038	10·2	1594·651	+4·9	–1·2
	Sept.	6·18	254·21	+17·0	·048	11·7	1616·672	+6·1	–0·8
		16·14	264·17	–2·9	·049	11·8	1618·213	–15·1	+0·4
	Oct.	22·15	300·18	+25·3	·052	12·2	1623·784	+13·2	–0·1
	Nov.	13·11	322·14	–3·4	·053	12·4	1627·182	–16·2	+0·4
	Dec.	20·94	359·97	+7·7	·056	12·7	1633·034	–5·4	+0·4
2005	Jan.	4·98	53375·01	+3·9	1·057	12·8	1635·361	–8·9	0·0
	Feb.	8·89	409·92	+23·5	·060	13·1	1640·762	+11·7	–1·3
	Mar.	17·89	446·92	+10·6	·062	+13·4	1646·486	–3·3	+0·5

TABLE II (*continued*)

Date (UT)			*MJD*	*Velocity*	*Long-period orbit*		*Pulsation 'orbit'*		*(O – C)*
					Phase	*Velocity*	*Phase*	*Velocity*	
				km s⁻¹		*km s⁻¹*		*km s⁻¹*	*km s⁻¹*
2005	Sept.	28·20	53641·23	+15·4	1·076	+14·6	1676·548	−0·4	+1·2
	Nov.	4·12	678·15	+1·6	·079	14·8	1682·259	−13·3	+0·1
		13·14	687·17	+19·5	·079	14·9	1683·655	+5·1	−0·5
		30·04	704·07	+1·6	·081	14·9	1686·269	−12·9	−0·5
	Dec.	17·11	721·14	+35·8	·082	15·0	1688·910	+21·9	−1·2
		18·01	722·04	+5·9	·082	15·0	1689·050	−9·8	+0·7
2006	Jan.	28·89	53763·92	+14·5	1·085	15·2	1695·529	−1·3	+0·6
	Feb.	25·88	791·90	+34·7	·087	15·3	1699·859	+18·8	+0·6
	Mar.	4·82	798·84	+37·1	·087	15·4	1700·933	+22·1	−0·4
	Apr.	3·86	828·88	+17·4	·090	15·5	1705·580	+1·2	+0·7
	Sept.	20·20	998·22	+29·1	·102	16·0	1731·778	+12·8	+0·3
	Oct.	25·12	54033·14	−0·6	·104	16·1	1737·181	−16·2	−0·5
	Nov.	1·14	040·16	+2·6	·105	16·1	1738·267	−13·0	−0·5
		17·11	056·13	+25·0	·106	16·1	1740·737	+10·1	−1·2
	Dec.	9·07	078·09	−1·6	·107	16·2	1744·135	−17·1	−0·7
2007	Jan.	14·92	54114·94	+33·6	1·110	16·3	1749·836	+17·0	+0·3
		22·98	123·00	+0·4	·111	16·3	1751·083	−15·2	−0·7
	Feb.	3·96	134·98	+38·4	·111	16·3	1752·936	+22·0	+0·1
	Apr.	1·82	191·83	+24·8	·116	16·4	1761·733	+9·8	−1·3
		9·85	199·86	+32·5	·116	16·4	1762·975	+16·4	−0·3
		10·85	200·86	−1·6	·116	16·4	1763·130	−17·1	−0·9
	Oct.	5·17	378·18	+18·7	·129	16·6	1790·562	+0·3	+1·8
		21·11	394·12	+13·8	·130	16·6	1793·029	−3·5	+0·7
	Nov.	3·17	407·18	+7·0	·131	16·6	1795·049	−9·7	0·0
		9·10	413·11	+34·1	·131	16·6	·966	+18·5	−1·0
		16·08	420·09	+8·4	·132	16·6	1797·046	−9·0	+0·7
	Dec.	11·01	445·02	+38·5	·134	16·7	1800·903	+21·6	+0·2
2008	Jan.	5·98	54470·99	+39·1	1·136	16·7	1804·921	+22·2	+0·3
		24·90	489·91	+34·8	·137	16·7	1807·848	+18·0	+0·2
	Feb.	26·93	522·93	+36·4	·139	16·7	1812·958	+20·0	−0·3
	Mar.	30·85	555·85	+7·4	·142	16·7	1818·051	−10·1	+0·8
	Apr.	23·85	579·85	+27·3	·143	16·7	1821·764	+11·8	−1·2
	Oct.	11·12	750·12	−0·4	·156	16·7	1848·106	−16·6	−0·5
		17·23	756·23	+7·3	·156	16·7	1849·051	−10·2	+0·8
	Dec.	7·06	807·06	+38·9	·160	16·7	1856·915	+22·1	+0·1
		26·98	826·98	+25·4	·161	16·7	1859·997	+9·1	−0·4
2009	Jan.	2·97	54833·97	+1·8	1·162	16·7	1861·078	−14·7	−0·2
	Mar.	20·84	910·83	+33·5	·167	16·7	1872·970	+17·6	−0·8
		27·88	917·87	+4·8	·168	16·7	1874·060	−11·9	+0·1
	Apr.	8·85	929·84	+38·4	·168	16·6	1875·911	+22·0	−0·2
	Oct.	12·19	55116·18	+25·6	·182	16·5	1904·740	+10·2	−1·1
2010	Jan.	31·00	55226·98	+37·5	1·190	16·4	1921·883	+20·5	+0·6
		31·95	227·93	+11·5	·190	16·4	1922·030	−3·9	−1·0
	Feb.	26·94	253·92	+7·0	·192	16·4	1926·050	−10·0	+0·6
	Oct.	20·18	489·16	+11·7	·209	16·2	1962·444	−5·2	+0·7
	Nov.	15·08	515·06	+12·0	·210	16·2	1966·451	−4·9	+0·7
		26·10	526·08	−0·7	·211	16·1	1968·156	−16·8	0·0
2011	Jan.	9·93	55570·91	+0·2	1·214	16·1	1975·091	−15·9	0·0
	Apr.	8·86	659·83	+34·7	·221	16·0	1988·849	+18·1	+0·7
	Sept.	24·20	828·17	+38·4	·233	15·8	2014·893	+21·1	+1·5
	Oct.	1·15	835·12	+34·9	·233	15·8	2015·968	+18·2	+1·0
		7·16	841·13	+38·8	·234	15·8	2016·898	+21·4	+1·7
	Nov.	23·11	888·08	−1·8	·237	15·7	2024·161	−16·7	−0·8
		28·08	893·05	+37·2	·238	+15·7	·930	+22·2	−0·7

TABLE II (*concluded*)

Date (UT)			*MJD*	*Velocity* *km s⁻¹*	*Long-period orbit* *Phase*	*Velocity* *km s⁻¹*	*Pulsation 'orbit'* *Phase*	*Velocity* *km s⁻¹*	*(O – C)* *km s⁻¹*
2011	Dec.	6·01	55900·98	−0·2	1·238	+15·7	2026·157	−16·8	+0·9
		18·02	912·99	+17·1	·239	15·7	2028·015	+1·6	−0·2
2012	Jan.	5·95	55931·92	+37·3	1·240	15·6	2030·944	+21·6	+0·1
	Feb.	7·83	964·80	+11·9	·243	15·6	2036·030	−4·2	+0·5
	Apr.	5·83	56022·79	+21·6	·247	15·5	2045·004	+6·3	−0·3
	Sept.	15·19	185·15	−2·2	·258	15·3	2070·122	−17·0	−0·5
	Nov.	6·15	237·11	−1·8	·262	15·2	2078·160	−16·7	−0·3
		18·06	249·02	+22·7	·263	15·2	2080·003	+6·5	+1·0
		30·11	261·07	+34·9	·264	15·2	2081·867	+19·4	+0·3
2013	Jan.	3·04	56295·00	−2·1	1·266	15·1	2087·117	−16·9	−0·3
	Feb.	3·94	326·90	+6·5	·269	15·1	2092·052	−10·3	+1·7
	Apr.	1·84	383·79	+33·4	·273	15·0	2100·855	+18·5	−0·1
	Nov.	8·13	604·08	+36·6	·288	14·7	2134·935	+22·0	−0·1
		9·11	605·06	−1·1	·289	14·7	2135·087	−15·5	−0·3
	Dec.	5·07	631·02	−2·2	·290	14·7	2139·103	−16·5	−0·3
		22·98	648·93	+35·6	·292	14·6	2141·874	+19·9	+1·1
2014	Jan.	4·99	56661·94	+36·0	1·293	14·6	2143·887	+20·7	+0·7
		11·92	668·87	+33·7	·293	14·6	2144·959	+19·9	−0·8
	Mar.	4·85	720·80	+25·1	·297	14·5	2152·993	+10·6	0·0
	Sept.	25·19	925·13	+17·0	·312	14·2	2184·606	+2·5	+0·3
	Oct.	10·18	940·12	+37·4	·313	14·2	2186·925	+22·2	+1·0
		28·12	958·06	+20·7	·314	14·2	2189·700	+7·8	−1·2
	Nov.	6·12	967·06	−2·1	·315	14·1	2191·093	−16·0	−0·3
		8·11	969·05	+7·0	·315	14·1	·401	−7·1	0·0
		24·04	984·98	+33·7	·316	14·1	2193·865	+19·2	+0·3
	Dec.	6·04	996·98	+21·5	·317	14·1	2195·722	+9·1	−1·7
		29·93	57020·87	+7·7	·318	14·1	2199·418	−6·4	0·0
2015	Jan.	16·90	57038·84	−1·5	1·320	14·0	2202·198	−15·7	+0·1
	Feb.	17·84	070·78	−3·5	·322	14·0	2207·139	−17·0	−0·4
	Apr.	19·84	131·78	+15·3	·326	13·9	2216·576	+1·0	+0·4
	Sept.	7·19	272·13	+0·5	·336	13·7	2238·290	−12·0	−1·2
	Nov.	26·04	351·97	+16·8	·342	13·5	2250·643	+4·5	−1·2
	Dec.	7·98	363·91	+11·4	·343	13·5	2252·490	−3·1	+1·0
		31·95	387·88	−1·9	·345	13·5	2256·199	−15·6	+0·3
2016	Jan.	15·92	57402·85	+11·9	1·346	13·5	2258·515	−1·9	+0·4
	Feb.	11·89	429·82	+18·3	·348	13·4	2262·687	+7·0	−2·1
	Apr.	5·85	483·78	+8·0	·352	+13·3	2271·035	−5·8	+0·5

*Observed with Palomar 200-inch telescope.
†Observed with DAO 48-inch telescope.
‡Observed by Dr. S. K. Jain at Cambridge.
§Observed with original Cambridge spectrometer.

been kept under observation ever since, with several measurements being made in every calendar year apart from 1998, when the writer was in difficulties over a new spectrometer. The observations are set out in Table II; the great majority come from one or other of three sources — the instruments upon which the writer mainly relied in successive intervals of time. There are 89 measurements made with the original spectrometer[19] at Cambridge, 104 made on a guest-investigator basis with the *Coravel* instrument[36] on the Haute-Provence 1-m telescope, on which the writer was kindly granted observing time by

Dr. M. Mayor, and 159 made since 1999 with the Cambridge *Coravel*. There are enough data from each of the three sources to assess reasonably reliable relative weightings for them: the weighted mean-square residuals have been brought into near-equality by giving the velocities obtained with the Haute-Provence *Coravel* weight ½ and those stemming from the original spectrometer ⅓. (The weightings of four of the latter, noted as uncertain at the respective times of observation, have been halved.) In addition there are six velocities obtained by the writer with the spectrometer[37] on the DAO 48-inch reflector; they have been given half-weight, which is approximately what their residuals suggest, but are not numerous (or bad!) enough to cause any uncertainty in their weighting to have any considerable effect on the solution of the orbit. There is also one measurement made with the spectrometer[38] on the 200-inch telescope and given full weight. The total number of radial velocities is 359; the unusual richness of the data set has arisen because it has been needful to track the 6½-day Cepheid pulsation (whose radial-velocity amplitude is almost double that of the orbit) in addition to the orbital variation.

The pulsation can be represented approximately by a Keplerian orbital velocity curve, and that is the basis upon which the velocities are discussed here. They have been treated as if they were documenting simultaneously an outer and an inner orbit, as indeed has been the actual case with certain stars previously treated in this series of papers*. Of course the residuals of the AW Per velocities from the 'orbits' would be somewhat reduced if a fully realistic velocity curve were adopted for the Cepheid-type velocity variation. The results of the writer's efforts are presented in the two figures showing respectively the orbital and pulsational velocity curves, and in the corresponding numerical results given in Table III.

