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MY COMPANION IS BIGGER THAN YOUR COMPANION!

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We provide an analysis of the mass-ratio distribution as gathered from almost all of the 559 orbital solutions derived by Professor Roger Griffin in his long series in the *The Observatory* about ‘Spectroscopic Binary Orbits from Photoelectric Radial Velocities’. The total distribution we determine is close to a uniform one, with a dearth of the smallest companions and an excess of almost-twins. When splitting our sample between main-sequence and red-giant primaries, however, we discover a different picture: the excess of twins is limited to the main-sequence stars, for which it appears even more pronounced. The mass-ratio distribution of red giants is characterized by a decline of systems with mass ratio above 0.6 and an excess of systems with a mass ratio around 0.25, which we attribute to post-mass-transfer systems. The difference between the two mass-ratio distributions is likely due to the different primary masses they sample.

*A brief outline of a long career*

Cambridge Professor Emeritus Roger Francis Griffin, whose extraordinary 45 years of studying spectroscopic binary stars form the basis for this analysis, is a native of Surrey, England. His early education came from the Caterham School (plus a certain amount of ‘home schooling’, because his mother had been a teacher). Roger received his PhD in 1960 from Cambridge University for work with Prof. Roderick Olivier Redman (first director of the combined Observatories of Cambridge) on narrow-band stellar photometry, which was never fully published, using a narrow-band spectrometer of their own devising. A visiting scholarship (we would probably now say postdoctoral fellowship) at

the Radcliffe Observatory in Pretoria, South Africa, with A. David Thackeray, yielded spectroscopy of Nova RS Oph with photographic plates, which Griffin already knew were not the most efficient technology for the purpose. A second excursion from 1961 to Pasadena (Caltech and Mt. Wilson Observatory) was supported by a Carnegie Fellowship for a project that turned out not amenable to research. He participated in optical identification of 3C radio sources using plates from the 1.2-m Schmidt and 5-m *Hale* telescopes, then turned to the 2.5-m *Hooker* telescope to begin taking extraordinarily high-dispersion spectra of Arcturus. He returned to the 2.5-m to finish this after being appointed a Fellow of St. John's College. The tracings went to a new graduate student at Cambridge, Rita Elizabeth Mary Gasson (later Griffin) in 1963 for her PhD work, which resulted in the *Arcturus Atlas*<sup>1</sup>, her PhD degree in 1966, and joint papers from the next year onward. The *Arcturus Atlas* is Roger's second-most cited paper. Their joint work on the *Procyon Atlas*<sup>2</sup> recognized the value of using telluric lines for precise radial-velocity calibration<sup>3</sup>.

Roger's explanation<sup>4</sup> of how to do a better job of measuring radial velocities using a photomultiplier tube and coded mask as a radial-velocity spectrometer\* remains, at 290, his most cited paper. It contains a brief but inclusive history of stellar radial-velocity measurements in general and the method in particular (with due credit to Babcock and Fellgett, who, however, never built the relevant widgets). Babcock was, however, the director at Mt. Wilson–Palomar Observatories when Roger F. Griffin and James E. Gunn built a radial-velocity spectrometer (including ten Lego motors) to operate on the Palomar 5-m and study stars in globular clusters (no binaries to speak of, and no dark matter) and such.

Paper 1 (Arabic, not Roman numerals, because he had already used Roman numerals for another series of papers) appeared in *The Observatory*<sup>5</sup> in 1975 with co-author B. Emerson (of the Royal Greenwich Observatory). A successor appeared in every issue of *The Observatory* until recently, a few with co-authors (including the present first author), but most as single-author papers, written in a unique style that you must experience for yourself. He is the only Editor ever to have modified a paper by the present second author without arousing her eternal enmity. The series has now reached paper 265, and we thought it time to take another look at the distribution of binary-system mass ratios in this remarkable sample. We do this with the gracious permission of Prof. Roger Griffin and some biographical assistance from Dr. Elizabeth Griffin.

It is also reasonable to note here that some of the observing was done with the *Coravel* at the Haute-Provence Observatory, and some of the devices with which extrasolar planets have been discovered by radial-velocity measurements make use of both the photoelectric photometer with coded-mask concept and the use of telluric lines for wavelength calibration.

#### *A revised look at the mass-ratio distribution*

More than a decade ago, on the occasion of the publication of the 200th paper in Griffin's *Series*, one of us presented an analysis<sup>6</sup> of the mass ratios that derived from these data, supplemented from additional orbits published by Griffin in other publications. As we have now reached number 265 in the series a critical reader may wonder why is there a need for another such analysis *now*. One reason might be that the methodology used by the present second author

\* His friends secretly call these Griffinometers.

of the current paper was questioned by, among others, the current first author<sup>7</sup>, and working together seemed the obvious solution. Another reason, and more important, is that the last decade has seen in the papers of the Series a change in ground rules from a strict one star per paper to, often, as many as 4–6 per paper and in one case, even 20. Thus, if in the Papers 1–200 of the *Series*, there were 290 orbits presented, in the remaining Papers 201–265, there were no fewer than 269! This almost doubling of the number of systems justifies on its own a reanalysis of the sample. Finally, one should also note that since the last analysis, we have now entered the *Gaia* era of Galactic astronomy, which will probably completely revolutionize our field.

### *The sample*

The reanalysis is even more warranted as the 559 orbits covered in this Series encompass a most amazing range of the various orbital elements: the orbital period,  $P$ , ranges from 0.31020614 to 31292 days\* (~86 years, *i.e.*, more than Griffin's age!), while the non-zero significant eccentricities,  $e$ , vary between 0.0078<sup>†</sup> and 0.9119. Those are by no means record holders, but are quite remarkable indeed and bear witness of Griffin's method to derive orbits: if one star happens to catch his attention for some reason or another, it will be observed on several occasions, over many years, so that if it happens to be a spectroscopic binary, it will be sooner or later unmasked! This is also visible through the range of semi-amplitudes of the primary radial-velocity curve ( $K_1$ ) that is covered: between 0.89 and 96.27 km/s. The distribution of those elements, shown in Fig. 1, bear a strong resemblance to those shown by Griffin in his own summary<sup>8</sup> more than a decade ago.

The distribution of elements described above leads to a range of spectroscopic mass functions,  $f(m)$ , for single-lined binaries that is comprised between 0.00000070 (!) and 1.823  $M_\odot$ . The methodology used by Griffin and the long time spans that cover these orbits imply that we shouldn't expect any bias in terms of the inclinations of the orbits — something that will be useful when determining the mass ratios of SB1 systems.

The sample we extracted from Griffin's papers consists of 111 double-lined spectroscopic binaries (SB2) and 448 single-lined spectroscopic binaries (SB1). We have cross-matched this sample with the *Gaia* DR2 data set<sup>9,10</sup>. For most of our targets (431 SB1 and 109 SB2 — our final sample), the *Gaia* DR2 provides us with the effective temperature and radius, allowing us to place them in an H–R diagram (Fig. 2). From this, it is clear that there aren't many SB2s with a giant component, and that the contribution from the companion in SB2s shift them up and to the red with respect to the tracks.

### *Mass ratios of SB2 systems*

For SB2s, deriving the mass ratio is a trivial thing as this is simply the ratio between the two semi-amplitudes of the orbits ( $K_1$ ,  $K_2$ ) of the components in the system. We note that a few systems yield quotients with a mass ratio,  $q$ , *formally* above one. This is at first hand unexpected as the primary is by most

\*Not counting one system whose orbital period was fixed at 50 000 days.

<sup>†</sup>Such tiny, but possibly significant eccentricities are often due to the presence of a third component that perturbs the orbit, and indeed in those cases Griffin either computed an outer orbit or showed that the centre-of-mass velocity of the binary was changing with time — a clear sign of a third companion.

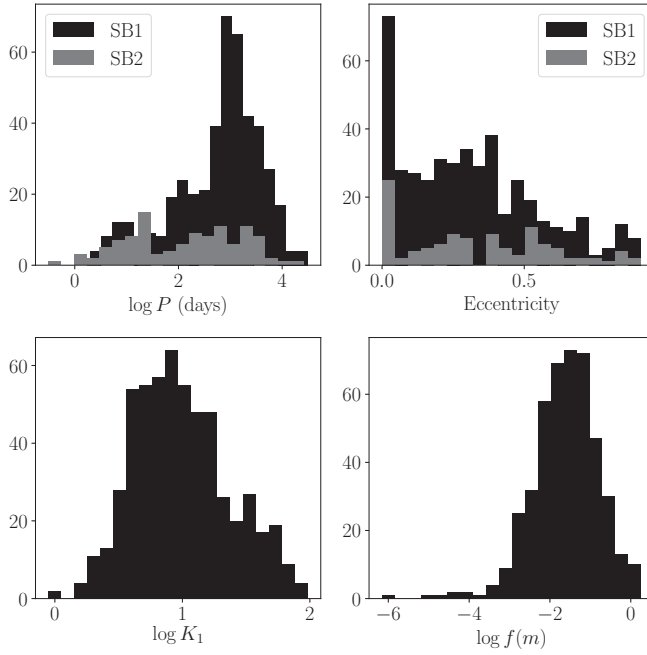


FIG. 1

The distribution of the orbital elements for the sample considered.

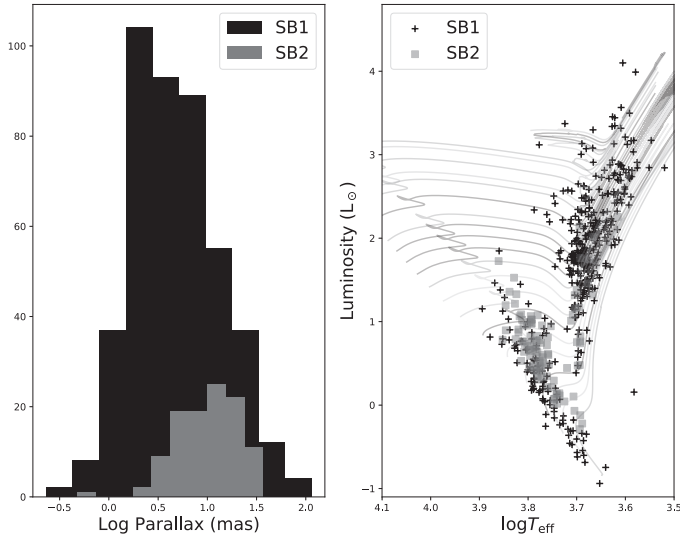


FIG. 2

(Left) The distribution in parallaxes of the stars in the initial sample, split among SB1 and SB2 systems. (Right) H-R diagram of the systems from our final sample based on *Gaia* DR2 effective temperatures and radii. These are compared to MESA stellar evolutionary tracks for a wide range of masses and of solar metallicity.

definitions the brighter, which in normal stellar evolution also implies the more massive, unless there has been mass transfer. Although this is a possibility, we note that in all cases where  $q > 1$ , the error bars make it easily move on to the *correct* side of the inequality, within one standard deviation. We should thus consider that these systems are in fact compatible with being twins ( $q \approx 1$ ). Additionally, by the very nature of the observations done — cross-correlation with a mask of the red giant Arcturus — the primary in Griffin’s papers will be the one that gives the deeper dip in his tracings, which is usually the brighter, although for pairs of quite different spectral types, it could be the less luminous but redder star. A look at the spectral-type distribution for these systems reveal that most are of F-type.

Most of the SB2s have mass ratios between 0.6 and 1 (see Fig. 3). This is expected, as the majority is on the main-sequence: a system will appear as an SB2 if the difference in brightness between the two is less than about 2–2.5 magnitudes (depending on the colour and the matching with the spectral type of the Arcturus mask), *i.e.*, roughly a factor ten in luminosity (with a clear colour dependence). Given the mass–luminosity relation on the main-sequence for solar-like stars,  $L \propto M^4$ , this leads to a minimum mass ratio of about 0.6, as observed. There are, however, four systems with mass ratios below this value:

(i) HD 192785 ( $q = 0.13$ ;  $P = 19.2735$  d) is clearly an example of a mass-transfer system.

(ii) HD 31738 ( $q = 0.21$ ;  $P = 0.45$  d) was also reported by Griffin has having a “period [that] is unexpectedly, indeed astoundingly, short,” and “one in which there has been a lot of mass exchange”.

(iii) HD 158209 ( $q = 0.46$ ) is a triple system, where the primary is a binary system containing a subgiant, while the secondary is a main-sequence star.