TABLE III

'Orbital' elements of AW Persei from the writer's observations

Element	*Binary orbit*	*Cepheid pulsation, as if an orbit*
P (days)	13954 ± 181	6·463637 ± 0·000005
T (MJD)	52580 ± 28	51873·116 ± 0·006
γ (km s^{-1})	+8·03 ± 0·08	
K (km s^{-1})	10·33 ± 0·08	19·63 ± 0·08
e	0·474 ± 0·008	0·4925 ± 0·0033
ω (degrees)	250·4 ± 1·3	74·6 ± 0·6
$a_1 \sin i$ (Gm)	1746 ± 28	1·519 ± 0·007
$f(m)$ ($M_\odot$)	1·09 ± 0·06	0·00335 ± 0·00005
$P(true)$ (days)		6·463464 ± 0·000005

Difference between observed and true periods of pulsation = 34·5 *s.d.s*

The large mass function, of slightly more than one solar mass, certainly demonstrates that AW Per has a massive companion; in the absence, however, of knowledge of the Cepheid's mass or of the radial-velocity amplitude of the companion (or even whether the companion is itself a binary), we cannot make much further progress in elucidating the nature of the system. What is needed

* Most recently, HD 20577[34], but a better example, that has been seen completely round its outer orbit, is HD 103613[35].

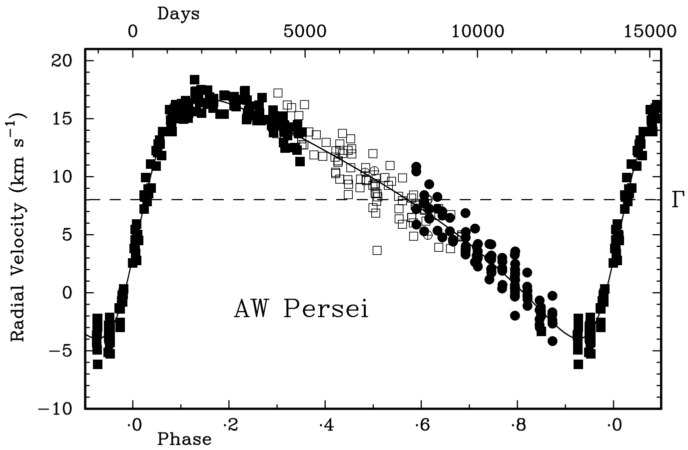

FIG. 1

Orbital radial-velocity curve for AW Persei. The velocity components attributed to the Cepheid's 6½-day pulsation, whose amplitude is almost double that of the orbital variation, have been subtracted from the observed radial velocities. The great majority of the observations have been made in more or less distinct ranges of phase by three instruments successively, represented by open squares, filled circles, and filled squares. They represent, respectively, the original spectrometer[19] at Cambridge (weight ⅓ in the solution of the 'orbits'; open squares), the *Coravel* at Haute-Provence[36] (weight ½, filled circles), and the Cambridge *Coravel* (weight 1, filled squares). There are also six observations made with the spectrometer at the DAO[37] (weight ½, plotted as open circles with plusses in them), and one with the one at the 200-inch reflector[38] (weight 1) which in principle is represented by a star symbol but it is actually hidden by other points.

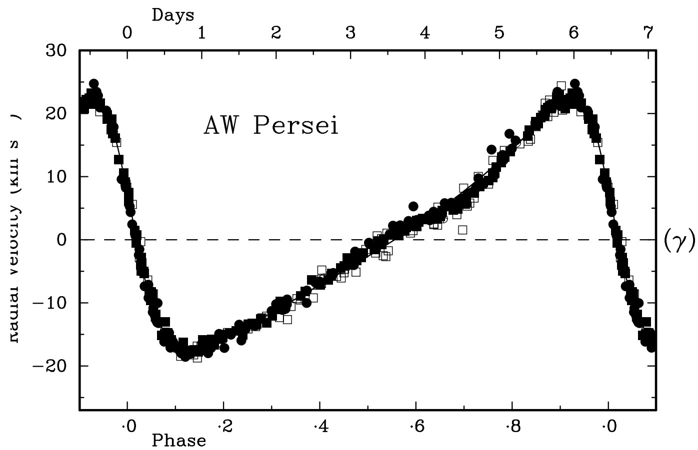

FIG. 2

Pulsational radial-velocity curve for AW Persei. The full line (mostly hidden by the points) is not drawn to follow faithfully the trend of the points but is the nearest-matching Keplerian velocity curve. The observations are represented by the same symbols as in Fig. 1.

next is a series of spectroscopic observations, probably best made near minima in the Cepheid's brightness, with a view to disentangling the mutually blended spectra to determine the nature and possible multiplicity of the companion. It will also be most helpful to resolve the system on the sky, and (necessarily after considerable delay) to determine the orbital inclination and the absolute masses of the components.

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AN UPPER LIMIT TO THE MASS OF A CLOSE COMPANION CANDIDATE TO σ ORI E

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The famous, very young, helium rich, magnetically active, radio and X-ray emitter, short-period rotationally variable, spectroscopically peculiar star σ Ori E may have a close late-type stellar companion, which could explain flaring activity observed in some σ Ori E X-ray light-curves. In 2009, Bouy *et al.* announced the detection of a faint companion candidate in the *Ks* band at 0·330 arcsec (130 AU) from the B2 Vp primary. Here, we carry out z'-band lucky imaging with *AstraLux* at the 2·2-m Calar Alto telescope in an attempt to constrain the properties of the companion candidate to σ Ori E. We impose a maximum mass of $2{\cdot}0^{+0{\cdot}2}_{-0{\cdot}1}\,M_{\odot}$ and an earliest spectral type of K2 ± 1, which leaves the door open to a new, inexpensive, near-infrared, adaptive-optics study.

Introduction

The helium-rich peculiarity of the spectrum of the B2 Vp star σ Ori E (48 Ori E, V1030 Ori, HD 37479, Mayrit 42062) was first noticed in 1956 by Berger[1], and two years later made widely public by Greenstein & Wallerstein[2]. Six decades later, approximately 50 dedicated works on σ Ori E have received over 1000 citations (*e.g.*, *The magnetic field of σ Ori E*[3]*, The rigidly rotating magnetosphere of σ Ori E*[4]*, Shell and photosphere of σ Ori E – New observations and improved model*[5]*, A new phenomenon in the spectrum of σ Ori E*[6]*, etc.*). Actually, for decades the star attracted more attention than the rest of stars in the 3-Myr-old σ Orionis cluster, which is now a cornerstone for studies of circumstellar discs, coronal emission, accretion, and, especially, the mass function down to the substellar limit and beyond[7–9]. With an early-B spectral type and a mass of 7–8 $M_{\odot}$, σ Ori E is one of the most massive stars in the homonymous Trapezium-like system σ Ori, which also gives the name to the cluster and illuminates the Horsehead Nebula[10–12].

The B2 Vp star σ Ori E is abnormally rich in helium[13–17] and magnetically active[18,19]; it is indeed the prototype of magnetic peculiar Bp stars. Furthermore, it also displays periodic variability of 1·19 d in optical photometry and spectroscopy[17,20–25], photospheric and wind absorption lines[5,26,27], linear and circular polarization[3,18,28–30], emission in Hα[6,31,32], non-thermal radio[33–37], and X-rays[38–41]. According to the most accepted scenarios proposed by Nakajima[42], Groote & Hunger[43], and Townsend *et al.*[4], the origin of the variability resides in abundance heterogeneities on the stellar surface that rotate rigidly with, and are connected through, radiatively driven wind streams to at least two clouds of confined plasma in a circumstellar magnetosphere. The very different inclinations of the stellar magnetic and rotational axes shape such a weird configuration.

Besides that, strong X-ray flares in σ Ori E were reported by Groote & Schmitt with *ROSAT*[44] and Sanz-Forcada *et al.* with *XMM–Newton*[45]. Observed flares are typical in young late-type stars, but virtually missing in early-type stars like σ Ori E. Magnetohydrodynamic simulations supported a centrifugal-breakout hypothesis that could explain the reconnection heating and following X-ray flaring from the B2 Vp star[46,47]. However, centrifugal breakout was afterwards ruled out with an accurate photometric monitoring of σ Ori E with the *MOST* microsatellite[25]. Another explanation for the X-ray flares, proposed by Caballero *et al.*[41,48], is the existence of an unresolved K–M-type stellar companion. In this scenario, σ Ori E would become a Lindroos binary system made up of a B-type primary and a late-type companion[49–51].

In 2009, using multi-conjugate adaptive optics in the near infrared, Bouy *et al.*[52] discovered a companion candidate to σ Ori E, 3–4 magnitudes fainter in *Ks*, at only $\rho \sim 0{\cdot}330$ arcsec and $\theta \sim 301°$ (note the corrected position angle[12]). In spite of the numerous works devoted to σ Ori E, this companion candidate at the limit of resolution and sensitivity of the Bouy *et al.* observations has never been confirmed. At the cluster distance of 385 pc[11,53], the measured angular separation translates into a projected physical separation of 130 AU. The radius of σ Ori E is of the order of 3–4 $R_{\odot}$[25,30], while the circumstellar magnetosphere with its two plasma-confinement regions could extend to up to 2·4 stellar radii[30] (*i.e.*, about 0·04 AU). In spite of the apparently large physical separation between the candidate companion to σ Ori E and its circumstellar magnetosphere, the existence of wind collision and/or magnetic channelling might explain the high-order variations to the rigidly-rotating-magnetosphere model[4,19]. If it were not the case, a (young, active) late-type companion may at least explain the observed X-ray flares observed by Groote & Schmitt and Sanz-Forcada *et al.*

In this work, we present new, red-optical, lucky-imaging observations of very high spatial resolution with the aim of characterizing the faint companion to σ Ori E and of improving the uncertain measures of position and flux by Bouy *et al.*

Observations and analysis

On 2014 Oct 22, we observed σ Ori E ($V = 6^{\rm m}{\cdot}61$) with the lucky-imaging camera *AstraLux Norte*[54] in service mode under director's discretionary time. *AstraLux* was attached to the Cassegrain focus of the 2·2-m telescope of the Calar Alto Observatory, in Almería, Spain. We got 50 000 frames of 15 ms in frame-transfer mode for each of the two passbands used, SDSS i' and z'. We fixed the gain for both filters, did windowing in a 256 × 256-pixel sub-array, used the right part of the electron-multiplying high-speed CCD to exclude the bad column #242, chose the quadrant least affected by dust, and set all other parameters to default. Total exposure time per filter was 750 s. For a precise astrometric calibration, we also observed a field centred on the M3 globular cluster.

We did a standard reduction of the data with the dedicated *AstraLux* pipeline[54] by selecting only the best 1·0, 2·5, and 5·0% of all frames, and by shifting, stacking, and re-sampling them into a nearly diffraction-limited image[55,56] (the *AstraLux* pipeline also provides the option of selecting the best 10% frames). The final plate scale was 0·02327 arcsec/pixel. Unfortunately, the i'-band image showed an apparent elongation in the north–south direction, probably due to incorrect focussing, and could not be used for the following analysis. The full final z'-band image, together with a *SofI/NTT* image with a larger field of view for comparison, is shown in Fig. 1.

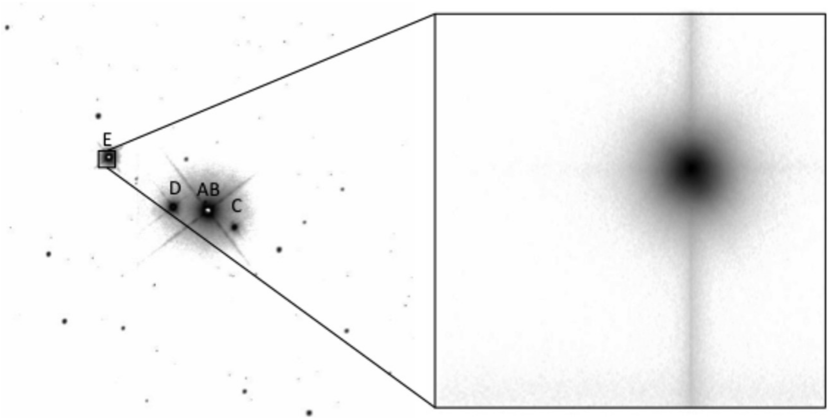

FIG. 1

Left: part of a *SofI*/3·6-m *New Technology Telescope J*-band natural-seeing image centred on σ Ori Aa,Ab,B; approximate size is 150 × 150 arcsec^2. The brightest stars of the Trapezium-like system are labelled. *Right*: *AstraLux Norte*/2·2-m Calar Alto z'-band lucky image roughly centred on σ Ori E; size is 6·0 × 6·0 arcsec^2. In both images, north is up and east is left. Note the very small size of the *AstraLux* field of view with respect to the *SofI* one.

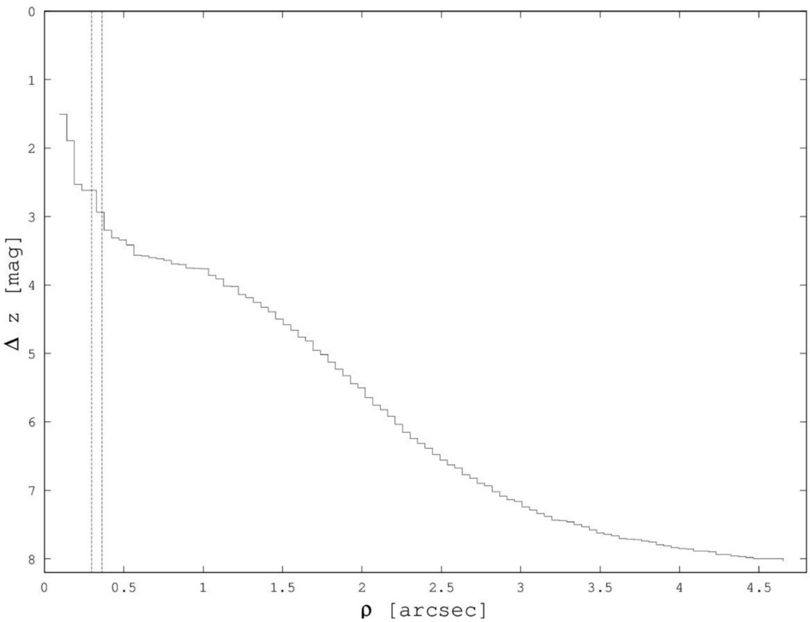

FIG. 2

Limit of our *AstraLux Norte* z'-band image: magnitude difference $\Delta z'$ as a function of angular separation ρ to σ Ori E (2·5% best frames). The vertical dotted lines indicate the expected location of the candidate companion to σ Ori E, at $\rho = 0{\cdot}33 \pm 0{\cdot}03$ arcsec.

Fig. 2 shows the largest detectable difference of magnitude between primary and secondary in our stacked *AstraLux* z'-band image as a function of angular separation from σ Ori E. It was computed from the average of the 3σ noise measurements in increasing concentric annuli of 1-pixel width centred on our target (the north–south read-out 'spikes' barely affect the standard-deviation calculation). The derived maximum magnitude limit is valid for angular separations between 0·25 and 4·6 arcsec. The hunchbacked point-spread function, which avoids quantifying any standard full-width-half-maximum, is typical of all *AstraLux* images. At the largest separations to σ Ori E, the minimum magnitude difference of our stacked image is as high as $\Delta z' = 8^{m}{\cdot}0$, which translates into an apparent magnitude depth of $z' = 15^{m}{\cdot}0$ (see below). This companion-detection method is widely used in the literature; see an example by the authors and with this instrument, including hunchbacked point-spread function, generation of artificial signals, and identification of false positives, in Lillo-Box *et al.*[56].

Results and discussion

The close companion candidate to σ Ori E is at 0·33 arcsec, according to Bouy *et al.* At such angular separation, and with an uncertainty of 10%, we imposed a minimum magnitude difference $\Delta z' = 2^{m}{\cdot}9 \pm 0^{m}{\cdot}3$ for the 2·5% best *AstraLux Norte* frames. The magnitude difference for the 1% and 5% best frames is identical within error bars.

We made a simple interpolation between well-calibrated magnitudes of σ Ori E in neighbouring passbands[57,58] for estimating its apparent magnitude in the z' band at $7^{m}{\cdot}04 \pm 0^{m}{\cdot}04$ (σ Ori E saturates in Sloan Digital Sky Survey DR9[59] z' band). With the *AstraLux* value of $\Delta z' > 2^{m}{\cdot}9 \pm 0^{m}{\cdot}3$, we concluded that the companion candidate must be fainter than $z' = 10^{m}{\cdot}0 \pm 0^{m}{\cdot}3$. At the σ Orionis distance[53] (distance modulus $= 7^{m}{\cdot}93^{+0{\cdot}08}_{-0{\cdot}15}$), this limit translates into a minimum absolute magnitude $M_{z'} = 2^{m}{\cdot}1 \pm 0^{m}{\cdot}3$ (see Table I). This magnitude is brighter than that of the most massive, hottest stars in the Lyon BT–Settl models[60] for 3 Myr (1·4 $M_{\odot}$, 4700 K). Thus, we used the Siess *et al.*[61] models for 3 Myr, solar metallicity $Z = 0{\cdot}02$, and no overshooting for putting limits on the astrophysical parameters of the companion candidate.

After making another simple interpolation (the Siess *et al.* models do not tabulate absolute magnitudes in z', but in R, I, J, and H, just to mention the neighbouring passbands), the companion candidate must be less massive than $2{\cdot}0^{+0{\cdot}2}_{-0{\cdot}1}\ M_{\odot}$, cooler than $T_{\mathrm{eff}} = 4960^{+190}_{-70}$ K, and later than K2 ± 1. At 3 Myr, while the B2 Vp primary is already on the main sequence, the companion is still

TABLE I

Apparent and absolute magnitudes in the red optical and near-infrared of σ Ori E and its close companion candidate

	σ Ori E		Companion candidate	
Band	Apparent magnitude	Absolute magnitude	Apparent magnitude	Absolute magnitude
R	6·84 ± 0·01	$-1{\cdot}09^{+0{\cdot}08}_{-0{\cdot}15}$	…	…
I	7·08 ± 0·01	$-0{\cdot}85^{+0{\cdot}08}_{-0{\cdot}15}$	…	…
z'	7·04 ± 0·04	$-0{\cdot}89^{+0{\cdot}10}_{-0{\cdot}16}$	>10·0 ± 0·3	>2·1 ± 0·3
J	6·974 ± 0·026	$-0{\cdot}96^{+0{\cdot}08}_{-0{\cdot}15}$	…	…
H	6·954 ± 0·031	$-0{\cdot}98^{+0{\cdot}09}_{-0{\cdot}15}$	…	…

in the contracting phase and has lower surface gravity (and greater mass) than field K dwarfs of the same effective temperature.

The depth of our stacked image allowed us also to discount the existence of lower-mass companions at larger separations. In our *AstraLux* image, we were not able to identify another source apart from σ Ori E; in their deeper *MAD* near-infrared images, Bouy *et al.* did not find any other source at less than 5 arcsec from σ Ori E either. In Table II, we show the upper limits of masses and spectral types at four angular separations. We used the Siess *et al.* models at 1·0 arcsec (as at 0·33 arcsec), and the BT–Settl models for 3 Myr and the T_{eff}–spectral-type conversion of Reid & Hawley[62] for 2·0 and 3·0 arcsec.

The earliest spectral type of the companion candidate to σ Ori E derived from our *AstraLux* observations, K2 ± 1, agrees with the "late-K to early-M" spectral-type interval hypothesized by Caballero *et al.*[48] from the existence of X-ray flares. The minimum magnitude difference in z' between primary and candidate companion is also consistent with the 3–4-magnitude difference in *Ks* estimated by Bouy *et al.* The ESA *Gaia* mission will probably not be able to resolve any very close companion 7–8 magnitudes fainter in (the *Gaia*-based magnitude) *G* than the bright primary[63]. Besides, given the very low cluster proper motion ($\mu < 5$ mas/yr) and its location at the antapex[64], an astrometric follow-up of the pair may not be feasible, even with *Gaia*. Therefore, new high-resolution multi-band imaging in the red-optical and/or near-infrared, deeper by about 2 magnitudes than our current *AstraLux* data, is necessary to constrain the properties of the companion candidate at 0·33 arcsec to σ Ori E. The *Hubble Space Telescope* could easily answer this question (the primary star may be too bright for the *James Webb Space Telescope*), but a near-infrared adaptive-optics system at a 4–8-m ground-based telescope, such as *NACO*, *SPHERE*, *GPI* or *MagAO*, could do it faster and cheaper, in just 10 minutes of observing time (around 30 minutes including overheads). The over 1000 citations and six decades of time-consuming works on σ Ori E may warrant this small observational effort.

TABLE II

Upper limits to the presence of resolved companions to σ Ori E

ρ arcsec	s AU	z' mag	M_{max} $M_\odot$	Earliest sp. type
0·33	130	10·0 ± 0·3	$2{\cdot}0^{+0{\cdot}2}_{-0{\cdot}1}$	K2 ± 1
1·00	385	10·9 ± 0·3	0·65 ± 0·15	K4 ± 1
2·00	770	12·6 ± 0·3	0·69 ± 0·09	K7 ± 1
3·00	1160	14·3 ± 0·3	0·25 ± 0·04	M3 ± 1

Acknowledgements

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CORRESPONDENCE

To the Editors of 'The Observatory'

Roger Griffin's Effect on the Barr Effect

A quarter-century ago, correspondence[1,2] in this *Magazine* lauded the signal achievement of the 100th paper[3] in the series of *Spectroscopic Binary Orbits from Photoelectric Radial Velocities*. How much more remarkable that the series has continued without interruption since that landmark, and we join with others in extending our congratulations to Professor Roger Griffin, the lead (and usually sole) author of all 250 papers now published, on this most noteworthy feat.

There is, perhaps, a danger that familiarity with the series may cause the casual reader to overlook the unfailing quality of the content: every orbit can be trusted to be of the highest standard (or to be subject to scrupulous qualification in the rare cases where some scintilla of uncertainty exists), and is invariably based on appropriately extensive observations of excellent quality (exemplified by the ~40 years' data reported in Paper 250). That such work is reliably packaged in an eloquent text with a comprehensive critique of previous investigations is a welcome bonus.

Although we hope that Griffin will conduct his own synopsis of the series in due course (*cf.* ref. 4), publication of the sestercentennial paper prompted us to assemble some statistics which brought home to us the scale of his achievement. For example, the span of well-established orbital periods is some five orders of magnitude(!), ranging from 7½ hours (HD 31738; ref. 5) to 86 years (39 Cyg; Paper 200[6]), with orbital eccentricities running up to 0·912 (HD 117901; Paper 173[7]). We have also revisited[8] the 'Barr effect' in the Griffin SBO sample; subjectively, the cumulative distribution function of ω, the longitudes of periastron of eccentric orbits in the sample, is sensibly linear (Fig. 1) — an impression quantitatively confirmed by the Rayleigh statistic (*e.g.*, ref. 9), which verifies that the ω determinations show no detectable departure from a uniform distribution in angle.

The SBO series was initiated more than 40 years ago[10], but, far from flagging, the rate of publication of orbits is accelerating. The first 150 papers presented orbits for somewhat fewer than 160 systems; but, if our counting is reliable, the 500th orbit in the series appeared, unheralded, in Paper 245[11]. We look forward to the 50th-anniversary paper, and to the 1000th orbit.

Yours faithfully,
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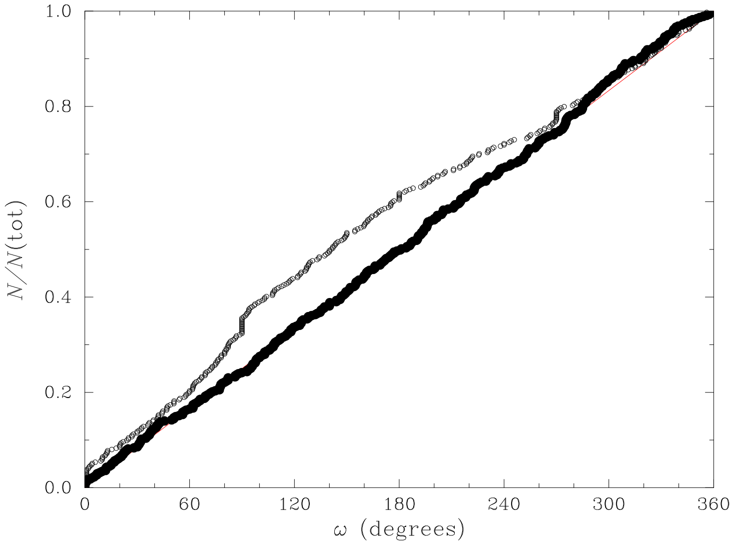

FIG. 1

The cumulative probability distribution of longitudes of periastron for 444 eccentric orbits in Papers 1–250 of Griffin's *Spectroscopic Binary Orbits* series (large filled circles) and for 374 eccentric orbits with periods 0·5–5·0 d in the *Ninth catalogue of spectroscopic binary orbits* (ref. 12; 2016–02–19 digital release). The *SB9* results are very unlikely to be drawn from a uniform distribution (probability $P = 0{\cdot}003\%$), while the distribution for Griffin orbits is practically uniform ($P = 65\%$; the straight line representing a uniform distribution is almost entirely concealed by the large dots).