(iv) HD 100125 ( $q = 0.56$ ;  $P = 48$  d) shows a secondary peak so weak, that only the experienced eye of Griffin would have seen it, and the secondary orbit is based mostly on data obtained by others at Kitt Peak. With  $q = 0.56$ , it is indeed at the limit of what we expect to be an SB2.

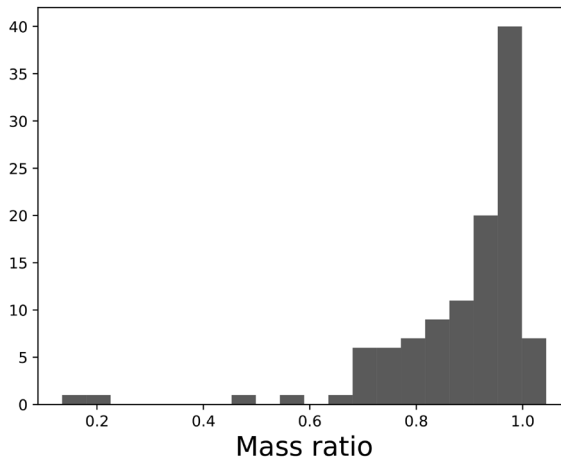


FIG. 3  
The distribution of the mass ratio for all SB2 systems.

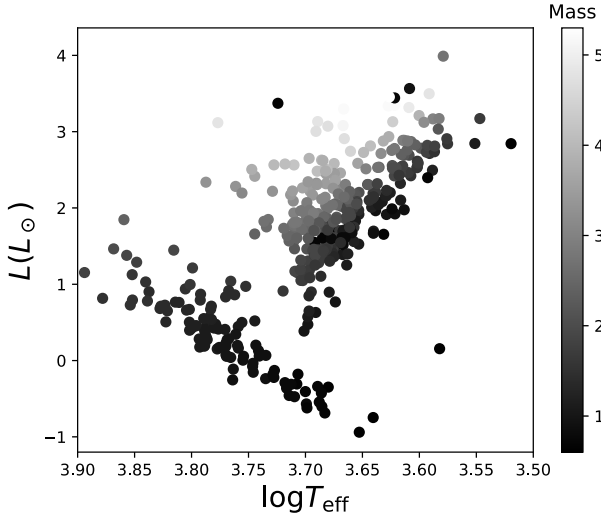


FIG. 4

H-R diagram showing all SB1 systems for which *Gaia* DR2 provides temperature and radius. They are greyed based on the primary mass we derived based on MESA evolutionary tracks.

#### Mass-ratio distribution

For SB1s, things are more complicated, as the sole information we have is the spectroscopic mass function,  $f(m)$ , which is a certain combination of observables ( $K_1, P, e$ ) and corresponds to

$$f(m) = M_1 \frac{q^3}{(1+q)^2} \sin^3 i,$$

where  $i$  is the (unknown) orbital inclination on the plane of the sky,  $M_1$  the primary mass, and  $q$  is the mass ratio. If we can estimate  $M_1$  or make reasonable assumptions about it, and if we can assume that  $i$  is randomly distributed on the sky, that is, the probability of having a given value of  $i$  is  $\sin^2 i$ , then one can use statistical methods<sup>7,11</sup> to derive a distribution of the mass ratio; the individual mass ratio for a given system cannot be obtained, however.

To derive  $M_1$  we made use of the *Gaia* DR2 data — our final sample consisting of those stars for which the consortium working on the data was able to derive the effective temperature and radius (Fig. 4). Comparing their position in an H-R diagram with the MESA stellar evolutionary tracks as obtained with MIST<sup>12</sup> allows us to derive the stellar mass, using a least-squares method. The result is shown in Fig. 5 (top), assuming all stars have solar metallicities. This figure shows nicely how the mass-ratio distribution of SB1s complements that of SB2s, although there is possibly a deficit of systems with mass ratios between 0.6 and 0.8\*, as well as the well-known deficit of systems with  $q < 0.1$ , the latter being the ‘brown-dwarf desert’.

\*Already found by the second author in 1974<sup>13</sup>.

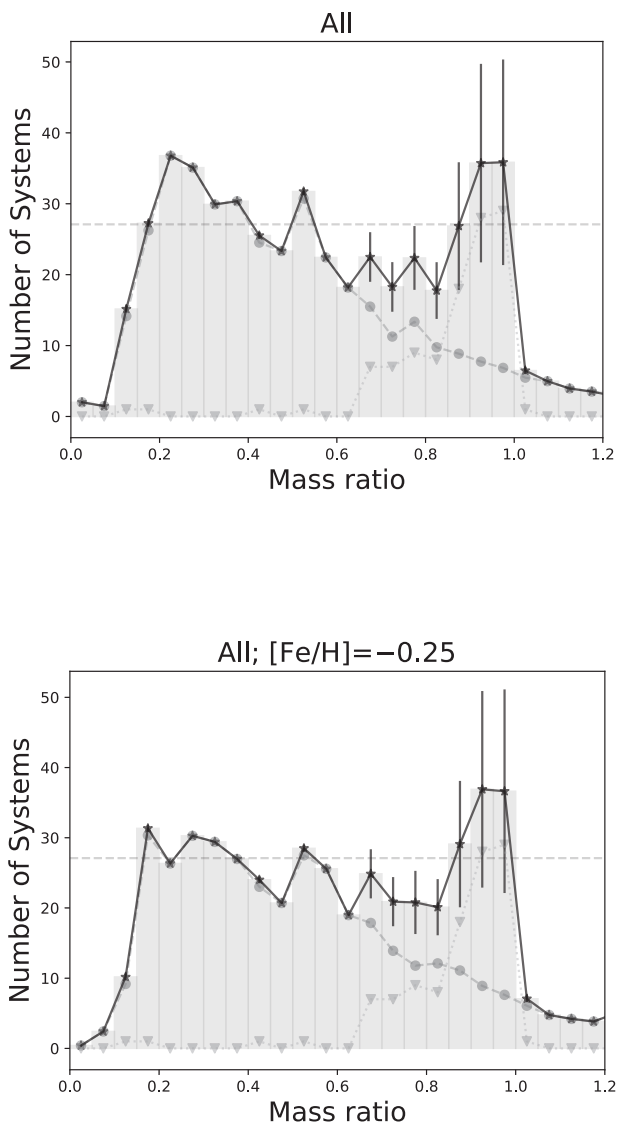


FIG. 5

The distribution of the mass ratio for all the systems we studied. SB1s and SB2s are shown separately as solid dots and triangles, respectively, and the sum is then shown as dark stars, with the error bars indicating the range we obtain if we vary the relative number of SB2s by a factor 0.5 and 1.5, respectively. On top, we show the distribution when using solar-metallicity tracks, while the bottom plot shows the same when using  $[\text{Fe}/\text{H}] = -0.25$  tracks.

Assuming solar metallicities is of course a very crude approximation, which is certainly not correct — for some stars in our sample, *Simbad* gives values for the metallicity, and some are clearly sub-solar, although the average over the sample is apparently not very far from solar. Stars which are metal deficient will follow a different path in the H–R diagram, and although the effect is negligible on the main sequence, it will lead to a shift on the red-giant branches. Assuming solar metallicity will thus lead to an incorrect primary mass, especially for the red giants in our sample. It would therefore be better to use stellar evolutionary tracks of the metallicity of each star in our sample in order to derive the primary mass. Unfortunately, this information is not yet available for the majority of our sample, and we need to accept resorting to a simplified method. As the mass ratio depends only on the cube root of the primary mass, we can, however, hope that the resulting effect is not very large. To test this, we have also determined the primary mass, using  $[\text{Fe}/\text{H}] = -0.25$  tracks, and determined the new resulting mass-ratio distribution. The results are shown in the bottom plot of Fig. 5, where one can see that the differences with the upper panel are small, with the most striking difference being that the distribution is now closer to a uniform one.

To obtain the final mass-ratio distribution it is obviously necessary to combine the distribution of mass ratios obtained for SB1 and those for SB2 systems. The simplest way to do so is to assume that our sample is not affected by any bias that would alter the ratio between SB2 and SB1 systems. Given the methodology of Griffin, this seems to be a very reasonable assumption, as the selection is mostly done because the system has a spectral type that matches the *Coravel*'s mask and is bright enough to be observed. A possible bias would be that an SB2 may appear on average brighter than an SB1 as the companion contributes light. However, when looking at the distribution of magnitudes, it appears that SB2s from the current sample are, on average, fainter than SB1s. This bias is thus not operating. Nevertheless, in order to show what would be the effect of any bias affecting the ratio between SB1 and SB2 systems, we indicate with error bars in Fig. 5 the effect of adding or subtracting half the contribution of SB2 systems to the final distribution.

#### *Looking in more detail*

In order to see if the features we detect in our final mass-ratio distribution are due to a particular population, we have split our final sample into main-sequence stars and red giants and determined the mass-ratio distributions for these sub-samples (Fig. 6). When doing so, it is now very clear that the peak of systems with mass ratios above 0.85 is restricted to main-sequence stars only. As mentioned before, in fact this is mostly due to a population of F-type stars in our sample. For main-sequence stars, we also clearly see the brown-dwarf desert at the lowest mass ratios. It is important to note that given the smallest semi-amplitudes that Griffin could measure, such brown dwarfs can be detected (in fact, some have), so their paucity must be a reality. There is also an apparent peak of systems with mass ratio around 0.5, but its significance is barely at the 3-sigma level and it is probably better not to give it too much attention.

Turning now to the mass-ratio distribution of red giants, it is clear that there is a decline of systems with a mass ratio larger than about 0.6. This result was also found by Van der Swaelmen *et al.*<sup>14</sup> in a less-pronounced way when studying a sample of red-giant members of open clusters. Its origin must lie in the fact that the red giants in our sample originate mostly from stars with masses around  $2\text{--}2.5 M_{\odot}$ , *i.e.*, evolved A-type stars, unlike our sample of main-sequence stars



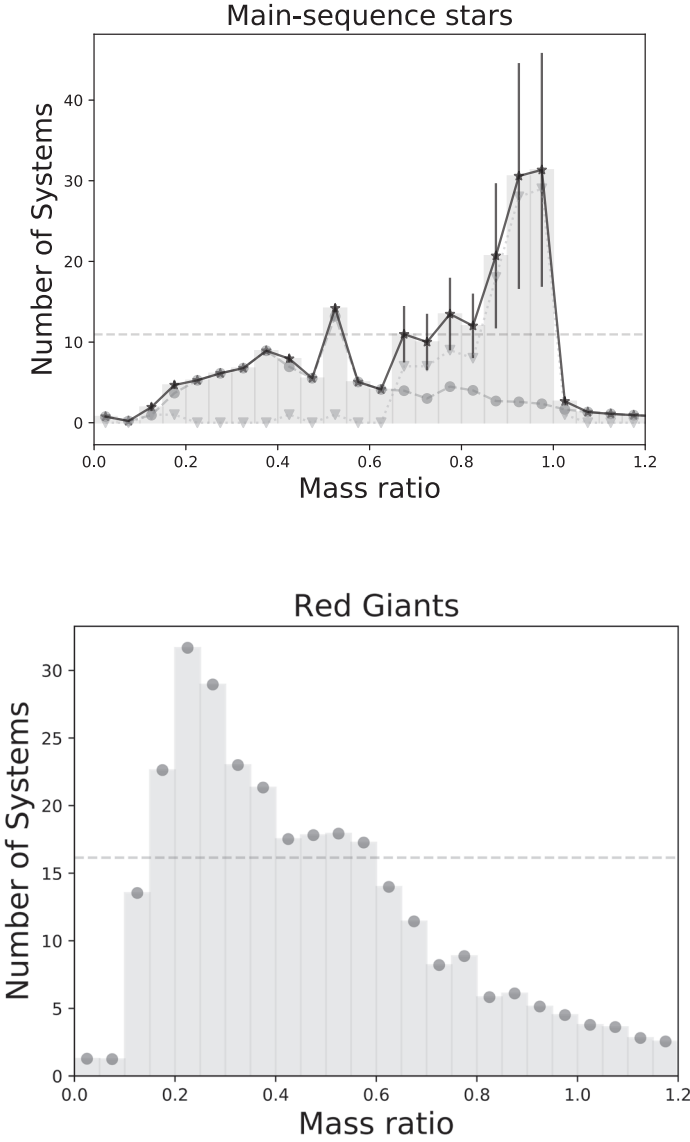


FIG. 6

Same as Fig. 5, separating the sample into main-sequence stars (top) and red giants (bottom).

which is comprised of mostly G and F-type stars. This could thus point to the fact that A-type stars have an inherent deficit of relatively massive companions.