Celebrating Paper 250

In anticipation of Paper 250 in the series *Spectroscopic Binary Orbits from Photoelectric Radial Velocities* by Roger Griffin, I thought it would be fun to show a recent example of an orbital solution for a spectroscopic binary that Roger and Jim Gunn first observed with the Palomar 200-inch telescope starting in 1972 January[1].

The initial five velocities of Sanders 721 from Palomar spanned seven years and hinted that there might be a long-term drift downward (see Fig. 1). In 1984, a few years after the Palomar instrument was retired, Bob Mathieu convinced us to restart and extend the M 67 radial-velocity survey, a collaborative effort that has continued for more than thirty years now. Although the velocity of S721 continued to drift downward over the next six years, there was little

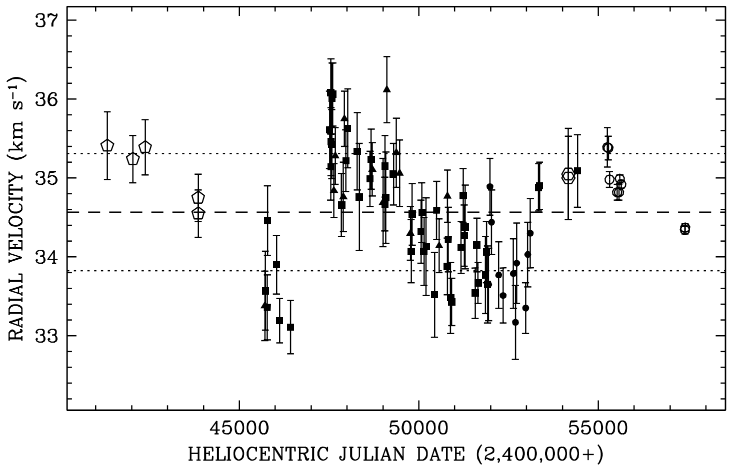

FIG. 1

The velocity history for S721 from five telescopes: Palomar 200-inch: open pentagons; filled symbols for the *CfA Digital Speedometers* on three telescopes: *MMT*: triangles, *Wyeth Reflector* at the Oak Ridge Observatory in the town of Harvard MA: squares, *Tillinghast Reflector* at the Whipple Observatory on Mount Hopkins AZ: circles; *WIYN* telescope on Kitt Peak: two open circles near HJD 2454000; and *TRES* on the *Tillinghast Reflector*: open circles after HJD 2455000.

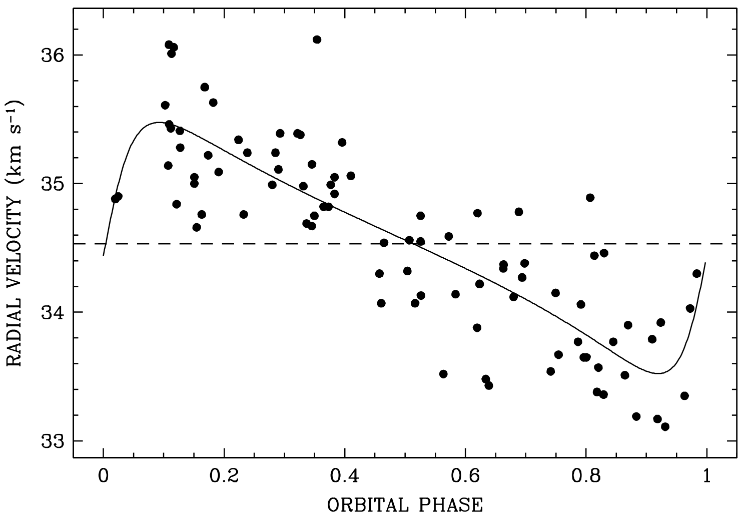

FIG. 2

Orbital solution for S721. $P = 6346 \pm 221$ days, $\gamma = 34{\cdot}53 \pm 0{\cdot}06$ km s^{-1} on the CfA native system (correct by $-0{\cdot}14$ km s^{-1} to get onto the IAU system), $K = 0{\cdot}98 \pm 0{\cdot}07$ km s^{-1}, $e = 0{\cdot}54 \pm 0{\cdot}07$, $\omega = 266 \pm 9$ degrees, companion minimum mass = $0{\cdot}084\ M_{\odot}$ assuming a primary mass of $1{\cdot}2\ M_{\odot}$.

constraint on the period and certainly no orbital solution to include among the 22 orbits reported by Mathieu, Latham & Griffin[2]. However, we have now covered more than two cycles of the 17-year period, and the orbital parameters are well constrained by the 89 velocities obtained with five different instruments (see Fig. 2).

We congratulate Roger on the publication of Paper 250, and hope that he enjoys as much as we do the satisfaction of seeing another long-period orbit emerging from a project that he started 44 years ago.

Yours faithfully,
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On Having Orbital Inclinations

Roger Griffin and I share an inclination to study orbits. Nearly sixty years ago, as I faced the oral examination for the degree of Doctor of Philosophy, my external examiner and later good friend, Michael Ovenden, threw me at least one entirely unexpected question. He cited a theory, which he made clear he did not necessarily believe, that the orbital planes of all binary systems contained the Galactic Centre. The question was "What group of objects would you study to test this theory?" Having spent the three previous years intensively studying eclipsing binaries under Zdeněk Kopal, I quickly answered binaries that were both spectroscopic and eclipsing, realizing almost as I said it that that was wrong. I recovered and collected myself and gave the correct answer: binaries that one could observe both visually and spectroscopically. The next question was: how many such systems are there? At that stage in my career, I had no idea and had to make an outright guess. I forget what answer I actually made but I believe I suggested that the number was less than 100, so I had the right order of magnitude.

Perhaps because of Michael's question, some years later, in 1966, when I was to present a paper at IAU Symposium No. 30, *The Determination of Radial Velocities and their Applications*[1], I decided to look at the question whether or not there was a preferred orientation for the orbital planes of binary systems and I found a total of 52 binaries for which the orientation of the orbital plane could be found, although many of them depended on only a few spectroscopic observations, some of poor quality. I ended with the astronomer's time-honoured conclusion (although not in so many words): "clearly, more observations are desirable". I mention that symposium for two reasons: it was, I believe, the first occasion on which I met Roger Griffin, who was presenting some of the first results of his photoelectric method of measuring radial velocities[2], while another participant at the symposium was the late Jean Dommanget, who invited me to go to another IAU meeting at the Royal Belgian Observatory in the Brussels suburb of Uccle. At that time, that Observatory was a centre for the study of visual binaries. My paper was subjected to critical appraisal especially by S. Arend (of Comet Arend–Roland fame) but Dommanget himself was pleased to find a spectroscopist who was interested in increasing the number of visual binaries for which radial velocities were determined. He quickly gave me a copy of his recently completed *Catalogue d'Éphémérides des Etoiles Vitesses Radiales Relatives*[3], a work which later ran to other editions and which provided both Roger and me with material for making up our observing programmes. That was the beginning of my own attempts to observe visual binaries spectroscopically and perhaps led to the remark I made in my own book[4] that "a classification based on [methods of observation] is very useful for distinguishing the astronomers who study binary systems."

In the intervening years, two developments have greatly increased the number of binary systems for which the orientation of the orbital planes can be completely determined. One is the photoelectric method of determining radial velocities, originally pioneered by Roger Griffin but now employed at many observatories, and the other is the development of speckle interferometry, devised by Labeyrie[5] and applied particularly by the group working with Hal McAlister in Atlanta, Georgia. The first has enabled the precise determination of very small amplitudes of radial-velocity variation (leading eventually to the detection of planets around other stars[6], but that is another story), while the second has greatly increased the number of systems for which apparent orbits in the plane of the sky can be determined. For example, in one system on which Roger and I collaborated, Σ2367, we were able to make use of radial-velocity measures that we made around the time of periastron passage, traditional astrometric measures, and speckle-interferometric measures. That paper did not lead to a definitive orbit and we pointed out that, with the system's orbital period of over 90 years, none of the authors "expects to be in a position to apply for time on ground-based telescopes" at the next periastron passage[7]. I can now reveal that the adjectival phrase "ground-based" was inserted at Roger's suggestion!

In the far-off days of IAU Symposium 30, we were concerned with another problem besides that of the orientation of orbital planes. There appeared to be two distinct populations of binaries: those with short periods, measured in days — the spectroscopic and eclipsing binaries; and those with orbital periods to be measured in years, decades, or even centuries — the visual binaries. I think that, even then, I strongly suspected that this was a result of observational selection, but opinion was by no means unanimous in those days. It was plausible to suppose that the origins of such widely different kinds of binary were also different[8]. The twin developments of photoelectric radial-velocity determination and speckle interferometry have also thrown light on this problem. Thanks to Roger and to Hal and his associates, we now know many binary systems with orbital periods in the range that was apparently avoided when I began my career. This is one measure of the importance of the 250 papers whose publication we are now celebrating.

Roger's output has indeed been prolific: we all know that it is not limited to the 250 papers in this series. Moreover, he sets himself very exacting standards and a paper by him contains results which, if not always definitive, can safely be assumed to be the best obtainable with the techniques of the day. With only just over 200 papers to my own credit, I can only admire his industry which, apparently, is still continuing. I can, perhaps, lay claim to comparable stamina: this note will appear close to the sixtieth anniversary of the acceptance of my first paper for publication[9]. Roger has stamina too: I understand that he has completed the eightieth circuit of his own personal orbit around the Sun. In welcoming him to the club of octogenarians, I express the hope that his inclination to study orbits will continue to bear fruit for many years to come.

Yours faithfully,
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Roger Griffin as 'Dutch Uncle'

I first met Roger Griffin when I was a graduate student at a conference in Pine Mountain, Georgia (USA), in early 1992. The topic which we discussed, the Hyades Cluster, is of great interest owing to its place as a fundamental rung in the cosmic-distance ladder. Roger's knowledge and depth of work on this open cluster are arguably greater and more significant than those of anyone else in the field. Having someone of that stature take an interest in the work of a first-year graduate student was profoundly important to me personally as well as professionally. Over the next several years he served me as an overseas 'Dutch Uncle' on quite a number of topics, resulting in a very healthy collaborative relationship.

Without his work in determining accurate and precise radial velocities of binary stars, interferometry would not be capable of making as many contributions to stellar astrophysics. It is only the synergy of visual/interferometric data with high-quality radial velocities that can produce orbital parallaxes — distances independent of trigonometric parallax and modelling — with errors small enough to make constraints on fundamental assumptions in stellar modelling.

Thanks to the scope of his work, his contributions will continue to be felt for many, many years. The very nature of binary-star research is that it is a continuing process which has gone on since the time of Herschel to the present day. Orbits (and, consequently, masses and other parameters) will continue to be refined as we strive to understand stars in greater detail than before. The objects in his *Spectroscopic Binary Orbit* series in *The Observatory* serve as observing-list inputs for optical interferometers worldwide and those articles are a delight to read. For binary stars, masses and orbital parallax depend upon the synergy of spectroscopy and resolved measures. Roger has, by his technique, by his industry, and by the exacting standards and quality of his work, made contributions which will make him at the very least a silent collaborator for decades to come. As Ejnar Hertzsprung said, "If we look back for a century or more and ask: what do we today appreciate mostly of the observations made then? the general answer will be: observations bound to time. They can, if missed, never be recovered. Of these observations measures of double stars contribute a major part."

The eightieth birthday of Roger Griffin and the publication of the 250th paper in his orbit series are conspicuous and signal events, both worthy of celebration. His contributions, especially in the area of binary-star astronomy, will be felt throughout the 21st Century.

Yours faithfully,
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2016 February 1

A Quite Remarkable Scientist

I had the honour of participating in a tribute to Roger Griffin at the Royal Astronomical Society in 2008 March on the occasion of his 200th paper in his *Spectroscopic Binary Orbits* series in *The Observatory*. And, now we are celebrating his 250th contribution to this journal as well as his 80th birthday!

One of the highlights of that 2008 trip was a visit to Roger to see his observing facilities at the 36-inch in Cambridge. I had first heard of Roger Griffin and his revolutionary radial-velocity spectrometer (or "speedometer" as some called it) as a graduate student back in the early 70s. That enormously clever instrument changed stellar radial-velocity determination forever by virtue of its detection scheme as well as its method of velocity extraction through cross-correlation. Roger's creation of that technique is seminal to the ensuing development of precise-radial-velocity instruments that launched the new world we now live in of extrasolar planets. Paper No. 1 of this series appeared in the 1975 February issue of *The Observatory*. Who would have thought that he would continue producing these wonderful orbits at the mean rate of six papers per year! And, more personally for me, I would never imagine that I would eventually co-author a couple of papers with him myself.

Roger is world class in his unrelenting dedication to observational productivity while simultaneously and routinely achieving a rare level of excellence in his analyses of those observations. Symptomatic of his indefatigable nature are his famous 1300-km commutes by bicycle for observing runs from Cambridge to Haute Provence or from LAX [Los Angeles International Airport — Ed.] to Mount Wilson, a mere 95 km horizontally but with an elevation change of 1700 m. The tale of his heroic race from Calar Alto to Mount Palomar, this time not involving a bicycle, in the hope of observing an eclipse in the γ Persei system, was told in the 1991 June issue of *Sky and Telescope*.

I have had the pleasure of refereeing several Griffin papers over the years. Working as hard as I can to find mistakes, shortcomings, or even grammatical missteps — and, believe me, I give it the best shot I can — I invariably have almost nothing to say about his papers other than "accept and publish without modification". His prose is precise, often cleverly ironic, and always a pleasure to read. If a Griffin paper touches upon one's own published work, it is wise to brace for a verbal dart that may be headed your way. My personal favourite of those is when Roger described (in *JApA*, **7**, 45, 1986) the speckle interferometric determination of the quadrant of the secondary of the Capella system on two successive occasions thus: "McAlister (1981) asserted that Koechlin *et al.* had 'positively shown that the new choice of quadrants is the correct one'. However, only two years later McAlister himself (Bagnuolo & McAlister 1983) showed at least equally positively that the *old* choice of quadrants was the correct one." I now wear that minor wound as a badge of honour given me by a dear friend and colleague. May we all look forward to his 300th *Spectroscopic Binary Orbits* paper.

Yours faithfully,
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2016 February 19

Hunting Multiple Stars

A long time ago, hunting was essential for survival. While most food is nowadays produced industrially, the spirit of ancestral hunters inherited by us appears in many different ways. The satisfaction of discovering a new astronomical object or computing an orbit, familiar to the writer, may have something to do with it. The work of Roger Griffin, done rarely with a co-author, can be likened to a hunting adventure where spectroscopic binaries of all kinds are first discovered, then tracked down patiently to get an orbit, and eventually published in a paper, adorned by a rich literature review. This style contrasts with the work done by large teams and fed by data from 'industrial' surveys and catalogues, which has become the prevailing trend in astronomy.

Among diverse trophies featured in the famous series of Griffin's papers on spectroscopic orbits published in *The Observatory*, I choose to comment here on hierarchical multiples, *i.e.*, systems containing more than two stars. Binaries, either eclipsing, spectroscopic, or visual, can, at least in principle, be discovered and studied by 'data machines' collecting a large number of measurements and performing their automated analysis. The *Kepler* and *Hipparcos* binaries are good examples, soon to be joined by the *Gaia* binaries. Radial-velocity (RV) robots at Lick Observatory and elsewhere look for exo-planets and discover spectroscopic binaries as a by-product. However, hierarchies still require the case-by-case approach so typical of Griffin's work and their study is less likely to be automated in the near term, if ever.

The name HD 123 is easy to remember. It is a known visual binary, ADS 61, where two solar-type stars orbit each other in 106·7 years. Located at 21·5 pc from the Sun, it has been the subject of numerous papers. A strong suspicion that the secondary component is itself a close binary, originally coming from astrometry, was definitely confirmed in Paper 144 published by Griffin in 1999[1], with 19 pages of text luxuriously devoted to that single object. It was placed on his programme in 1993 because the author, in his own words, is "chronically inquisitive about binary stars" (ref. 1, page 34). I placed the star on my own RV programme in 1995 in a systematic effort to detect close subsystems in visual binaries. In 1998, I determined the period of 48 days. My communication with Griffin revealed that he also determined the orbit using data of larger volume and better quality. He managed to resolve the $1''\cdot 5$ pair from Cambridge and measured its components separately, showing that the spectroscopic subsystem indeed belonged to the secondary. I did the same from Moscow, but only a couple of times. Our orbit of Ba,Bb was published[2] in 2001 with the weak excuse of being independent confirmation of Griffin's orbit. Incidentally, the seven remaining subsystems in our paper were original discoveries and the first-time orbits, including the massive tertiary in HD 27638, later studied in greater detail by G. Torres[3]. For our science it does not really matter who was first — only the quality of research matters.

Long-term spectroscopic monitoring is particularly useful for the unbiassed multiplicity study of nearby stars, where a 10-year system or subsystem has a chance to be resolved, thus covering all periods without a gap between close (spectroscopic) and wide (visual) binaries. Griffin's monitoring of the Hyades cluster[4], reaching periods of $\sim 10^4$ days (*i.e.*, 30 years), is an excellent example. In the notes to my compilation[5] on 4846 F- and G-stars within 67 pc, which includes the Hyades, Griffin is mentioned 81 times. This counts non-detections reported in his 2003 paper[6] (unfortunately, the on-line catalogue lists only average velocity, while individual RVs are found in the paper). Regretfully, a much larger survey of Nordström *et al.*[7] also 'forgot' to publish individual RVs, although they did tabulate the average velocity, scatter, and time coverage. Griffin criticized those authors more than once for not making the velocities available, and I concur.

Coming back to the 67-pc sample, I counted 40 entries (*i.e.*, ~1%) with spectroscopic orbits by Griffin, all but one published after 2000 (some are improvements of previously known orbits). Almost half (18) are in the Hyades, undoubtedly the result of greater priority and persistence vested in that cluster. Among those 40 objects, ten are triple and four are quadruple. In the recent Paper 238 Griffin[8] contributes a 5244-day orbit of HD 95241 (HIP 53791), also within 67 pc. As he always pays attention to surrounding stars, the faint common-proper-motion companion B at 37″ (this pair is known as KUI 53) was measured and confirmed as physical by its velocity, in agreement with other existing data on that system. Griffin also measured three times the velocity of another, even more distant companion C (HIP 53971), at 15 arcminutes from A, and found it discordant. Despite compelling evidence from parallax, proper motion, and photometry that C also belongs to the system, he puts this conjecture in doubt on the basis of velocities. In fact, discordant RVs in a wide physical binary is a strong indication of a spectroscopic subsystem[9]. The three RVs measured by Griffin do show a trend, however insignificant it might be. It is likely that further monitoring will reveal the spectroscopic subsystem in C, converting this hierarchy from quadruple into quintuple. Griffin discovered the subsystem in C without admitting it. I would be surprised, however, if he does not follow this star in the future.

Yours faithfully,
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2016 February 8

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REVIEWS

The Human Side of Science, by A. W. Wiggins & C. M. Wynn Sr. (Prometheus, Amherst), 2016. Pp. 275, 23·5 × 16 cm. Price $25 (about £17) (hardbound; ISBN 978 1 63388 157 0).

The Human Side of Science is a hugely creative popular-science book showcasing fourteen major discoveries in the physical sciences and genetics. The story-telling describes the "good, bad, and even ugly interactions" that make science a remarkable social activity in which "contention, cooperation and connection" lead by unexpected turns to new knowledge. Almost 400 individuals feature in the narrative's arresting message that progress in science is never a straightforward business with inevitable outcomes. Why not? Because science is a creative activity carried out by humans. In a text of about 250 pages we meet protagonists and antagonists, together with their families, parents and children, lovers and mistresses aplenty, friends and enemies, masters and students. Real people. The usual suspects accompanied by lives forgotten. Real lives: Nobel prizes won or lost, suicides, terminal illnesses, a murder, a state execution, divorces, refugees, and migrants. The text is a page-turner, well-illustrated with photographs and diagrams. The delightful cartoon commentary by Sidney Harris adds a witty take on the matters of gravity that drive progress in science. In a book of this kind the balance reflects the interests of the authors. So, we get 50 pages on Einstein and his milieu, 28 on Hubble & Co., and just a couple of hundred lines on Wegener and the continental-drift controversy — arguably the biggest discovery in geophysics in the last century. Astronomy and cosmology are well represented. A final chapter has ten sketches described as honorable mentions. The back matter includes useful notes on sources that will enable the engaged reader to explore more widely. Young people in their final years in high school will find this book very stimulating if they are aiming to become research scientists. Professionals in astronomy are well aware of the large numbers who enter our field as a result of reading popular science. Here's a great title for careers advisors to put on reading lists. — SIMON MITTON.

Images of Time, Mind, Science, Reality, by George Jaroszkiewicz (Oxford University Press), 2016, Pp. 336, 24 × 16·5 cm. Price £25 (hardbound; ISBN 978 0 19 871806 2).

This is a fascinating book that explores the notions of time in a variety of contexts. Very often one can get a good idea of a book's merits without reading every word and, as a result, provide a review in a timely fashion. This review is late simply because I wanted to read all of it quite carefully, as it raises very many interesting questions. The scope covers everything from cultural notions of time, to some of the most esoteric ideas in mathematical physics, which are sometimes treated at a technical level. As a result the book is quite heterogeneous, with the cultural passages forming some Shakespearean light relief from the physics narrative. From the physics perspective, ideas continue to evolve, so definitive answers on the nature of time are not given, although a particular view is sometimes apparent. Many of the relevant concepts that inform the debate, such as closed time-like curves in General Relativity, or many aspects of quantum gravity, are not possible to investigate in a volume that covers as much territory as this, so the reader is not going to get a deep understanding of each of the relevant fields, but instead will get wide-ranging exposure to the current ideas, and the book would act as a useful springboard for readers wanting to explore the ideas in more detail at a technical level. From that perspective, the book does well, and a reader with a background in physics will come away with a flavour of what the issues are at the forefront of the subject, with enough technical detail to get under the surface. All-in-all, this is a stimulating and unusual book that is well worth a read. — Alan Heavens.

Einstein for Anyone: A Quick Read, by D. Topper (Vernon Press, Malaga), 2015. Pp. 88, 23·5 × 16 cm. Price £20/$30 (hardbound; ISBN 978 1 62273 039 1).

"Dear Aunt Agatha," a 10-year old girl is supposed to have written in response to a Christmas present, "Thank you for the beaded blue handbag. I have always wanted one, but not very much." Author David Topper begins by explaining that he has written this book for anyone who has always wanted to know about Einstein, but not very much. Hence the brevity and the title *Einstein for Anyone*, rather than 'Einstein for Everyone', since "most people neither give a darn about Einstein nor care much at all about science."

For those who want to know more, there are many longer books (some of which he cites). There are also other short books, but this one has been written in the light of new details currently emerging from the Einstein Papers Project, which aspires to print or reprint everything he ever wrote, and which is currently up to Volume 13 (1923).

Topper gets right many things about which I have prejudices. He describes Einstein's parents, for instance, as "unobservant" not "assimilated" Jews (a description claimed by many for many at similar times and places). The reader is reminded that Einstein began his oration at the dedication of the site for the Hebrew University in Hebrew, but continued in French, not German. The tragic end of the story of Fritz Haber (who had been a good friend in pre-WWI Germany) is laid out briefly but clearly. A national hero in 1918, Haber necessarily fled to Basel in 1933 and died the next year. His wife had killed herself during the First World War, and his son and oldest daughter did the same in 1947.

Some points puzzle. The FBI compiled an Einstein file that eventually ran to 1800 pages. Topper tells us about the introductory "Biographical Sketch: from the start and into the first few sentences there are five factual errors. (127)". I turn madly to footnote 127 to learn what they were and find "127. Jerome 2002, illustration between p. 170 & 171." "Jerome 2002"* is indeed a book about Einstein and the FBI, and I suppose that the illustration shows relevant pages of the file, but couldn't Topper have told us what the errors were?