The mass-ratio distribution of red giants also shows a clear peak around a mass ratio 0.25–0.3, which was again seen by Van der Swaelmen *et al.*<sup>14</sup>. They conclude that 22% of their sample consists of post-mass-transfer systems, in which the red giant's companion is a white dwarf. This result is in agreement with what we find here as well.

### Acknowledgements

It is an immense pleasure to thank Prof. R. F. Griffin for having patiently collected so many orbits in his Series in this *Magazine*, and for allowing us to perform the current analysis of his systems. We are also very grateful to Dr. Elizabeth Griffin for biographical information. This research has made use of the *Simbad* database, operated at CDS, Strasbourg, France, and of the *VizieR* catalogue access tool, CDS, Strasbourg, France (DOI: 10.26093/cds/vizieR). The original description of the *VizieR* service was published in *A&AS*, **143**, 23. This work has made use of data from the European Space Agency (ESA) mission *Gaia* (<https://www.cosmos.esa.int/Gaia>), processed by the *Gaia* Data Processing and Analysis Consortium (DPAC, <https://www.cosmos.esa.int/web/Gaia/dpac/consortium>). Funding for the DPAC has been provided by national institutions, in particular the institutions participating in the *Gaia* Multilateral Agreement.

### References

- (1) R. F. Griffin, *A Photometric Atlas of the Spectrum of Arcturus* (Cambridge Philosophical Society), 1968.
- (2) R. Griffin & R. Griffin, *A Photometric Atlas of the Spectrum of Procyon  $\lambda\lambda 3140\text{--}7470$*  (Institute of Astronomy, Cambridge), 1979.
- (3) R. Griffin, *MNRAS*, **162**, 243, 1973.
- (4) R. F. Griffin, *ApJ*, **148**, 465, 1967.
- (5) R. F. Griffin & B. Emerson, *The Observatory*, **95**, 23, 1975.
- (6) V. Trimble, *The Observatory*, **128**, 286, 2008.
- (7) H. M. J. Boffin, N. Cerf & G. Paulus, *A&A*, **271**, 125, 1993.
- (8) R. F. Griffin, *The Observatory*, **128**, 448, 2008.
- (9) *Gaia* Collaboration, T. Prusti *et al.*, *A&A*, **595**, A1, 2016.
- (10) *Gaia* Collaboration, A. G. A. Brown *et al.*, *A&A*, **616**, A1, 2018.
- (11) H. M. J. Boffin, *A&A*, **524**, A14, 2010.
- (12) J. Choi *et al.*, *ApJ*, **823**, 102, 2016.
- (13) V. Trimble, *AJ*, **79**, 967, 1974.
- (14) M. Van der Swaelmen *et al.*, *A&A*, **597**, A68, 2017.

## SPECTROSCOPIC ORBITS OF THREE DWARF BARIUM STARS

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Barium stars are thought to result from binary evolution in systems wide enough to allow the more massive component to reach the asymptotic giant branch and eventually become a CO white dwarf. While Ba stars were initially known only among giant or subgiant stars, some were subsequently discovered also on the main sequence (and known as dwarf Ba stars). We provide here the orbital parameters of three dwarf Ba stars, completing the sample of 27 orbits published recently by Escorza *et al.* with these three southern targets. We show that these new orbital parameters are consistent with those of other dwarf Ba stars.

### Introduction

Barium stars are not evolved enough to synthesize in their interior and dredge up to their surface the *s*-process elements (including Ba) that are very abundant in their atmospheres. On the other hand, we have convincing statistical indications that they all belong to SB1-type binary systems<sup>1,2</sup>, and UV observations have revealed the white-dwarf nature of the companion of some of them<sup>3–5</sup>. This leads to the following scenario — that has become common wisdom — to explain their overabundance of *s*-process elements: the initially more massive component evolved into an asymptotic-giant-branch (AGB) star, synthesized and dredged up carbon and *s*-process elements, expelled its envelope, part of which was accreted by the ‘innocent bystander’, namely the initially secondary component, and the latter thereby became the Ba star we observe today while the other component cooled to a white dwarf. The mass ratio underwent a reversal in the process. The mass transfer may occur through wind, (wind) Roche-lobe overflow, or common-envelope evolution<sup>6</sup>; the details are still debated, but the net result is a long orbital period (a few hundred days to several decades) and a small eccentricity<sup>2,7</sup>.

Interestingly, Ba stars were known initially only among G- and K-type giants (they were dubbed Ba giants when belonging to Population I, and CH giants when belonging to Population II)<sup>8,9</sup> and subgiants (dubbed CH subgiants)<sup>10</sup>, though some of the latter are actually dwarfs<sup>11</sup>. The existence of main-sequence Ba stars was fully recognized only in the early 1990s<sup>12–19</sup>, among F- and G-type stars. The question then arose as to whether giant Ba stars might be the descendants of Ba dwarfs. Even though the latter appear on average less massive than the former<sup>7</sup>, this is the result of a selection bias (dwarf Ba stars are difficult to detect among the more-massive main-sequence A and late-B stars).

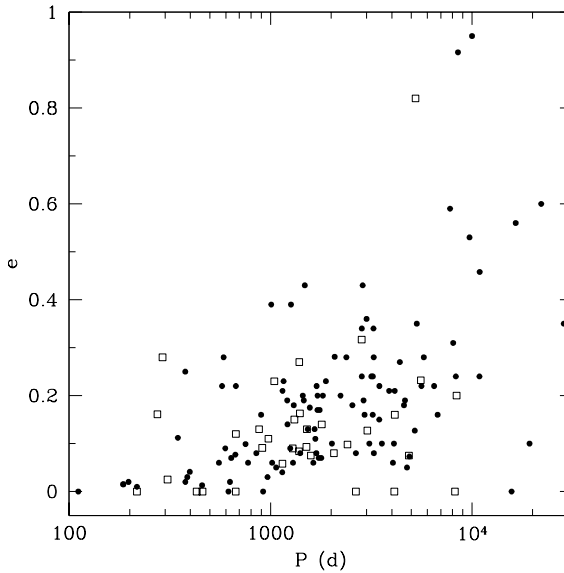


FIG. 1

The  $e$ - $P$  diagram for dwarf Ba and subgiant CH stars (open squares; from ref. 7 and the present work) and giant Ba and S stars (filled circles<sup>2</sup>).

From a dynamical viewpoint, the two families appear similar, as revealed by their almost perfect overlap\* in the eccentricity–period diagram (Fig. 1).

Ba dwarfs and subgiants are interesting because their mass determination is easier than for Ba giants. Therefore if a relative astrometric orbit is accessible in addition to the spectroscopic one, the mass of the companion can be determined. If only the spectroscopic orbit is known, but for a large enough sample of Ba systems, a statistical estimate of the companion mass can be obtained assuming random orbit orientations. This was done by, *e.g.*, North *et al.*<sup>18</sup> and by Escorza *et al.*<sup>7</sup>, and resulted in a companion mass close to  $0.6 M_{\odot}$ , as expected for a white dwarf. The first sample consisted of 14 orbits, while the second sample included 27 orbits.

In this work, we present the orbital parameters of three more Ba stars, namely HD 202400, HD 222349, and HD 224621. The elemental abundances of the first two were determined by North *et al.*<sup>16,17</sup>, and by Luck & Bond<sup>19</sup> for the third. All three can be considered as belonging to the main sequence, even though HD 224621 had been classified as a ‘CH subgiant’, because their surface gravities determined through high-resolution spectroscopy are  $\log g > 3.7$ .

\*The three dwarf Ba stars with  $P > 2000$  d seemingly falling in the ‘low-eccentricity gap’ ( $P > 1000$  d,  $e \leq 0.05$ ) of the eccentricity–period diagram (Fig. 1) have error bars on the eccentricity compatible with them lying just at the boundary of the gap.

### Sample and observations

The stars HD 202400 and HD 222349 had been classified as F2 Ba 1 and G2 Ba 1 respectively by Lü *et al.*<sup>20</sup> and were studied with high-dispersion spectroscopy by North *et al.*<sup>16</sup>. HD 224621 was first classified as a subgiant CH star by Bond<sup>10</sup>, then studied with high-dispersion spectroscopy by Luck & Bond<sup>19</sup>. Table I lists the stellar parameters adopted by those authors and shows that they indeed belong to the main sequence. The magnitudes, colour indices, and *Gaia* DR2 parallaxes are also listed. The spectral classification and photometry were taken from the *Simbad* database. All three stars populate the southern sky, with declinations  $\delta < -36^\circ$ . The masses listed in Table I were derived as in ref. 7.

TABLE I

*Basic properties of the sample stars. The stellar parameters are those adopted by North et al.<sup>16</sup> and by Luck & Bond<sup>19</sup>, except for the mass (see text). The B and V magnitudes are taken from the Simbad database, and the parallaxes from the Gaia DR2.*

Star HD	Other id.	Sp. type	V	B-V	$\pi$ [mas]	$T_{\text{eff}}$ [K]	$\log g$ [cgs]	[Fe/H] [dex]	M [ $M_\odot$ ]
202400	HIP 105294	Ap Sr	9.18 $\pm 0.01$	0.39 $\pm 0.02$	5.92 $\pm 0.07$	6200 $\pm 100$	4.0 $\pm 0.2$	-0.7 $\pm 0.1$	0.98 $\pm 0.08$
222349	SAO 247972	G5/K0+A/F(Sr)	9.22 $\pm 0.01$	0.48 $\pm 0.02$	8.16 $\pm 0.10$	6000 $\pm 100$	3.8 $\pm 0.2$	-0.9 $\pm 0.1$	0.73 $\pm 0.05$
224621	HIP 118266	GoIII/IV	9.55 $\pm 0.02$	0.63 $\pm 0.03$	12.60 $\pm 0.30$	6000 $\pm 200$	4.0 $\pm 0.3$	-0.4 $\pm 0.1$	0.90 $\pm 0.06$

The radial-velocity (RV) observations were carried out mainly with the *Coravel* spectrovelocimeter<sup>21</sup> attached to the 1.54-m Danish telescope at ESO-La Silla (Chile). For HD 202400 and HD 222349, recent observations were carried out with the 11-m *Southern African Large Telescope (SALT)*<sup>22,23</sup> using the *High Resolution Spectrograph (HRS)*<sup>24–26</sup> in the medium resolution (MR) mode, providing resolving powers  $R=43\,000$  and  $R=40\,000$  for the blue and red arms, respectively. The basic data products<sup>27</sup> were reduced with the MIDAS pipeline developed by Kniazev *et al.*<sup>28</sup> which is based on the ECHELLE<sup>29</sup> and FEROS<sup>30</sup> packages. Heliocentric corrections were applied to the data using VELSET of the RVSAO package<sup>31</sup>. While the *Coravel* radial velocities are obtained at the hardware level by a physical cross-correlation between the observed spectrum and a mask based on the spectrum of Arcturus, the *HRS* velocities are obtained *a posteriori* by a digital cross-correlation between the observed spectrum and Fo or G2 masks<sup>7</sup>. These two stars were also observed once each with the *Coralie* spectrograph attached to the Swiss 1.2-m telescope at ESO-La Silla, and their radial velocities obtained as well by cross-correlation with an appropriate mask. A few RV measurements (five for HD 202400, five for HD 222349, and one for HD 224621) are based on spectra taken with the *CES* spectrograph attached to the 1.4-m *Coudé Auxiliary Telescope (CAT)* at ESO-La Silla with a resolving power  $R=60\,000$ . The RV values are averages

over a few lines fitted by Gaussians, and their adopted errors are the r.m.s. dispersion of the RVs given by the individual lines. A single RV estimate for HD 202400 is based on the positions of the Mg I  $\lambda 5172$ ,  $\lambda 5183$  lines of the Mg I triplet and of the two lines of the Na I D doublet, measured on a spectrum taken with the *FEROS* instrument attached to the 1.52-m telescope at ESO-La Silla. The radial velocities are listed in Table II.