Chapter V is the saga of Einstein's hair — from classic 'Jewfro'† to wild, white halo in 60 years. Topper thinks that the 'Einstein's biggest blunder' story about the cosmological constant is true‡. But he also thinks that Einstein's last words, heard but not understood by a night nurse, were in Yiddish, not German, as the nurse had said. This struck me as extraordinarily unlikely, given

*Meaning Fred Jerome.

†Very curly hair occurs on a subset of European–American Jewish heads (including my best friend Eileen in junior high and a fine colleague here at UCI). Unless cut very short, the appearance is much like the 'Afro' hairstyle of a few decades ago.

‡It was George Gamow in a late autobiography who wrote that Einstein had told him that the cosmological constant was his biggest (scientific) blunder. The record of published papers shows that AE took Λ out of his equations in due course, and a surviving letter mentions that he is no longer very much attracted to it, which is not quite the same thing.

my simplistic impression of language distribution across land and social classes in 19th- and 20th-Century Europe. A much more expert colleague, who also has a copy of the book, confirms this, saying that Topper is "making the final words up without any evidence, and against AE's whole cultural tradition and family background". That background included considerable enmity between the Yiddish-speaking and German-speaking communities in Germany, Austria, and Prague, which Einstein had hoped to overcome by turning them all into Zionists.

That the mathematical papers on Einstein's bedside table after his death were part of yet another attempt at a unified field theory is perfectly plausible, though no reference to the contents is given. We will probably have to wait for Volume 53 or thereabouts of the Papers Project. Modern lovers and practitioners of theoretical physics would nearly all regard this 30-year fixation on attempting to unify General Relativity and electromagnetism as a much bigger blunder than the cosmological constant, and certainly a much sadder one, which left AE largely isolated from the physics community, a point that is not really obvious from Topper's discussion.

My cautious recommendation is that *Einstein for Anyone* might be a good, quick read to provide a temporal framework before tackling one of the longer volumes, of which Abraham Pais' *Subtle is the Lord* is surely the king. But perhaps read the present volume with a grain of Kosher salt. — VIRGINIA TRIMBLE.

Astrobiology: Understanding Life in the Universe, by C. S. Cockell (Wiley, Chichester), 2015. Pp. 449, 24·5 × 19 cm. Price £42·50 (paperback; ISBN 978 1 118 91333 8).

Charles Cockell is one of the UK's foremost astrobiologists, and any book by him has much to commend it. This one is well written and well and abundantly illustrated. The cover blurb says it is aimed at science undergraduates but also 'anyone with an interest'. It is presumably the latter that has led to excursions into various quite distantly related areas of science such as Dark Matter, covalent bonds, phase diagrams, states of matter, $E = hf$ and quantum theory, the laws of planetary motion, Wien's Law, the H–R diagram, rock types, and plate tectonics. I suspect these will be skimmed over by many readers, who might nevertheless be comforted to know that those sections are available to go back to for reference.

Cockell's approach is to lay out the evidence, and invite readers (preferably in class groups) to discuss and come up with opinions. I can see that it would be a good book to teach from. An example from the final chapter, which covers the desirability of our becoming a multiplanet species (he does not consider space habitats, except as interstellar arks) to reduce the risk of extinction reads: "what is our civilisation's long-term objective? What do you think your role is in this future?"

Omissions that I was surprised to find concern the related topics of shadow biospheres, second genesis, and recent controversy over life using arsenic in place of phosphorus. Although Chapter 6 discusses phylogeny, gene transfer, and molecular clocks, the concept of biospace is established in Chapter 7, and various pathways for the possible origin of life are described in Chapter 11, the terms 'shadow biosphere', 'second genesis', and 'arsenic' are all absent from the index. So far as I could see, shadow biospheres are mentioned only as a debating point in a box near the end of Chapter 6.

There is a companion website, www.wiley.com/go/cockell/astrobiology, hosting mainly slide sets from each chapter and related exam questions. This is a useful resource. It is open access and I recommend a visit to get a fuller flavour of the book. Cockell writes that he used feedback from learners on his astrobiology MOOC (Massive Open Online Course) to refine the content and level. This is offered by Coursera (https://www.coursera.org/learn/astrobiology) and might be worth a look at too before investing in the book. — DAVID A. ROTHERY.

How Do You Find an Exoplanet?, by J. A. Johnson (Princeton University Press, Woodstock), 2016. Pp. 178, 21 × 13 cm. Price £24·95/$35 (hardbound; ISBN 978 0 691 15681 1).

While there are numerous popular texts on exoplanets as well as higher-level textbooks for senior undergraduates and postgrads, John Asher Johnson's book *How do You Find an Exoplanet* is an excellent short textbook directed at a relatively under-served population. Johnson specifically targets his text as a primer for undergraduate students seeking to pursue exoplanet research. This book would also be ideal for interested amateurs with strong maths and science backgrounds. I will certainly be recommending it as background reading for my own undergraduate research students.

Johnson has a light and conversational writing style, interspersed with anecdotes from his own scientific career that add a personal touch to the text. The first chapter introduces the subject *via* an historical discussion connecting the study of the Solar System planets to that of exoplanets. The two longest chapters of the book go to discussion of the radial-velocity and transit techniques, by which the vast majority of currently known planets have been detected (and are also the two techniques primarily used by the author). Both techniques are first presented using the approximation of a circular planetary orbit, which is definitely the best choice for building intuitive understanding. Johnson then builds on that basis, introducing the effects of orbital eccentricity. There are two somewhat shorter chapters on microlensing and direct-imaging detections as well. The direct-imaging chapter nicely lays out the main technical challenges (specifically resolution and contrast) and how those challenges are overcome from the ground using adaptive optics and techniques such as angular differential imaging. The book concludes with a discussion of the future of exoplanet detection, which provides a summary of likely scientific gains from numerous upcoming missions and instruments.

The only thing I found clearly missing from this book was a discussion of astrometric detection of exoplanets. While it's true that no astrometric detection has been reported to date, that will probably change in the near future with results from the *Gaia* mission. I suppose it may be premature to devote a whole chapter to astrometric detections at the moment, but I would have liked to have seen it included in the final chapter on the future of exoplanet detection. — BETH BILLER.

Mars via the Moon: The Next Giant Leap, by E. Seedhouse (Springer, Heidelberg), 2016. Pp. 170, 23·5 × 15·5 cm. Price £19·99/$34·99 (paperback; ISBN 978 3 319 21887 8).

Norwegian ex-soldier, athlete, and suborbital astronaut Erik Seedhouse considers that humankind is more likely to reach Mars *via* the Moon, and that key materials for the mission may be obtainable from the lunar crust. Lunar mining could generate precious metals, and their sale on Earth (less freight and processing costs) might be commercially viable. The extraction of helium-3 from the lunar regolith is also discussed, though the author sceptically reminds us that its practical use in nuclear fusion is as yet unproven. The Moon, too, could serve as a test bed for any mission to Mars, involving a six-month lunar orbital phase for the Mars spacecraft, followed by descent to the surface for a year-long stay. A permanent lunar base would be highly desirable for many reasons, but unless the practical extraction of water from the lunar poles can be demonstrated, we would have to take supplies with us. Even then would we be able to construct a truly closed biosphere? Biomass figures for crops are discussed. Of course, the other camp in the debate would argue that the Moon merely provides a distraction from the ultimate goal of reaching the Red Planet. Nearly half a century has passed since the heady days of *Apollo 11*. How long should such a project take? Why involve the Moon at all?

Seedhouse's book abounds with interesting medical details such as cataracts formed in the eye by cosmic rays, and a gory self-appendectomy performed at a Russian polar base. Exploring Mars surely has parallels with the classic polar journeys of the last century. And yes, the summer of 2016 marks the 100th anniversary of Ernest Shackleton's daring rescue of his crew with a 920-mile dash in an open boat. Certainly future Mars explorers ought to read Shackleton's *South* and Cherry-Garrard's *The Worst Journey in the World* before they have their appendices and gall bladders removed through precautionary surgery. The author fully discusses the commercial aspect, as would be expected from an Assistant Professor in Commercial Space Operations at Embry-Riddle Aeronautical University. But the bottom line will be whether commercial sponsors will provide the 25 billion US dollars required to fund the Shackleton Energy Company's lunar propellant plant. Even if we go to Mars *via* the Moon, it will not be an easy task. Will there ever be lunar tourists?

Mars via the Moon is the author's twentieth book. Attractively illustrated and priced, I found it to be thoughtful and intriguing. Its brief Index is the only weak point. — RICHARD MCKIM.

Spaceshots and Snapshots of Projects Mercury and Gemini, by J. Bisney & J. L. Pickering (University of New Mexico Press, Albuquerque), 2015. Pp. 224, 31 × 23·5 cm. Price £39·95 (hardbound; ISBN 978 0 8263 5261 3).

The era of human spaceflight began more than 50 years ago. Since then, millions of words have been written about the exploits of the astronauts and cosmonauts who pioneered the exploration of the 'final frontier'. Despite the innumerable newspaper and magazine articles, books, TV documentaries, and other video material, pictorial coverage of the first manned NASA missions has usually been restricted to a few-hundred stock photographs and videos that were released to news media at the time. The treasure trove of imagery in public and private archives has largely remained unseen.

Created in a hardback, coffee-table format, this glossy book is one of two volumes dedicated to the publication of hundreds of official images taken during the early years of the US human space endeavour — many of which have never previously seen the light of day. In this labour of love, spaceflight enthusiasts J. L. Pickering and John Bisney have brought to light a selection of rare or unpublished photographs, both colour and black and white. Many of these high-quality pictures are from Pickering's personal archive, which now contains more than 100 000 spaceflight images.

The obvious attraction of this assemblage is the hundreds of photos that reveal many different personalities and technical features of each Mercury and Gemini mission. However, the value of this collection is enhanced many times over by the exhaustive research that has gone into providing informative and accurate captions for each picture — many of which had minimal labelling, or none at all, when they were originally placed in storage by NASA. — PETER BOND.

Exploring the Planets: A Memoir, by F. Taylor (Oxford University Press), 2016. Pp. 363, 24 × 16·5 cm. Price £25 (hardbound; ISBN 978 0 19 967159 5).

In this very reasonably priced book, the Halley Professor of Physics at the University of Oxford recounts his personal involvement in many NASA and ESA planetary missions. His interest in the subject began when truly close-up views of the planets had to be imagined by artists such as Frank Hampson who drew the *Dan Dare* strip for the *Eagle* comic.

Following his PhD at Oxford, Fred Taylor worked for ten years in the USA at JPL and CalTech, arriving as the Apollo programme was winding down. He then spent 21 distinguished years as Head of the Atmospheric, Oceanic and Planetary Physics Department at Oxford. This heart-warming romp through the increasingly familiar Solar System in particular and academia in general is peppered with fascinating insights into the projects he worked upon and the lives of fellow scientists and administrators. He constantly reminds us how such a journey is a steady battle against politics and finance as well as the evolving technology. From the California earthquake of 1971, *via* a succession of fast cars, world travel, climate-change talks over tea with Mrs Thatcher to the limits of the Solar System, there are plenty of nice anecdotes, all delivered with a liberal dose of dry humour. Fred Taylor was Principal Investigator on *Pioneer Venus Orbiter* (1979) and is presently involved with the *BepiColombo* mission to Mercury, four decades later. This is a richly human story which I warmly commend to fellow astronomers. — RICHARD MCKIM.

Discovery of the First Asteroid, Ceres: Historical Studies in Asteroid Research, by C. Cunningham (Springer, Heidelberg), 2016. Pp. 333, 24 × 16 cm. Price £117/$179 (hardbound; ISBN 978 3 319 21776 5).

This is the first of what are to be four books on the discovery of the first four asteroids. I gather that the plan is not one book for each of these four asteroids. The first volume concentrates on Ceres, but apparently there is much more on Ceres to come in the second volume. The series will appeal to those who are very, very interested indeed in the discovery of these asteroids, for, if all four books are the same size and price as the first, you will have 1332 pages to read, and will pay £468/$716 for them. That is, 35p/54¢ per page.

That is not to say that it is not an interesting story. Indeed I regard the history of the discovery and recovery of Ceres as at least as exciting and significant as the prediction and discovery of Neptune. For those who are unfamiliar with the story, it is roughly this.