TABLE II

*Measured radial velocities for the sample stars. Columns 3 and 7 indicate the instrument used.*

Star HD	HJD -2400000	Instr. or ref.	RV [km s <sup>-1</sup> ]	$\sigma$ (RV) [km s <sup>-1</sup> ]	HJD -2400000	Instr.	RV [km s <sup>-1</sup> ]	$\sigma$ (RV) [km s <sup>-1</sup> ]
202400	47831.533	CES	-24.53	2.0	50705.654	Coravel	-27.64	3.66
	47833.579	CES	-27.72	1.52	51320.925	Coralie	-15.40	1.0
	47834.572	CES	-26.94	1.97	51449.636	FEROS	-16.10	1.44
	48765.938	Coravel	-22.10	2.8	58026.336	HRS	-18.38	0.92
	49235.658	CES	-27.09	0.56	58051.258	HRS	-17.86	0.73
	49237.584	CES	-26.36	1.76	58061.290	HRS	-18.04	1.23
	49522.860	Coravel	-24.67	2.30	58064.262	HRS	-17.89	1.11
	49526.858	Coravel	-21.43	2.42	58238.651	HRS	-12.92	0.67
	49613.607	Coravel	-24.24	3.16	58292.501	HRS	-12.80	0.74
	49880.838	Coravel	-12.39	1.76	58329.501	HRS	-12.80	0.75
	50083.534	Coravel	-17.05	2.99	58361.458	HRS	-14.87	1.66
	50274.821	Coravel	-25.62	2.27	58413.347	HRS	-16.49	0.60
	50410.513	Coravel	-27.21	2.98				
222349	47830.618	CES	39.28	0.54	50083.528	Coravel	32.30	0.40
	48842.873	Coravel	30.36	0.34	50276.941	Coravel	35.61	0.42
	48887.707	CES	30.09	0.27	50410.529	Coravel	36.91	0.39
	49234.652	CES	27.28	0.41	50705.751	Coravel	39.88	0.44
	49236.648	CES	27.43	0.58	51320.935	Coralie	38.73	0.09
	49237.665	CES	27.20	0.41	58084.343	HRS	28.24	0.15
	49522.947	Coravel	27.55	0.42	58097.304	HRS	27.86	0.16
	49610.759	Coravel	28.16	0.43	58355.587	HRS	25.39	0.12
	49880.923	Coravel	30.72	0.42	58409.275	HRS	26.42	0.03
224621	43054.791	Ref. 19	14.0	0.5	47400.747	Coravel	7.82	0.36
	45544.942	Coravel	9.11	0.40	47514.549	Coravel	13.20	0.32
	45979.627	Coravel	14.67	0.34	47756.814	Coravel	6.53	0.35
	46274.842	Coravel	12.22	0.37	47783.732	Coravel	7.37	0.33
	46338.704	Coravel	21.77	0.34	48055.927	Coravel	5.78	0.35
	46395.566	Coravel	20.21	0.34	48074.928	Coravel	6.03	0.35
	46399.535	Coravel	19.12	0.34	48160.791	Coravel	18.42	0.33
	46632.880	Coravel	20.19	0.36	48463.862	Coravel	17.00	0.31
	46667.773	Coravel	22.20	0.32	48842.861	Coravel	21.81	0.32
	46687.751	Coravel	20.85	0.33	48872.783	Coravel	18.37	0.35
	46692.706	Coravel	20.97	0.39	49235.747	CES	10.26	0.38
	46724.637	Coravel	17.06	0.32	49522.898	Coravel	13.11	0.36
	46728.617	Coravel	16.26	0.30	49610.765	Coravel	5.87	0.34
	47043.744	Coravel	15.64	0.33	49880.926	Coravel	6.97	0.40
	47049.782	Coravel	14.08	0.35	50083.546	Coravel	19.95	0.37
	47069.667	Coravel	11.30	0.35	50276.937	Coravel	11.84	0.36
	47100.598	Coravel	7.17	0.33	50410.535	Coravel	18.91	0.36
	47104.615	Coravel	7.20	0.35	50706.750	Coravel	21.01	0.39
	47370.933	Coravel	12.41	0.38	50795.536	Coravel	6.66	0.49

### Results

The search for the most probable orbital period and the determination of the orbital parameters were made using the DACE software that is publicly available (<https://dace.unige.ch>) and is optimized for the search of exoplanets but also appropriate for the analysis of binary stars. The analysis is made in three steps: the first consists in a periodogram, on which the user can select the most probable period; the second is a first Keplerian fit of the orbital parameters, following the method described by Delisle *et al.*<sup>32</sup>; the third and final step consists of a Monte-Carlo Markov Chain (MCMC) that determines final values and realistic errors for the orbital parameters (as described by Díaz *et al.*<sup>33,34</sup>). The MCMC even allows us to adjust possible RV zero-point offsets between different instruments. We have determined the orbital parameters both using this possibility and under the assumption of negligible offsets; in general the former option remains unsatisfactory in that it artificially lowers the reduced chi-square, so we rather adopted the latter option. The resulting orbital parameters are displayed in Table III. The RV curves are shown in Figs. 2, 3, and 4.

### Discussion

Adding these three new orbits to the 27 published by Escorza *et al.*<sup>7</sup>, the number of orbits for systems hosting dwarf or subgiant Ba stars now amounts to 30. However, one of the systems studied by Escorza *et al.* is an SB2 system (HD 114520) and could actually be a triple system, if one accepts the prevailing

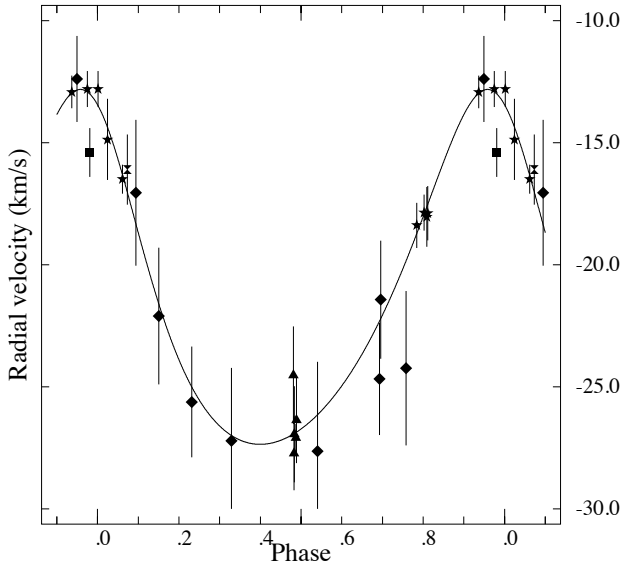


FIG. 2

Radial velocities (RV) of HD 202400 as a function of orbital phase. Symbols are as follows: triangles (*CAT*), hourglass (*FEROS*), stars (*SALT*), square (*Coralie*), lozenges (*Coravel*). The large RV errors and dispersion around the fitted curve are due to a relatively high projected rotational velocity.

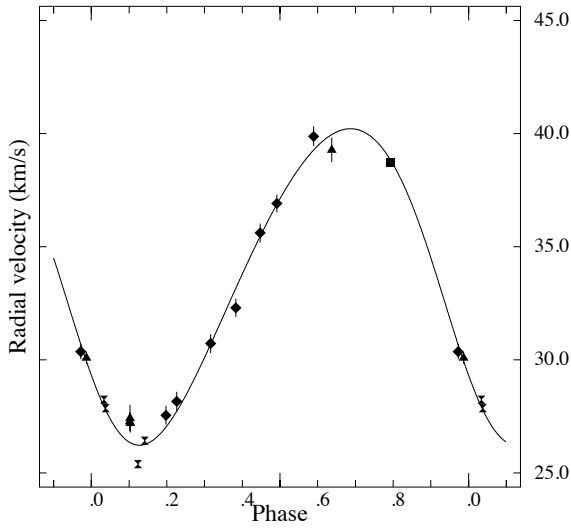


FIG. 3

Same as Fig. 2, but for HD 222349. Symbols are as follows: triangles (*CAT*), hourglasses (*SALT*), square (*Coralie*), lozenges (*Coravel*).

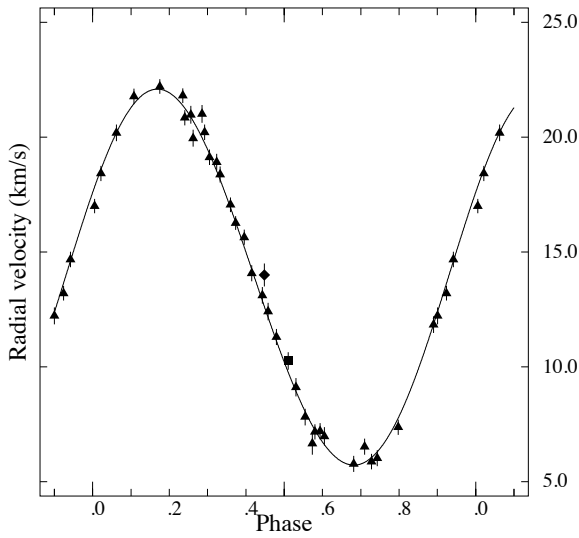


FIG. 4

Same as Fig. 2, but for HD 224621. Symbols are as follows: triangles (*Coravel*), square (*CAT*), lozenge (ref. 19).



TABLE III

*Orbital parameters of the sample stars obtained using the DACE code, including the MCMC. The errors quoted correspond to  $1\sigma$ , i.e., to the 68.27% confidence interval.*

Star HD	$P_{\text{orb}}$ [d]	$e$	$T_p$ [HJD −2400000]	$\omega$ [°]	$K_1$ [km s <sup>−1</sup> ]	$\gamma$ [km s <sup>−1</sup> ]	$f(m)$ [ $M_{\odot}$ ]	$a_1 \sin i$ [AU]	$\sigma_{\text{res}}$ [km s <sup>−1</sup> ]	$N$
202400	1396.6 ±7.3	0.222 ±0.067	48523 ±133	14 ±33	7.26 ±4.6	−21.56 ±4.2	0.0513 ±0.0100	0.906 ±0.055	0.89	25
222349	3018.6 ±5.6	0.112 ±0.023	54964 ±45	123.9 ±5.7	6.89 ±1.1	33.657 ±0.076	0.1004 ±0.0048	1.899 ±0.033	0.268	18
224621	308.092 ±0.094	0.023 ±0.011	48172.6 ±15.5	316.8 ±18.2	8.173 ±0.092	13.822 ±0.060	0.01741 ±0.00059	0.2314 ±0.0026	0.376	38

paradigm about the formation of Ba stars as a given; the WD would then follow a much wider orbit, the period of which remains to be determined. Another system, HD 48565, is clearly triple but, as it is an SBI, it is not possible to know whether the WD belongs to the inner or to the outer system. Thus we are left with 28 binary systems whose statistical properties may be investigated.

In Fig. 1, we presented the sample  $e$ – $P$  diagram which revealed an almost perfect coincidence between the locations of the two samples, suggesting that giant Ba stars (and their cooler analogues — the extrinsic S stars) are indeed the descendants of the dwarf Ba stars. Using the BINSTAR evolution code, this hypothesis will be further evaluated in a paper in preparation (Escorza et al. 2020).

In Fig. 5 we show the relation between the mass of the Ba star and its metallicity [Fe/H] for both giant (filled circles) and dwarf (open squares) Ba stars. Here, the triple system HD 48565 is included, because the orbital elements do not matter, and one can be confident that the non-degenerate, non-Ba component is faint enough that neither the mass nor the metallicity of the primary component is biased; the diagram thus includes 29 dwarf Ba stars (open squares). The giant Ba stars are taken from Fig. 17 of Jorissen et al.<sup>2</sup>. For the reason mentioned in the introduction (dwarf Ba stars are difficult to detect among the more massive main-sequence A and late-B stars), dwarf Ba stars so far appear to be restricted to a narrower mass range than are giant Ba stars. Low-mass Ba stars (with  $M < 2 M_{\odot}$ ) cover a large metallicity range ( $-1 \leq [\text{Fe}/\text{H}] \leq 0$ ), whereas the most massive (giant) Ba stars ( $M \geq 4 M_{\odot}$ ), being relatively young, are restricted to high metallicities ( $-0.2 \leq [\text{Fe}/\text{H}]$ ).

It seems appropriate here to dig a bit deeper into the question as to why no dwarf Ba star is known with a mass larger than about  $1.6 M_{\odot}$ . A selection bias undoubtedly does occur, due to the fast rotation of most intermediate-mass stars on the main sequence that broadens the spectral lines and thus makes abundance determinations difficult. However, some A-type stars are slow rotators, therefore some of them could in principle be detected as Ba stars. Indeed Ba has been found overabundant in several of these (e.g., by Lemke<sup>36</sup>, and Takeda et al.<sup>37</sup>), but many of them are classified as Am stars (see, e.g., Fig. 1 of Çay et al.<sup>38</sup> for the elemental abundances in two typical Am stars), and most Am stars are short-period binary systems, with a period

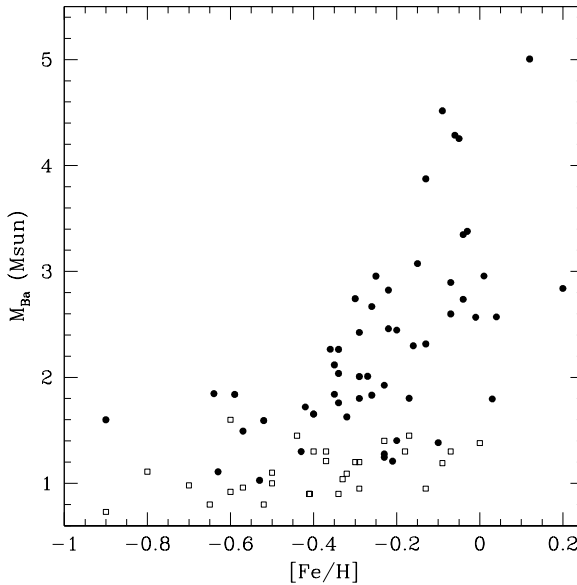


FIG. 5

Barium star mass *vs.*  $[\text{Fe}/\text{H}]$ , for barium giants (filled circles (ref. 2)) and barium dwarfs (open squares, from this work and ref. 7).

distribution that is not compatible with that of Ba stars. Ba is overabundant in many chemically-peculiar stars, from those of the HgMn type (among the late B-type stars, see, *e.g.*, Monier *et al.*<sup>39</sup>), to those of the SrCrEu type (among the mid A-type stars, see, *e.g.*, Guthrie<sup>40</sup>, Cowley<sup>41</sup>, and Kochukov *et al.*<sup>42</sup>). The problem is that such stars also show underabundance of carbon, contrary to both dwarf and giant Ba stars, and their abundance anomalies are thought to be due to radiative diffusion rather than mass-transfer in a binary system (see refs. 43 and 44). Especially telling is the case of the magnetic Ap star HR 3831, where the Ba overabundance may reach a factor as large as  $10^5$  in some places of the stellar surface, according to abundance Doppler imaging<sup>42</sup>: such high overabundances cannot be explained by the mass-transfer scenario invoked for Ba stars. Furthermore, the high efficiency of radiative diffusion in slowly rotating intermediate-mass stars suggests that any abundance anomaly due to mass transfer in a binary system will be quickly superseded and erased by the radiative-diffusion mechanism, making the identification of such systems all the more problematic. Interestingly, the possible link between Am stars and barium stars had already been proposed by Hakkila<sup>45</sup>, though his discussion about how to reconcile the discrepant period distributions remains unconvincing.

Related questions are whether Sirius is a Ba star or not, and why Procyon does not show Ba overabundance. The first question has been addressed by Landstreet<sup>46</sup>: Sirius does show a significant (1.4 dex) Ba overabundance and it does have a white-dwarf companion, but it is classified as a mild Am star (AomA1 Va, according to Gray *et al.*<sup>47</sup>) and indeed has abundances typical of

Am stars. Its orbit has a long period (50.13 yr) and a rather large eccentricity (0.591), but such figures are still within the orbital parameters covered by Ba stars (see Fig. 1). For instance, HD 119185<sup>2</sup> has  $P_{\text{orb}}=60$  yr and  $e=0.6$ . It is highly probable that radiative diffusion has been and is still at work in Sirius A, but precisely because of this, it remains impossible to know how much processed material it has accreted from its former AGB companion. Sirius A has a mass  $M=2.06 M_{\odot}$ , so it is perfectly representative of those stars that are massive enough to have almost no convective zone, thus permitting radiative diffusion to take place. On the other hand, the WD has a mass  $M=1.02 M_{\odot}$ , corresponding to an initial stellar mass  $M \sim 5 M_{\odot}$  according to the semi-empirical initial-final mass relation of Cummings *et al.*<sup>48</sup>. Such high-mass AGB stars with solar metallicity are unable to yield substantial quantities of *s*-process elements<sup>49</sup>, suggesting that radiative diffusion alone is responsible for the Ba overabundance of Sirius A. Procyon A has a mass  $M=1.5 M_{\odot}$  that is similar to that of dwarf Ba stars. It also has a white-dwarf companion, with  $M=0.60 M_{\odot}$ , on an orbit with  $P_{\text{orb}}=40.82$  yr and  $e=0.407$ , quite compatible with some orbits of Ba stars. However, its Ba abundance, although slightly enhanced, remains solar within  $1 \sigma$  (and other heavy *s*-process elements like Nd and Sm are  $2 \sigma$  below solar) according to Kato & Sadakane<sup>50</sup>. Why, then, is Procyon A not a Ba star? Although this seems to contradict the mass-transfer scenario at first sight, at least two factors may reconcile this scenario with the lack of Ba overabundance: (i) the anti-correlation between the overabundance of *s*-process elements and the orbital period, and (ii) the anti-correlation between that overabundance and [Fe/H] (see ref. 2), and the solar metallicity of Procyon.

#### Acknowledgements

PN thanks Dr. Maxime Marmier for digging into the old *Coravel* database, thereby providing us with precious RV values obtained with the southern *Coravel* scanner attached to the 1.54-m Danish telescope at ESO La Silla, Chile. PN also thanks the colleagues who contributed to this observational effort, especially Mr. Bernard Pernier of Geneva Observatory and Dr. Jean-Claude Mermilliod of Institut d'astronomie de l'Université de Lausanne. Recent measurements were gathered with the *Southern African Large Telescope (SALT)* using the *HRS* within the *SALT* programme 2017-1-MLT-010 (PI B. Miszalski). This research has been partly funded by the National Science Centre, Poland, through grant OPUS 2017/27/B/ST9/01940 to JM. Polish participation in *SALT* is funded by grant No. MNiSW DIR/WK/2016/07. PN also thanks Dr. Damien Segransan for his help in using the DACE software. This research has been partly funded by the Belgian Science Policy Office under contract BR/143/A2/STARLAB. AE acknowledges support from the Fonds voor Wetenschappelijk Onderzoek Vlaanderen (FWO) under contract ZKD1501-00-W01. BM acknowledges support from the National Research Foundation (NRF) of South Africa. This research has made use of the *Simbad* database, operated at CDS, Strasbourg, France.

#### References

- (1) R. D. McClure & A. W. Woodsworth, *ApJ*, **352**, 709, 1990.
- (2) A. Jorissen *et al.*, *A&A*, **626**, A127, 2019.
- (3) E. Böhm-Vitense *et al.*, *ApJ*, **278**, 726, 1984.
- (4) E. Böhm-Vitense *et al.*, *ApJ*, **533**, 969, 2000.
- (5) R. O. Gray *et al.*, *AJ*, **141**, 160, 2011.

- (6) M. I. Saladino *et al.*, *A&A*, **626**, A68, 2019.
- (7) A. Escorza *et al.*, *A&A*, **626**, A128, 2019.
- (8) W. P. Bidelman & P. C. Keenan, *ApJ*, **114**, 473, 1951.
- (9) P. C. Keenan, *ApJ*, **96**, 101, 1942.
- (10) H. E. Bond, *ApJ*, **194**, 95, 1974.
- (11) A. Escorza *et al.*, *A&A*, **608**, A100, 2017.
- (12) P. North & A. Duquennoy, *A&A*, **244**, 335, 1991.
- (13) P. North & T. Lanz, *A&A*, **251**, 489, 1991.
- (14) A. Jorissen & H. M. J. Boffin, in A. Duquennoy & M. Mayor (eds.), *Binaries as tracers of star formation* (Cambridge Univ. Press), 1992, p. 110.
- (15) P. North, in A. Duquennoy & M. Mayor (eds.), *Binaries as tracers of star formation* (Cambridge Univ. Press), 1992, p. 202.
- (16) P. North *et al.*, *A&A*, **281**, 775, 1994.
- (17) P. North *et al.*, *A&A*, **292**, 350, 1994.
- (18) P. North *et al.*, in R. F. Wing (ed.), *The carbon star phenomenon*, IAU Sym. 177, 2000, p. 269.
- (19) R. E. Luck & H. E. Bond, *ApJS*, **77**, 515, 1991.
- (20) P. K. Lü *et al.*, *ApJS*, **52**, 169, 1983.
- (21) A. Baranne *et al.*, *Vistas in Astronomy*, **23**, 279, 1979.
- (22) D. A. H. Buckley *et al.*, in Proc. SPIE Vol. 6267, *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series*, **62670Z**, 2006.
- (23) D. O'Donoghue *et al.*, *MNRAS*, **372**, 151, 2006.
- (24) D. G. Bramall *et al.*, in Proc. SPIE Vol. 7735, *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series*, **77354F**, 2010.
- (25) D. G. Bramall *et al.*, in Proc. SPIE Vol. 8446, *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series*, **84460A**, 2012.
- (26) L. A. Crause *et al.*, in Proc. SPIE Vol. 9147, *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series*, **91476T**, 2014.
- (27) S. M. Crawford *et al.*, in Proc. SPIE Vol. 7737, *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series*, **77372S**, 2010.
- (28) A. Y. Kniazev *et al.*, *MNRAS*, **459**, 3068, 2016.
- (29) P. Ballester, in *European Southern Observatory Conference and Workshop Proceedings*, Vol. 41, eds. P. J. Grosbøl & R. C. E. de Ruijscher, 1992, p. 177.
- (30) O. Stahl *et al.*, in ASP Conference Series, Vol. 188, *Optical and Infrared Spectroscopy of Circumstellar Matter*, eds. E. Guenther, B. Stecklum & S. Klose, 1999, p. 331.
- (31) M. J. Kurtz & D. J. Mink, *PASP*, **110**, 934, 1998.
- (32) J.-B. Delisle *et al.*, *A&A*, **590**, A134, 2016.
- (33) R. F. Diaz *et al.*, *MNRAS*, **441**, 983, 2014.
- (34) R. F. Diaz *et al.*, *A&A*, **585**, A134, 2016.
- (35) P. Davis *et al.*, *A&A*, **556**, A4, 2013.
- (36) M. Lemke, *A&A*, **240**, 331, 1990.
- (37) Y. Takeda *et al.*, *Journal of the Korean Astronomical Society*, **41**, 83, 2008.
- (38) I. H. Çay *et al.*, *PASP*, **128**, 054201, 2016.
- (39) R. Monier *et al.*, *Ap&SS*, **361**, 139M, 2016.
- (40) B. N. G. Guthrie, *Ap&SS*, **3**, 542, 1969.
- (41) C. R. Cowley, *ApJS*, **32**, 631, 1976.
- (42) O. Kochukhov *et al.*, *A&A*, **424**, 935, 2004.
- (43) G. Michaud, *ApJ*, **160**, 641, 1970.
- (44) J. Borsenberger *et al.*, *A&A*, **139**, 147, 1984.
- (45) J. Hakkila, *AJ*, **98**, 699, 1989.
- (46) J. D. Landstreet, *A&A*, **528**, A132, 2011.
- (47) R. O. Gray *et al.*, *AJ*, **126**, 2048, 2003.
- (48) J. D. Cummings *et al.*, *ApJ*, **871**, L18, 2019.
- (49) A. I. Karakas & M. Lugaro, *ApJ*, **825**, 26, 2016.
- (50) K. Kato & K. Sadakane, *A&A*, **113**, 135, 1982.

## REVIEWS

**Hubble Deep Field and the Distant Universe**, by Robert Williams (Institute of Physics Publishing), 2018. Pp. 135, 26 × 18.5 cm. Price £99/\$150 (hardbound; ISBN 978 0 7503 1754 2).