At the end of the 18th Century, astronomers were aware that there seemed to be an unnaturally large gap in the Solar System between Mars and Jupiter, and some felt that there ought to be a planet in that gap. Several searches were underway for such a planet, the best-known effort being the so-called 'Celestial Police' organized by von Zach — a group of astronomers, including Giuseppe Piazzi in Palermo, who were each allocated portions of the zodiac for that purpose. Piazzi and Niccoló Cacciatore observed together with a vertical circle. Piazzi would be the actual observer at the eyepiece, and would call out the declination for every star that passed the meridian, while Cacciatore, at a desk, would record the time (hence right ascension). It was on the night of the first day of the 19th Century (1801 January 01) that Piazzi called out a 'star' that was not in the catalogue. Since the instrument was a vertical circle, there would be no means of checking any suspect observation until the following night, and it was perhaps not surprising that for the next few nights there was a brief period in which Piazzi and Cacciatore each suggested that possibly one or the other of them had made a mistake. At any rate, although everyone today credits Piazzi with the discovery, while few will have heard of Cacciatore, it seems not unreasonable to credit both Piazzi and Cacciatore jointly with the discovery.

Neither of them had access to the Internet in those days, or to the NEO Confirmation Page, so communication of their discovery was a little less rapid that it would have been today. Further, a combination of illness and poor weather prevented follow-up observations after February 11, after which it was feared that the new object was lost. In one of the most significant achievements in the history of mathematical astronomy, Carl Friedrich Gauss in a few months showed how to determine the orbit of a newly discovered object from a few observations made over a short arc. The most difficult part was to determine the geocentric distance of the object. Gauss developed the technique for determining the famous 'triangle-to-sector ratio' that will be familiar to orbit computers, and also developed the method of least squares for obtaining the best result from all of the observations, not merely from the bare necessary three. Gauss published his computed orbital elements and ephemeris in November, and the new planet was recovered by von Zach in December, just ten to fifteen arcminutes from Gauss's predicted position. That story, and that of the naming of the new object, is a very exciting part of the history of our subject, and it has many intriguing wrinkles to it, well told by Clifford Cunningham, and which I shan't give away here.

The book is well produced and I spotted only two small typos in it. I am happy to say that I spotted the words "dwarf planet" only once. There are copious illustrations, including portraits of the many subsidiary actors in the drama, although curiously most of the illustrations have no attribution. I suppose most of them were lifted from the Web — indeed one of them has the words **Lessing**images.com scrawled right across the middle of it. I am told that once an image is on the Web it is in the 'public domain' — but is this considered quite cricket these days?

The author (who was born and educated in Canada — a small detail not mentioned in the author's brief biography) has produced a thoroughly comprehensive scholarly work, citing what I would estimate to be something like 340 references — mostly primary historical sources. The latter half of the book quotes at length from the voluminous personal correspondence between the astronomers of the day associated with the discovery. I have to admit that I did not read every single word of this — I leave that to historical scholars. The only important reference not listed is the 2001 book *L'Astronomo Valtellinese Giuseppe Piazzi e la Scoperta di Cerere*, by Invernizzi, Manara & Sicoli, which many of us picked up at the Asteroids 2001 conference in Sicily. — JEREMY TATUM.

The Starlight Night, by D. H. Levy (Springer, Heidelberg), 2016. Pp. 214, 24 × 16 cm. Price £117/$179 (hardbound; ISBN 978 3 319 19877 4).

Relationships between science and the arts are not often researched, and are difficult to manage since the number of people sufficiently qualified in both is decidedly limited. Levy is one of those exceptions: trained in English literature and poetry but also a renowned and successful comet hunter, he has encouraged non-scientists to introduce broad interpretations of science (in particular astronomy) into their own work, and in this book he examines the ways in which western prose and poetry of the last five centuries reflects (or could be reflecting) celestial events, both diurnal and phenomenal. The infectious fascination that he gained simply by 'looking upwards' comes across well in these pages; the scholarship that has produced it is unquestioned, and is amply mirrored in the wealth of citations which are its meat. It is attractively produced, appropriately illustrated, chronologically ordered, and updated. The main focus of the revision is the inclusion of works by Gerard Manley Hopkins, plus ones from Tennyson to bridge the latter to those referenced in the First Edition. The book includes an extensive catalogue of sources, both cited and additional.

But it is not without flaws. Though a scientific product (it is published in the ASSL series), its bibliography referencing style is unfamiliar and at times obscure. Although there are few typos *per se*, some unintentional repetitions of text have crept in, possibly where new sections were added; the 'Conclusion' contains a run of five paragraphs (over 1 page) that is repeated from the previous chapter. There is also a slightly jarring mixture of personal anecdotes with impersonal appraisals of literature, and a temptation to be over-fanciful about divining a writer's hidden meanings; the cosmos is part of our visible environment, and both its diurnal events and its mysteries are natural sources of inspiration for poets. A 2-page summary of Tycho Brahe's life as an astronomer omits any reference to his younger sister Sophia, who assisted his night-time work; many other historians make the same omission, and it is a pity that this opportunity to correct the record was missed. The Kant–Laplace nebular hypothesis is given a page-long description because Tennyson was interested in the Solar System, but there are rather few parallel instances and it leaves the book a bit unbalanced. The back-cover blurb states that the book provides a "learned and enchanting tour of the skies", but there is nothing of a systematic or comprehensive nature here which such a "tour" would imply.

It is not clear who is the intended readership. The book does not constitute a general astronomy text for the layman, and its inclusion in Springer's most expensive *scientific* series probably puts it out of budgetary reach anyway. Yet it is not designed for the professional scientist either. Historians of literature with a bent for worming out the 'Whys and Whens' of what may be only chance events should find quantities of useful material and ideas, though to anyone *not* in that field the attempts to impute relationships (which possibly never existed) between celestial apparitions and innocent writings may seem a little forced. Conjecture has its place, but can be overdone. — ELIZABETH GRIFFIN.

Galactic Bulges, edited by E. Laurikainen, R. Peletier & D. Gadotti (Springer, Heidelberg), 2016. Pp. 481, 24 × 16 cm. Price £117/$179 (hardbound; ISBN 978 3 319 19377 9).

Galactic bulges are a somewhat neglected research activity, compared to galactic haloes with their intimate connection to the field of galaxy formation and galactic discs with their implications for star formation. So, this collection of reviews is a timely stimulus to engage a wider community of researchers. The Local Group galaxies provide a sample of bulges which can be studied on a star-by-star basis, as compared to the integrated properties of more distant bulges. Many questions such as the kinematics, abundances, and ages of stars can be studied more easily in the Local Universe. Nonetheless, the well-known relationship between bulge mass and central-black-hole mass points to the greater cosmological conundrums implicit in bulge assembly and evolution. High-redshift searches for the progenitors of bulges, as well as cosmological simulations of bulge formation, complete the sweep of activity covered in this volume.

As always in collections of reviews, contributions are varied. Some of the contributors take the opportunity to review the hinterland, others take the opportunity to review merely their own parish. The overall unity of such volumes can often be patchy, with notation and convention changing from author to author, whilst some material is repeated again and again from chapter to chapter. However, this volume is assuredly one of the better ones in the *Astrophysics and Space Science Library* series, with some very well-written reviews. For example, Graham's article on 'Galaxy bulges and their massive black holes' is exemplary. The historical evidence, including almost-forgotten pioneering work, on how we came to believe in the existence of supermassive black holes in bulges, is recounted, before we are taken to the research frontier in sub-structure in the black-hole mass *versus* velocity-dispersion diagram. Another nicely-judged article is Shen and Li's 'Theoretical models of the Galactic Bulge', which narrates the paradigm shift in recent years in our understanding of the Galactic Bulge. Once thought to be a classical bulge driven by major mergers, the evidence from star-counts, kinematics, and chemistry now favours a picture of the Bulge as a bar viewed almost end-on and bloated from buckling and fire-hose instabilities during its evolution. Kormendy's magisterial concluding article, 'Summary of progress and outstanding issues', is a delight, and this reviewer certainly agrees with the conclusion that we appeal far too readily to feedback, whether from AGN or star formation, to alleviate difficulties in our current models of galaxy formation.

There are some reviews that are less successful, but overall the volume is helpful and excellent in parts. — N. W. EVANS.

Star Formation and Galaxy Evolution: Connecting Numerical Models to Reality, edited by N. Y. Gnedin, S. C. O. Glover, R. S. Klessen & V. Springel (Springer, Heidelberg), 2016. Pp. 365, 24 × 16 cm. Price £117/$179 (hardbound; ISBN 978 3 662 47889 9).

This book contains lectures given by leading scientists in the field of computational astrophysics during the 43rd Saas-Fee Advanced Course. Over the years the Saas-Fee winter schools have built up a reputation to deliver lectures that capture the state-of-the-art at a level accessible to graduate students and researchers not familiar with a given field. This book clearly lives up to that reputation.

Star formation is one of the still-unsolved problems in galaxy formation and evolution, and subject to intense debates within the community. The main issue is that a multitude of physical processes at different length scales play into it. The authors try to disentangle them and focus on the provision of gas for star formation in an evolving Universe, the evolution of gas to high densities and subsequent star formation once gas is settled in the interstellar medium, and numerical techniques to model such processes.

The authors do an excellent job explaining their individual topics with enough depth to give a good overview, and at the same time avoiding unnecessary repetition between each other. Whenever possible they include references to empirical data, which is an important cornerstone in the modelling of star formation as many of the physical processes still cannot be explained from first principles. At times the authors explore topics that seem only loosely connected to the main thesis of the book; however, those topics are chosen carefully and give a more complete picture.

The content of this book can be highly recommended to graduate students and researchers. It is not as detailed as one would expect from a textbook, and more along the lines of a mix between a review and lecture notes. The only real drawback is the price of the book. It is not easy to ask graduate students to buy it, especially as the individual chapters by the authors are available on the arXiv. — Sadegh Khochfar.

Heliophysics: Active Stars, their Atmospheres, and Impacts on Planetary Environments, edited by C. J. Schrijver, F. Bagenal & J. J. Sojka (Cambridge University Press), 2016. Pp. 383, 25 × 18 cm, Price £49·99/$79·99 (hardbound; ISBN 978 1 107 09047 7).

Active Stars, their Atmospheres, and Impacts on Planetary Environments is the fourth in a series of four volumes called *Heliophysics* (with a fifth, about space weather, societal impacts, *etc.*, on-line). And if the first three are anywhere near as good as this one, I might even consider buying them! The series had its origins in a summer-school series taught at the University Corporation for Atmospheric Research in Boulder, Colorado, funded by the NASA 'Living with a Star' programme. The editors don't quite say when, but additional information lives at http://www.vsp.ucar.edu/Heliophysics. The format has ended up that of an edited compilation, of 13 chapters provided by 20 authors, mostly American.

Different items will feel vital to different readers, but here are three of mine. First, a section by Rachel Oster on time-scales of explosive events on stars, young to old. This is something the Transient and Variable Source Working Group for the *Large Synoptic Survey Telescope* definitely needs to know about. The changes with stellar age might also be useful to folks trying to calibrate all the different ways of measuring stellar ageing.

Second, Mario M. Bisi (on 'Heliophysics with radio scintillation and occultation') is kind enough to provide a complete table of frequency-band definitions, ranges of frequency and wavelength, and their letter designations from P to D. The list from long to short wavelength is P, L, S, C, X, Ku, K, Ka, Q, U, V, E, W, F, and D. Why those letters were chosen remains a Deep, Dark, Secret. Several earlier writers and speakers have claimed answers, but they haven't all claimed quite the same things. Thirteen letters remain to label other things.

Third, and perhaps of the widest interest, David Brain reports on 'Climates of terrestrial planets', current ones and probable histories for Venus, Earth, and Mars, the processes involved, and implications for habitability of planets orbiting other Sun-like stars. He notes that estimates of habitability can be rather too optimistic, because Venus and Mars are generally counted as falling within the solar habitable zone. Venus has only one atmospheric circulation cell per hemisphere, while the Earth has three. Brain attributes the difference to Earth's rapid rotation and the resulting Coriolis influence. This is not quite what other books have claimed in years when I taught 'Astronomy from space', but perhaps it is so. In any case, the difference accounts for Venus having a much more uniform surface temperature than does Earth. The name 'Hadley cells' does not appear, missing the chance for a nice anecdote and making the section hard to find in the index.