This one is a real page-turner! Even though you know how the story turns out, with the Hubble Deep Field an enormous success in finding and characterizing galaxies with redshifts 0.6 to 0.9 and larger, you may find it difficult to take a deep breath when the author announces that he will fall on his sword and resign the STScI Directorship if the HDF turns out to be an embarrassment for the Institute or the *HST* (then less than two years past the first servicing mission, which had emplaced the bits and pieces needed to correct for the wrongly shaped primary mirror). That story and other prequels are well covered. Indeed the author starts the Universe with *WMAP* and astronomy with Aristotle.

The male, heroic lead is unquestionably Robert Williams, author of this retrospective. And there are three heroines, which is a lot for this sort of story. First Nancy Grace Roman, a student of Chandrasekhar and, at NASA headquarters, the driving force for a *Large Space Telescope* (*LST*, shrunk physically and politically to a mere ST, and then the *HST*, enabling Jesse Greenstein, never an enthusiast, to say that “Edwin Hubble finally got the telescope he deserved”, when the mirror defect was discovered). Next comes Senator Barbara Mikulski, who navigated *HST* funding through Congressional procedures. The data archive at STScI is named for her. Third is Sandra Faber of University of California, Santa Cruz, a competitor for use of *HST* time but still a strong supporter of the HDF at a time when many other more senior astronomers were pretty sure that the 140 or so orbits involved could be better used on their programmes.

No book is perfect. The author’s preference for look-back times, age of the Universe when photons were emitted, and distance in light years rather than redshifts, requires rapid translation by cosmological readers. The Doppler effect creeps in when expansion redshifts are meant, and the concept of photometric redshifts (Fig. 11.2) would have been clearer if the galaxies had been chosen to show one visible in all of *V*, *Y*, *J*, and *H*; one missing in *V*; one missing in *V* and *Y*, and one missing in *V*, *Y*, and *J* (rather than five all missing in *V* & *Y* but there in *J* & *H*). Those (in case you left your handy-dandy broad-band colour decoder at home) are visual into red into infrared.

The roughly 2700 HDF galaxies (and nine stars) showed first and foremost that the Universe has changed — galaxies when the Universe was younger were smaller, bluer, and less regular in shape than those in the here and now. Second, they made it possible to begin to estimate how the cosmic star-formation rate has changed with time, starting small long ago, peaking at  $z = 1-3$ , and dropping back down to the present. Annoyingly, the graphs provided have no numbers, but customary units are solar masses per year per co-moving Mpc<sup>3</sup>. Calibration of the photometric redshifts required ‘real’ spectra, most obtained with the *Keck* 10-m telescopes, as I write languishing untouched on Mauna Kea, but we hope for better times, because an important lesson of Williams’ book is that ground-based and space-based astronomy and the full range of wavelengths from radio to gamma rays are synergistic in attempting to understand the Universe and its contents.

The organizational lesson, of course, is that director’s discretionary time is a good thing, provided you have an adequately discretionary director. STScI has, on the whole, been fortunate in that over the years. The volume was apparently

intended at least as much for on-line reading as paper, because at a few points, the author advises those reading on paper to go to some specific web site to see a larger, better-resolved, version of some image. And the volume is sufficiently expensive that, by not buying it, you could almost afford the computing device on which to see the e-versions. With luck, there will be copies on display on the publisher's table at future conferences, so you can, by skipping lunch, stand in a corner and read it, turning pages rapidly, for free. — VIRGINIA TRIMBLE.

**The Cosmos: Astronomy in the New Millennium, 5th Edition**, by Jay M. Pasachoff & Alex Filippenko (Cambridge University Press), 2018. Pp. 730, 27.5 × 22 cm. Price £59.99/\$79.99 (paperback; ISBN 978 1 108 43138 5).

A truly massive tome, this is an undergraduate textbook intended as “a descriptive presentation of modern astronomy for liberal-arts students”, though it should appeal as well to those who enjoy popular-astronomy books. Both authors have extensive teaching experience, and the areas of their own research (the Solar System and observational cosmology) are at opposite ends of the scale. Essentially all of astronomy is covered in the twenty chapters; roughly a quarter each is assigned to general background (physics, history of astronomy, instrumentation), the Solar System, stellar astronomy and the Milky Way, and extragalactic astronomy and cosmology. Apart from the usual one-page table of contents just listing the chapters, an 11-page (though with photos) detailed table of contents makes it easy to find what one is looking for, as does the 22-page small-print index. It is impossible to summarize the contents in more detail in the space of a review in this *Magazine*; suffice it to say that the material is correct, up-to-date, and well presented (with very few typos); the book is obviously a labour of love. (The book would be impressive enough if the authors were only teachers; Filippenko is also one of the most highly cited research astronomers.) The authors state that it is a ‘how and why’, rather than a ‘what and where’, book. In other words, although not intended for science majors, and though maths is kept to a minimum, the presentation is not just qualitative, but an attempt (successful, but at the intended level) is made to explain the reasons behind the phenomena. Neither is it a ‘who and when’ book, though some basic history of astronomy is of course included.

A paragraph on origins, a nod to NASA's Origins programme, is at the beginning of each chapter, followed by a list of aims and a chapter introduction. There is at least one colour image, often several, on almost every page, with detailed captions, all referred to in the text. In addition to the main text, boxes of various sorts — self-contained side shows, so to speak — provide additional information: ‘Figure It Out’, ‘A Closer Look’, ‘Star Party’ (suggestions for stargazing), and ‘Lives in Science’. Important terms appear in boldface in the main text and in the end-of-chapter summaries, and are defined in a 16-page small-print glossary. Following the summary, each chapter ends with about 50 questions (regular questions as well as true-or-false, multiple-choice, and fill-in-the-blank varieties), with those requiring a numerical answer specially marked, and a handful of topics for further discussion. Eight appendices, including photos of all Messier objects, are a nice addition. Six-and-one-half pages of suggestions for further reading (again in small print), grouped by topic, some with comments, will probably satisfy the curiosity of most readers. The front and end papers (inside cover and facing page) contain eight sky charts, one for each season with views to the north and south, as seen from North American latitudes. (My only criticism is that the book sometimes assumes a North

American readership, though to be fair courses for which the book is intended are much more common there than elsewhere.) Even with modern technology, I still hear that publishing in colour can make the price prohibitive; the literally thousands of high-resolution colour images in this book are presumably made possible by economies of scale; indeed, the price would be reasonable for a book of this size with no pictures at all.

The preface is mostly an aggressive sales pitch, but the rest of the book more than lives up to it. This is the fifth edition, so previous editions obviously have been successful. Although many other readers should enjoy it, it is clearly intended as a textbook. The book itself is a treasure trove of information, but additional resources can be found at <http://thecosmos5.com/>, including some which can be accessed only by instructors authenticated by CUP; those include the figures in .JPG and .PPT formats, making it easy to tie one's own presentation in with the book, as well as test-banks and a solutions manual. Although the book itself is very up-to-date, the website provides chapter updates with even newer information. Some of the (very few) errata do not correct mistakes as such, but update material in the text (*e.g.*, revised names for facilities, changing the description of others from future to present tense). In an unusual move, the authors provide their institutional postal and email addresses for comments and corrections and promise a personal reply to each writer.

Recommended? Of course; very highly! — PHILLIP HELBIG.

**MHD Waves in the Solar Atmosphere**, by Bernard Roberts (Cambridge University Press), 2019. Pp. 508, 25 × 18 cm. Price £135 (hardbound; ISBN 978 1 108 42766 1).

The solar atmosphere can be compared with a classical symphony orchestra, which generates transverse oscillations in kink-modes (string instruments), longitudinal acoustic oscillations (wind instruments), as well as shock waves initiated by loud bangs (percussion instruments). This rich new field of scientific research should be called 'solar music', but instead has been dubbed 'coronal seismology', in contrast to the field of 'helioseismology' which describes the global oscillations and reflected waves in the *interiors* of the Sun and stars. Interestingly, the theory of magneto-hydrodynamic (MHD) waves has largely been developed in the 1980s by Bernard Roberts of St. Andrews University, building on previous theoretical work of Alfvén, Cowling, Parker, and Spruit. But observational confirmation with direct imaging of oscillating and propagating MHD waves in the solar corona started only in 1999, with data from the NASA spacecraft, the *Transition Region and Coronal Explorer* (*TRACE*). Triggered by those key observations, multi-faceted studies in all aspects of MHD modelling have been tackled, on the observational as well as theoretical side, such as by DeMoortel, Edwin, Erdelyi, Goedbloed, Goossens, Nakariakov, Oliver, Pascoe, Ruderman, Terradas, T. J. Wang, and Zhugzhda (to name a few with quintuple citations). What Bernard Roberts offers in his new book is a rigorous treatment of MHD waves propagating in uniform plasma, coronal loops, magnetic slabs, and magnetic flux tubes, including dispersion relations, wave speeds, gravitational effects, wave damping, and other nonlinear aspects. Parker is quoted: "The fundamental equations of physics may contain all knowledge, but they are close-mouthed and do not volunteer that knowledge". Nevertheless, Roberts lets no less than 2524 equations speak the truth eloquently, which testifies to the complexity of resonant cavities in solar and stellar atmospheres. The book is highly recommended to those students,



post-docs, and researchers who are willing to go further into the fundamental understanding of wave phenomena in astrophysical plasmas than just to fit a sine function to the shaken loops after a banging solar flare. — MARKUS ASCHWANDEN.

**An Introduction to Radio Astronomy, 4th Edition**, by Bernard F. Burke, Francis Graham-Smith & Peter N. Wilkinson (Cambridge University Press), 2019. Pp. 523, 25.5 × 18 cm. Price £59.99/\$79.99 (hardbound; ISBN 978 1 107 18941 6).

The growth in radio astronomy, driven by the forthcoming *Square Kilometre Array* and its precursors and pathfinders, is attracting many new students to the subject. Numerous texts cover aspects of radio astronomy in great detail but this book, a substantial revision and expansion of the ten-year-old third edition, aims explicitly at providing a single-volume introduction covering the entire subject for the beginning graduate student. It is challenging to do this at a level which is simultaneously useful and comprehensive, but the authors largely carry it off. Particular strengths of the book include the fact that the discussion makes frequent reference to modern instrumentation, which will be very valuable for the beginner trying to put the theory in the context of the work he or she is doing, and the effort that has been made to bring the necessarily brief survey of radio astrophysics in touch with modern developments. Slightly weaker are the first few pages, where a wide range of different topics is thrown at the reader without much development. Although it's difficult to separate the history of the subject from the astrophysics, the short timeline given in Chapter 1 will not leave a new student much the wiser, and a dedicated chapter on this subject might well be valuable in a future edition. Another minor problem in the early chapters on electromagnetic and emission theory is the inconsistent use of SI and cgs/Gaussian units, sometimes within pages of each other, often without explanation. The authors could say, with justification, that this simply reflects the astronomical literature, but it makes the book less accessible to the (UK) graduate-student readership who will exclusively have been trained on SI, and such students will probably need to look elsewhere for formulae that they can use easily to make calculations involving emission processes.

Despite these minor quibbles, the book succeeds in its overall aims, and the fourth edition, with nearly a hundred pages of extra material and substantial additional on-line resources, is a useful upgrade from the third. My copy will soon find its way to my next new PhD student's desk. — MARTIN HARDCASTLE.

**Gamma-Ray Bursts**, by Andrew Levan (Institute of Physics Publishing), 2018. Pp. 214, 26 × 18.5 cm. Price £99/\$150 (hardbound; ISBN 978 0 7503 1500 5).

Gamma-ray bursts (GRBs), as a research topic, have gone through several epochs of understanding. These include surprise that they even exist, trying to understand where they occur, trying to understand how they work, and trying to use them as probes of star formation and the Universe. Of late, GRBs are particularly remarkable because they can be seen near-simultaneously in so many bands of light — and now in gravitational waves as well. This latest 'multi-messenger' epoch is proper cause for a new and encompassing book about GRBs, and Dr. Andrew Levan has written just such a book — and a good one.



Before writing *Gamma-Ray Bursts* in 2018, Levan had been an active researcher on GRBs since the early 2000s. His work primarily involves counterparts to the gamma-ray emission in other wavelength bands, including *Hubble* in the optical, *Chandra* and *XMM-Newton* in the X-ray, and *Spitzer* in the infrared. He is currently a Professor of Astronomy and Astrophysics at the University of Warwick, UK.

In sum, this book is a good and timely introduction to GRBs. It starts with an historical account and chapter by chapter covers key areas of GRB research, including prompt emission, afterglows, long GRBs, short GRBs, progenitors, hosts, cosmological utility, and multi-messenger aspects. The book closes with an outlook for the future of GRB research.