Mars currently has more extreme seasons than does Earth, because the orbital eccentricity and axial tilt are acting together instead of opposing each other as currently on Earth. (You knew we are closest to the Sun in January, didn't you?!) Presumably precession of the Martian equinoxes will eventually change that, though, with only the Sun to contribute, the time-scale is presumably long

Really, every chapter has a highlight. Brian E. Wood and Jeffrey L. Linsky compare the effects of the solar wind with the winds of other stars and, I am pleased to say, prefer 'astrosphere' to 'asterosphere'. They note that our motion relative to the local interstellar medium is so close to Mach = 1 that you can argue whether there should be a bow shock or merely a bow wave. And some influences of the Sun extend very much further out than were envisaged by Eugene Parker when he first told us in 1961 that the solar wind existed. I was brought up on Biermann (Ludwig) and Lust (Reimar), but who am I to argue with the authors?

One complaint: all the references are at the end, instead of being properly divided among the 13 chapters. This perhaps saves a page or two, since more than one chapter might cite the same paper or book, but the price is extra paper cuts to the fingers of the reader flipping madly back and forth. — VIRGINIA TRIMBLE.

Transport Processes in Space Physics and Astrophysics, by G. P. Zank (Springer, Heidelberg), 2014. Pp. 286, 23·5 × 15·5 cm. Price £40·99/$59·99 (paperback; ISBN 978 1 4614 8479 0).

Transport Processes in Space Physics and Astrophysics: Problems and Solutions, by A. Dosch & G.P. Zank (Springer, Heidelberg), 2016. Pp. 257, 23·5 × 15·5 cm. Price £40·99/$59·99 (paperback; ISBN 978 3 319 24878 3).

The subject of this pair of books, published in the Springer *Lecture Notes in Physics* series, is focussed on the form, properties, and solution methodologies of the basic equations that describe the transport of particles in gases, whether consisting of electrically neutral particles in ordinary gases, or of charged particles in Solar System and cosmic plasmas. The fundamental equation, Boltzmann's equation, can readily be written down in words in one sentence — that the rate of change of the particle distribution function along a particle trajectory in six-dimensional position-momentum phase space is equal to its rate of change due to 'collisions'. If collisions can be neglected the distribution function, or phase space density, is then constant on a trajectory, this being a statement of Liouville's theorem. A central topic of these books, however, is the mathematical description of the effect of random collisions on the particle-distribution function, and hence upon the macroscopic variables of the medium such as number density, number flux, and energy density, that are obtained from suitable 'moment' integrations of the distribution function over momentum space. The fact that this subject matter well fills the more-than-500 pages of these volumes is testament to the physical richness and difficulty of solution of the complex systems that arise from such apparently simple theoretical origins. The description of these processes evidently depends upon the physical circumstances within the gas, which may variously be represented by hard-sphere scattering in ordinary gases, by binary Coulomb interactions in a collisional magnetized plasma, or by random scattering due to model distributions of waves and field fluctuations in an otherwise collisionless plasma medium. Topics developed in the book by Zank include, for example, the relaxation-time (BGK) approximation to the collision operator, the

Chapman–Enskog expansion and the Navier–Stokes equation, the Fokker–Planck equation and the determination of diffusion coefficients, the transport of energetic particles in a turbulent plasma, and concludes with a brief discussion of the transport of turbulent fields themselves. The approach is resolutely mathematical throughout, with rather few diagrams or illustrations, and just about enough physical discussion to motivate the development of the subject matter and to illuminate the results. A feature of the book is the numerous 'exercises' that are set at the end of each major section, which form the occasion of the *Problems and Solutions* companion volume by Dosch and Zank. Many of these 'exercises' are of the deceptively simple form of "fill in the gap between lines A and B in the previous derivation", which after hopefully locating the relevant 'solution' (the mapping between the two books is not entirely 1:1) one often finds a significantly large number of pages of tight algebra. It is no accident that the 'solutions' manual has almost the same printed length as the book itself! Overall, these books undoubtedly provide a valuable theoretical resource for researchers in space physics and astrophysics, written by authors who are clearly deeply immersed in their subject material. I conjecture, however, that it must have been a rather tough experience for the graduate students at the University of Alabama in Huntsville who "grappled with this class", and "tenaciously and thoroughly worked through all [257 printed pages of !] the problems". — S. W. H. COWLEY.

Astronomical Data Analysis Software and Systems XXIV (ASP Conference Series, Vol. 495) edited by A. R. Taylor & E. Rosolowsky (Astronomical Society of the Pacific, San Francisco), 2015. Pp. 593, 23·5 × 15·5 cm. Price $88 (about £60) (hardbound; ISBN 978 1 58381 874 9).

This reports the 24th conference in the ADASS series, held in Calgary in 2014 October. As usual, many papers are associated with major missions such as *Gaia*, *SKA*, *ALMA*, *JWST*, *Euclid*, *Herschel*, *LOFAR*, *etc.* Those papers may help astronomers to understand how the projects operate and how the data and results are being or will be made available to the scientific community. Although these large projects generally employ teams of skilled programmers and software engineers, it is encouraging to see that useful software packages are still being developed by individual astronomers or very small teams in order to solve some current problem. Their software is often made available to others, for example, *via* the Astrophysics Source Code Library; an index to packages mentioned in these proceedings that are in that library is provided at the end.

The buzzword count provides a crude measure of trends in astronomical computing: the winner this year is the "cloud", mentioned in no fewer than six titles. The use of GPUs was mentioned only once, a decrease on earlier years, while apps for smart-phones seem no longer to be of so much interest, perhaps because of the obvious limitations of such devices for astronomical visualizations.

The future development of the FITS format, or alternatives to it, were covered in several papers and also in a discussion session reported here. A few projects, including *LOFAR*, have adopted HDF5, already widely used in other branches of science, although it is more of a framework than a specific data format. While HDF5 is much more flexible, it is defined by its data-access software, whereas FITS is defined at the bit level in published papers, making it much more suitable as a long-term archiving format. Another issue is that while many FITS header keywords have a well-established meaning, and there are well-established conventions for things like world coordinates, the same is not yet true for metadata fields in HDF5 files. One of the references here is to volume 12 of the journal *Astronomy & Computing* which includes several papers giving a more extensive discussion of this topic.

I found few errors in this volume, which has been produced to the usual high standards of the ASP. But the figure on p. 299 has a caption explaining the meaning of the magenta, blue, green, and yellow circles which would have been useful had the figure not been printed in monochrome. Also the value of the author index has been slightly reduced by a few authors from France who chose to put their surnames before their given names in their papers, which the editors appear not to have noticed. — CLIVE PAGE.

Frontiers in Radio Astronomy 2015 (ASP Conference Series, Vol. 502), edited by Lei Qian & Di Li (Astronomical Society of the Pacific, San Francisco), 2016. Pp. 97, 23·5 × 15·5 cm. Price $88 (about £58) (hardbound; ISBN 978 1 58381 888 6).

Frontiers in Radio Astronomy contains the proceedings of a conference held in Guiyang, China, in 2015 July, looking ahead to the work to be done with *FAST* (the *Five-hundred-metre Aperture Spherical Telescope*) in Guizhou Province. It will dwarf the Arecibo dish of similar design, with more sky coverage, and a wider range of available frequencies. All undoubtedly good, but this volume is definitely a disappointment. The 18-member SOC included 12 members from outside the host country, only one of whom (Carl Heiles) came to the meeting.

The papers I found most interesting were a history of fixed-reflector radio telescopes (R. G. Strom of Dwingeloo and NAOC, Beijing) and the advice for the future from Peter Wilkinson of Jodrell Bank, advocating flexibility and maximization of the "human bandwidth" of users, extending to astronomers who have not yet even started school.

The most disappointing paper is by C. M. Zhang (NAOC) *et al.* on 'The investigation of neutron spin period evolution: Crab Pulsar and magnetar'. Hooray, I thought, at last a graph of the period of NP0532 from its 1969 discovery down to the present. No. Just a calculation. They say it started at 0.01556 seconds and has reached 33 msec in 960 years, but there is no plot of what is now happening. And you will pay nearly $4 for this lack of information, given the price and the number of pages (no index present). Another $5 covers a theory of fast radio bursts (collisions between neutron stars and asteroids, by Y. F. Huang & J. J. Geng of Nanjing), which is a bit reminiscent of the early theoretical, party-animal days of gamma-ray bursts.

On the other hand, the list of participants provides e-dresses for a number of people whom I would not otherwise know how to reach, which is likely to be useful in organizing future meetings. *FAST*'s first 'light' is expected this year. — VIRGINIA TRIMBLE.

Enhancing Hubble's Vision, by D. J. Shayler & D. M. Harland (Springer, Heidelberg), 2016. Pp. 333, 24 × 17 cm. Price £24·99/$44·99 (paperback; ISBN 978 3 319 22643 9).

More than a quarter of a century has passed since the *Hubble Space Telescope* was delivered to Earth orbit by Space Shuttle *Discovery*. The most successful space observatory ever flown remains in excellent condition, continuing to return a steady flow of spectacular images and ground-breaking data. Yet the *Hubble* saga nearly ended in ignominy when early test images revealed a misshapen primary mirror that was unable to focus light properly. The story of the near-disastrous manufacturing flaw and the revival of *Hubble* during the first Shuttle Servicing Mission in 1993 is told in a previous volume by Shayler & Harland. This book completes the story by detailing the complex astronaut activities of the next four Servicing Missions, which took place between 1997 and 2009.

Hubble's longevity was made possible because its design team had the foresight to build the observatory so that it could be repaired and upgraded in orbit. However, such foresight would have been in vain without the courage and dedication of the various Shuttle crews, particularly those who conducted the long, arduous spacewalks which enhanced its capabilities.

Aimed at space buffs, this is a well-written account of the Servicing Missions, providing plenty of information about the astronauts and their in-orbit activities. On the other hand, there is little attempt to describe the various scientific instruments and their capabilities, and the numerous discoveries that have caused the text books to be rewritten. The text includes a foreword from astronaut Dr. Steve Hawley, and an afterword from *SM-4* Flight Director Charles Shaw. — PETER BOND.

OTHER BOOKS RECEIVED

The Magnetodiscs and Aurorae of Giant Planets, edited by K. Szego *et al.* (Springer, Heidelberg), 2016. Pp. 333, 24 × 16 cm. Price £97/$179 (hardbound; ISBN 978 1 4939 3394 5).

This publication for the International Space Science Institute brings together observations and theory relating to the impact of the solar wind on atmospheres and magnetospheres of the giant planets. It was previously published in *Space Science Reviews*, **187**, 2015

The Strongest Magnetic Fields in the Universe, edited by V. S. Beskin *et al.* (Springer, Heidelberg), 2016. Pp. 583, 24 × 16 cm. Price $229 (about £165) (hardbound; ISBN 978 1 4939 3549 9).

This volume discusses the magnetic fields found in environments such as strongly magnetized stars — both degenerate and non-degenerate — magnetars, and around black holes. It was previously published in *Space Science Reviews*, **191**, 2015.

Pseudo-Complex General Relativity, by P. O. Hess, M. Schäfer & W. Greiner (Springer, Heidelberg), 2016. Pp. 250, 24 × 16 cm. Price £63·99/$109 (hardbound; ISBN 978 3 319 25060 1).

This volume presents an extension of GR in pseudo-complex situations involving a strong field near a large mass, such as the formation of a singularity by the collapse of a large mass, and the further creation of accretion discs around such objects. Problems and solutions are included as a resource for students of GR.

Plasma Sources of Solar System Magnetospheres, edited by A. F. Nagy *et al.* (Springer, Heidelberg), 2016. Pp. 295, 24 × 16 cm. Price £74·50/$129 (hardbound; ISBN 978 1 4939 3543 7).

This set of reviews has been coordinated by the International Space Science Institute and is reprinted from *Space Science Reviews*, **192**, Issues 1–4, 2015. It discusses what we know of the plasma sources for each of the intrinsically magnetized planets.

Here and There

PREDICTING THE NEXT BRIGHT COMET

Oort cloud – is 10,000 au (astrological units) from the Sun. Earth is 1 au from the Sun. — *The Times*, 2016 April 13, p. 7.

WAR OF THE WORLDS

An artist's impression of a gamma ray burst (GRB) striking the Earth's atmosphere. GRB's [*sic*] such as this may have been responsible for triggering mass executions in the Earth's past. — *Astronomy Now*, 2016 April, p. 25.

ABUNDANTLY WRONG

… helium is the most abundant element in the Sun … — *Nature*, **532**, 175, 2016.