Each chapter in the book has its own references and can stand alone, which I found useful. The book's chapters are accurate and quite readable summaries of most GRB topics, although they typically do not go into great detail. This makes it an effective reference for graduate students and researchers in other sub-disciplines planning to collaborate on GRB projects. In fact, I gave the book to one of my own graduate students starting to work in GRBs who regarded it very highly.

Another way that this book excels is in its topicality. Levan does well in identifying areas where GRB research has had recent impact on other fields of astronomy, in particular through observations. His summaries of the overlap of GRB 170817A and the coincident gravitational-wave event are particularly noteworthy.

Unfortunately, the book does have a few shortcomings. For one, Levan writes more about some areas of GRB research than others, including GRB theory. Some chapters have summaries, but, oddly, some do not. My biggest criticism of the book, however, is that it does not have an index. Perhaps a second edition of the book should be published after more GRB–gravitational-wave joint detections occur with these additions. In the meantime, if you want a modern introduction to gamma-ray bursts, this book is a very good place to start. — ROBERT NEMIROFF.

**Gas-Phase Chemistry in Space: From Elementary Particles to Complex Organic Molecules**, edited by François Lique & Alexandre Faure (Institute of Physics Publishing), 2019. Pp. 353, 26 × 18.5 cm. Price £99/\$150 (hardbound; ISBN 978 0 7503 1426 8).

As the editors state in their preface to this authoritative volume, astrochemistry is a rapidly growing field in astrophysics. Molecules are found in many types of astronomical region, from the Solar System to high-redshift galaxies, and molecular emissions can be used as thermometers and barometers that help astronomers probe the physical conditions in those objects. Molecules may also have active roles in which their behaviour controls the evolution of the region, as in the formation of galaxies, stars, and planets. A detailed understanding of the chemistry by which molecules are produced may also provide a remarkably thorough description of any astronomical molecular region and its evolution.

This book is a collaboration by fifteen experts in eight substantial chapters. These cover a wide range of topics from chemistry in the early Universe and the origin of the elements, to bimolecular reactions and collisional and radiative processes that may excite astronomical molecules. The final chapter reviews the success of gas-phase models and their insatiable appetite for molecular data.

The chapters are written at a level suitable for active researchers in fundamental astrochemistry who may need to broaden the range of their knowledge. For such workers, it would be a great advantage to have this volume readily to hand. The emphasis throughout the book is on the essential theory of topics that underpin all of astrochemistry, and some attention is given to the indispensable contribution of laboratory work to the subject. The book does not attempt to tell the magnificent story emerging from observational molecular astronomy. As the title emphasizes, the book is strictly limited to gas-phase processes.

The book is beautifully produced, with many high-quality diagrams; comprehensive references are provided in all chapters. It should be an essential companion to those working in this field, and I recommend it highly. — DAVID A. WILLIAMS.

**The Structure and Evolution of Stars**, by J. J. Eldridge & Christopher A. Tout (World Scientific), 2019. Pp. 338, 23.5 × 15.5 cm. Price £85 (hardbound; ISBN 978 1 78326 579 4).

When I started to work on stars, there was only a small number of recommended books to consult, with Eddington's and Schwarzschild's as the favourites. There is now a wide range of books on the structure and life histories of stars, from broad reviews for non-specialists through undergraduate textbooks to large monographs, so new graduate students are spoilt for choice. Do we need another one?

Eldridge & Tout have chosen to aim for the graduate-student market, and indeed their book is not for the average undergraduate. It is based on a lecture course given over the years for Part III of the Cambridge Mathematical Tripos, first introduced by Fred Hoyle in the 1960s and steadily updated by others. It therefore assumes a good grasp both of modern physics and of a broad range of mathematics to at least the final-year-undergraduate level, and in places beyond that, as well as a general knowledge of astronomy. This assumption has enabled them to tackle topics in depth, with some interesting asides and amplifications of standard results.

The topics are fairly standard, as is clear from the chapter titles: 'Observable Properties of Stars', 'The Equations of Stellar Structure', 'The Equation of State', 'Heat Transport', 'Stellar Atmospheres', 'Energy Generation', 'Stellar Models', 'Stellar Evolution', and finally 'Binary Stars'. However, the detailed ordering of topics is unusual and the level is challenging. For example, the structure equations are introduced by quoting the full time-dependent equations of hydrodynamics in vector form, and only later specializing to spherical symmetry with no time dependence, and polytropes are introduced early on. However, the dynamical time is defined purely for the Sun, leaving the reader to generalize. When detailed mathematical treatments are given, such as in the discussion of quantum tunnelling, the argument, while clear, is generally very condensed, requiring work from the reader to verify the final result. Unusually, thermohaline mixing is covered in some detail as part of a longer-than-usual discussion of mixing. There are challenging questions at the end of each chapter, and a useful if selective bibliography at the end, arranged by chapter.

The writing style is generally clear throughout, with some rather careful wording in places; *e.g.*, the interior of a white dwarf is described as 'quite

isothermal', rather than the usual 'isothermal'. Some of the interesting insights clearly reflect the authors' experience in numerical modelling, while one unique word betrays the Cambridge context (it appears in a 2014 Cambridge PhD thesis) — on p.226 'erythrogigantism' is used\* to describe the problem of why a star becomes a red giant! The balance of topics is also a little uneven: twice as much space, and much more detail, is given to energy generation than to stellar atmospheres, reflecting the fact that this book is mainly about stellar interiors. At each stage of evolution, detailed numerical models are used to illustrate the various physical processes, and there is an honest discussion both of the uncertainties in the physics, such as convection, semi-convection, and models for exploding supernovae, and also where more research is needed — very useful for a new graduate student, although most of the problems are too hard to be thesis material.

There are not many typos, but there are some, most of them easy to spot and unlikely to confuse. However, they include two misspellings of names: Kelvin's surname should be spelled with no 'p', and Russell's surname has two 'l's not one. Also Mayer's work on gravitational energy release to power the Sun was not published in 1941! 1841, perhaps? In equation (7.99), I think there is an exponent 19 missing on the left-hand side. On p.257, there is a discussion of mixing times where the criterion for homogeneous mixing seems wrong by an order of magnitude — maybe just another typo. I also found myself somewhat irritated by an idiosyncratic use of commas, where explanatory phrases generally have a comma before but not after the phrase, leaving it unclear where the phrase ends and sometimes obscuring the sense. But that's probably a pedantic point.

Apart from those minor complaints, I think this is indeed a worthy addition to the stellar-evolution library, written at an unusually high level but with a wealth of useful insights for the assiduous student. — ROBERT CONNOR SMITH.

**The Impact of Binary Stars on Stellar Evolution**, edited by Giacomo Beccari & Henri M. J. Boffin (Cambridge University Press), 2019. Pp. 333, 25 × 18 cm. Price £120 (hardbound; ISBN 978 1 108 42858 3).

*The Impact of Binary Stars on Stellar Evolution* resulted from a well-attended international 'Workshop' with that title held at ESO (Garching) in 2017 July. The book is neither a proceedings in the normal understanding of the term, nor is it in any way an attempt to reproduce every paper or — more seriously — the discussions that were presented. What we have here is a careful selection of what are seen today as the most pressing topics bearing on the impact which binary systems may (or may not) have upon stellar evolution, at least upon our understanding of how they shape our modelling and interpretations of it. The 21 chapters, most no more than a dozen or so pages, address selected topics ranging from massive stars to low- and intermediate-mass systems, binary components with very low metallicity, binaries in post-AGB systems, binaries in symbiotic stars, binaries heading towards planetary nebulae, binaries as possible progenitors of LBVs, GRBs, blue stragglers, and gravitational waves, binaries that have been observed or have only been modelled by evolution theory, and — throughout — binaries that are interacting in some manner. Discussions of

\* Ερυθρογίγαντις is Greek for red.

relevant statistics and descriptions of the roles expected to be played by new surveys such as *Gaia* have their place here, as also do considerations of the initial mass function, the formation of binary stars, and population synthesis. With little doubt, most of what an enquirer hopes to learn about binaries is likely to be found here, or *via* leads in the extensive reference list that concludes each chapter. The energy which the various authors impart ensures that this book is a first-class contemporary compendium of things binary.

A particular feature that adds to its success is the refreshing honesty and humility which comes across in many of the writings. These writers are not recent graduates whose bent (or need) is to assure their peers that everything fits nicely into a set of [their] computer models. Here are authors who are more mature, and while they wish us to believe that each individual sub-topic is actually the most important but unsolved aspect of binary stars and consequently needs the highest attention, they are also not above admitting where and how the gravest uncertainties lie — whether trying to extract meaningful statistics from too unwieldy or too sparse data, or whether confronting the ‘fragmentation crisis’ that raises its ugly head when a realistic level of magnetic support is introduced into the star-forming gas described by a model — and how such roadblocks will affect our progress in understanding and quantifying the impact which all these objects have on stellar evolution at some stage.

Produced in the long-running *Cambridge Astrophysics Series* as its no. 54, the book as a whole is well in line with what one expects from CUP: the texts are well-written, and the illustrations clear. Every department and observatory needs a copy of this book. Every astrophysicist will find something of value. — ELIZABETH GRIFFIN.

**Classic Telescopes: A Guide to Collecting, Restoring, and Using Telescopes of Yesteryear**, by Neil English (Springer), 2013. Pp. 239, 23.5 × 15.5 cm. Price £29.99/\$44.99 (paperback; ISBN 978 1 4614 4423 7).

**Chronicling the Golden Age of Astronomy: A History of Visual Observing from Harriot to Moore**, by Neil English (Springer), 2018. Pp. 665, 24 × 16 cm. Price £159.99/\$219.99 (hardbound; ISBN 978 3 319 97706 5).

Although these two books were published five years apart it was decided by the Managing Editor that they could be reviewed together. They are by the same author and the subject matter is inexorably intertwined. The invention of the telescope opened the gates for a long string of talented observers who would forever change the science of astronomy and help to explain the Universe to all mankind. Neil English, author of both volumes, is very knowledgeable about the construction and operation of telescopes, an astute observer, an excellent historian, and a reasonable poet as demonstrated by his poems preceding some of the chapters.

The first volume begins with a one-page poem dedicated to his father followed by a page of acknowledgements, a table of contents listing various manufacturers — in roughly historical order — and a preface. It concludes with an epilogue, a glossary, a short but thorough list of references, a bibliography, and an index. In the preface it is pointed out how the invention of the telescope revolutionized astronomy, and contains brief notes concerning some significant manufacturers. The first two chapters contain much interesting information about Dollond and Cooke, respectively, early manufacturers who produced a large number of refractors for both amateur and professional astronomers that were relatively small in aperture but high in quality. Successive chapters

go on to relate many vignettes and details about Clark, Brashear, Zeiss, Broadhurst, Clarkson & Fuller, a few small producers, and continues on into the 1950s era of Unitron. The book devotes almost a whole chapter to the small 60-mm refractors readily obtainable in department stores. The author lauds their performance. Unfortunately, after many years of experience in public astronomy and evaluating various instruments, this reviewer has found that those small refractors are a 'turn-off' and many would-be enthusiasts' closets abound with these unused instruments. They have small fields of view, poor mountings, are hard to locate objects with, have small eyepieces with minimal eye relief that are hard to focus, and have outrageous claims printed on their boxes, such as "496 times magnification". These instruments have turned off many novice observers both young and old. My friends and I, with many years of conducting introductory star parties, loosely refer to these as "department-store telescopes". Now, although I have this one disagreement with the author's opinion, that should not be taken to denigrate the whole book. This is a fine volume and I have learned many interesting new facts about other equipment despite my long experience in this field. I wholeheartedly recommend its purchase.

I was fortunate to have obtained a 3½-inch Skyscope Newtonian reflector for my first serious telescope. This popular instrument was advertised in numerous magazines for many years in the mid-20th Century and was a wonderful first scope. Unfortunately it is not covered in this volume but I encourage the author to publish a second volume highlighting the instruments missed or briefly glossed over. My Skyscope had a sturdy, easily assembled mounting that could be used either equatorially or as an alt-azimuth. It was equipped with a good finder, three .965 eyepieces with good eye relief that were easily focussed, and a comfortable height off the ground for the eyepiece. It was simple and a pleasure to use. I easily viewed Jupiter's moons, Saturn's rings and bright moons, craters on the Moon, and the stars embedded in the Orion Nebula from my home in the centre of Chicago! It so lit up my interest that I was afflicted with 'aperture fever' which still drives me today! The views encouraged a life-long interest in astronomy. If I were a billionaire I would like to give an instrument like this to every beginner in the world. I hope members of the IAU involved in astronomy outreach read this!

To continue, the book describes the Takahashi refractors and continues into my favourites — the catadioptrics: the Questar 3½-inch, the Meade 90-mm ETX, and 5- and 8-inch Celestrons. There is some coverage of Newtonians and could be more. Tom Cave, whom I was lucky to know in his later years and with whom I spent a couple of evenings observing in his home-made observatory which contained one of the best telescopes he ever made, told me that he thought from his years of experience that the Newtonian was the best optical design and gave the sharpest images. I also really enjoyed the section on the Meade 90-mm ETX, called the "working man's Questar" because of its reasonable price. I recently acquired one for an extremely good price at a camera swap meet and it is superb. There are many tips for observers in this work and it is well worth a slow and deliberate read.

And now for the main event, the second publication. *Chronicling The Golden Age Of [Visual] Astronomy* consists of a preface, acknowledgements, and a table of contents followed by 41 chapters in roughly historical order, and concludes with an appendix and index. This book contains such a wealth of information there is not enough room in this review to comment on everything in detail. I shall only cover some of the most significant highlights. There are very few

typographical errors, and even though a multitude of diverse topics are covered they are presented in a very readable style, the transition from one subject to another flowing smoothly. It should be on everyone's shelf and provide many evenings of education and entertainment.

The preface should be read first because it explains the author's aims. The first chapter describes Thomas Harriot, the first British telescopist and a contemporary of both Galileo and Hans Lippershey. Sadly, Lippershey is not mentioned anywhere in the text. The idea of the telescope spread quickly through Europe and many people caught on to the technique of its construction. History grants credit to Hans Lippershey (of the Netherlands) and Galileo because they were the first to publish the most detailed description of its design, and especially Galileo who documented his astronomical observations in detail. Simon Marius of Germany also constructed a telescope and published his observations, though after Galileo. Galileo openly condemned Marius. Apparently Galileo had a caustic personality and was antagonistic to several high church officials. This no doubt contributed to his being brought to trial. The story of these early inventors (except for Lippershey) and observers is well described in the first three chapters. Chapter 5, describing the development of speculum mirrors, tells of more obscure telescope builders and observers and deserves a careful read. Chapter 7 covers the extensive observations of Thomas Jefferson in more detail than many of the large number of biographies published about him. It does not, however, mention Benjamin Banneker, the first black American astronomer, whom Jefferson hired to do surveying work.

In Chapter 8, which runs to 39 detailed pages, the author goes extensively into the Herschel dynasty of William, John, and Caroline in a manner that holds your attention fast and gives you the impression that you are on the scaffold of William's great telescopes. Amazingly this writer learned that William Herschel met the great scientist James Watt, but Watt's name is not mentioned in the index. Chapter 9 describes how the Earl of Rosse at Parsonstown followed Herschel's exploits and after several years of struggle was able to construct a 72-inch reflector with two interchangeable mirrors. Speculum tarnishes rather quickly and has to be re-polished. Two mirrors reduce the downtime of the instrument. The later invention of silver or aluminium on glass eliminated this problem. Despite the low reflectivity of speculum the large diameter of the mirror permitted the spiral structure of nearby galaxies to be identified. The 72-inch remained the largest telescope in the world for many years and prominent astronomers of the day like George Biddell Airy, Otto Struve, Sir John Herschel, James Nasmyth, and William Lassell, among others, visited.

In my 60-year-plus pursuit of astronomical literature I attended many events and casually met several of the people mentioned in this book. Most of them grew old and passed into history. One, however, became a friend. I ran across a classified advertisement in an astronomical publication about some lunar journals for sale. The advertiser was Tom Cave, manufacturer of Cave Astrola Telescopes and a well-known lunar and planetary observer. I phoned him and he invited me to pick them up at his home in Long Beach, California. When I arrived we started to talk about our mutual interest. I listened to his stories far into the evening. Tom knew everybody that was anybody in astronomy. I wound up spending many evenings for the next few years listening to his stories until shortly before his death in 2003. If I had thought to take a tape recorder his stories would be priceless. If anyone deserves a biography it is Tom Cave.



The other prominent person in this book I had more than a passing acquaintance with was John Dobson. Dobson was the father of modern sidewalk astronomy and the inventor of his namesake the Dobsonian telescope, a design that made it easy to transport and operate a relatively large amateur instrument, usually eight to twelve inches aperture or larger. His design could have made him millions but he never patented it. He was not money-orientated. Several manufacturers cashed in and produced and sold thousands. They dominate most star parties today. I met John through Gerard Pardeilian who had spent many years learning how to grind, polish, and figure telescope mirrors. He ran the weekly Saturday night star party at the Lawrence Hall of Science in Berkeley, California. I volunteered during the 1970s to assist operating the telescopes. Gerard, although like many in the optical industry not professionally educated, had become a master optician and worked at the prestigious Tinsley Laboratories and later became a master optician at the Lick Observatory optical shop in Santa Cruz, California. He helped design and construct a massive spectrograph for the Mt. Palomar 200-inch telescope. On page 628 it states that the corner of Broderick and Jackson Streets was Dobson's favourite locale in San Francisco. The reason was that the sidewalk astronomers were either renting or given use of a large house at 1600 Baker St. a few blocks away. They stored and constructed their telescopes in that building and could easily dollie them to the corner of Broderick, which undoubtedly was in the shade of a large building. When John had to move I went over with some other people. He kindly presented me with several boxes of journals and several surplus eyepieces and prisms. Page 629 states that a light bulb was used to test their telescopes. Gerard informed me that they actually used the reflection from a street light on a telephone pole insulator a mile away. It acted just like a point source as a star would. It was then possible to figure their mirrors on cloudy nights.

A detailed reading of some chapters will demonstrate how expert observers using relatively small apertures could obtain amazing results, far beyond what most observers today would think possible. This is one of the finest books on the history of visual astronomy I have ever read. Virtually every sentence conveys a bit of history, and it is remarkably illustrated with sharp photographs. I can only suggest that every reader obtain a copy. The writing is excellent. The 653 pages of text are too short to contain everything of the rich history of 400 years of observing. Observers and constructors, such as Jack Marling the filter expert, Al Nagler of eyepiece fame, Charles F. Capen the Mars observer, comet hunters like Lewis A. Swift, William Robert Brooks, and John Tebbutt among others, either glossed over or neglected, should be covered in a following volume. Continue your story Neil English! — LEONARD MATULA.

**Celebrating the 2017 Great American Eclipse: Lessons Learned from the Path of Totality** (ASP Conference Series, Vol. 516), edited by Sanlyn R. Buxner, Linda Shore & Joseph B. Jenson (Astronomical Society of the Pacific), 2019. Pp. 527, 23.5 × 15.5 cm. Price \$88 (about £69) (hardbound; ISBN 978 1 58381 921 0).

NASA estimates that the 2017 August 21 total eclipse of the Sun, 'The Great American Eclipse', may well have been watched by around 215 million people *via* television, the internet and, of course, in person. In a little over 90 minutes, totality swept across 14 states and the whole of the contiguous United States

saw a minimum obscuration of the Sun of 48% up to a maximum duration of totality of 2 minutes and 45 seconds as predicted by *The Astronomical Almanac. Celebrating the 2017 Great American Eclipse: Lessons Learned from the Path of Totality* brings together the experiences, wisdom, and suggestions of a wide range of scientists, educators, planners, and outreach groups striving to inform the public about this event and to use it to stimulate people's interest in science.

The book is split up into five sections including a total of 58 contributed papers. Part I is entitled 'Stories from the Field: Expeditions and Public Engagement'. This section includes papers on events from many locations across the United States and the lessons learned from them. Part II covers 'Experiences with Schools and Libraries', including a number of outreach programmes for school students and those living in more rural areas. Part III addresses 'Eclipse Support and Resources for the Future'. This section includes offerings on the delivery of just-in-time information, the use of monthly webcasts and apps, as well as the provision of eclipse viewers. Transportation planning is described as well as the provision of data by the US Naval Observatory. Part IV covers 'Eclipse Products, Programs, and Lessons Learned'. This section includes several contributions from NASA, the National Park Service, the American Astronomical Society, and the Eclipse Megamovie project. Part V addresses 'Eclipse Science', including a variety of experiments that can be carried out by students and scientists alike. These range from the detection of shadow bands, the effect of the eclipse on weather, wildlife, and shadows, to observations from high-altitude balloons.

This is a book which can be dipped into as a reference resource and may well find a home on the shelves of libraries and astronomy departments, although I doubt this book will be bought by many amateur astronomers or researchers. However, there is much interesting information to be found in this volume, especially for those planning events for future eclipses. With the approach of the annular eclipse of the Sun on 2023 October 14 and the total eclipse of the Sun on 2024 April 8, it will be interesting to see whether the United States, or indeed any country undergoing such a phenomenon, learns from the experience gained from the 2017 total eclipse. — STEVE BELL.

**Advanced Lectures on General Relativity**, by Geoffrey Compère (Springer), 2019. Pp. 140, 23.5 × 15.5 cm. Price £49.99/\$69.99 (paperback; ISBN 978 3 030 04259 2).

Writing an advanced text on General Relativity which appeals to graduate students and other interested researchers is quite a difficult task. While there exists general agreement of what should be covered in a first course, it is much more difficult to go beyond the initial introduction. It will crucially depend on where the text wishes to go and what its aims are.

The first chapter of these lecture notes introduces the concepts of surface charges and conserved quantities in General Relativity. This is a natural subject to consider for an advanced topic. It connects with Noether's theorems and provides links with other field theories. The exposition is sufficiently explicit for readers to follow some of the longer derivations.

It was nice to see that the second chapter discusses three-dimensional Einstein gravity. Many texts which focus on General Relativity stay within the standard 4-D framework, so it is good to get students exposed to other theories of interest which share features of General Relativity. The 3-D model used can be seen as a simpler toy model than the full theory; anti-de Sitter spaces play a key role in this chapter and are discussed in detail. Readers should be somewhat familiar with Penrose diagrams and the concept of Hawking temperature, as



both feature in this and subsequent chapters.

The remaining two chapters are back in the 4-D setting. First, the notion of an asymptotically flat space is introduced using Bondi–Sachs coordinates, together with the required quantities which appear in the large-radius expansion, for instance, the Bondi news tensor. Of particular importance are the Bondi–Metzner–Sachs (BMS) group and gravitational-memory effects. In the final chapter rotating black holes are considered in some detail. This final chapter links the different parts of the book together very well and also touches upon some more-advanced concepts like the Newman–Penrose formalism and the Petrov classification. There is a wealth of material that is introduced which will give readers a good idea of what could be studied in more detail in the future.

Overall this is a nice proposal for advanced lecture notes focussing on some concrete topics without trying to cover every possible subject which might be of interest. Potential readers can access the arXiv version of these notes at <https://arxiv.org/abs/1801.07064>, and I would hope that those who enjoy the material would purchase the physical copy subsequently. — CHRISTIAN BÖHMER.

**Spacetime and Geometry: An Introduction to General Relativity**, by Sean M. Carroll (Cambridge University Press), 2019. Pp. 527, 25.5 × 19 cm. Price £49.99/\$64.99 (hardbound; ISBN 978 1 108 48839 6).

There is no shortage of books on General Relativity, even at the same level of presentation as this one. So why another book? Carroll notes that many of the well-known books on GR emphasize their own viewpoints, which are seen by some as idiosyncratic; this book offers a ‘neutral’ approach and also concentrates on the basics of learning GR — applications are discussed, but not extensively, and even there the emphasis is on learning GR. Most of the other standard textbooks are written by people well known for their work in GR (though some have worked on other topics as well); Carroll has worked on many topics, and perhaps for that reason the trees don’t block the view of the forest.

The book has the date “June 2003” in the preface. Although not mentioned in the book, at Carroll’s website<sup>1</sup> one can read that the book “...recently changed publishers, from Pearson to Cambridge University Press. It is *exactly the same book*, just with a different cover” [emphasis in the original].\* It is based on, and about twice the length of, Carroll’s lecture notes for a postgraduate course in GR at MIT in 1996 (the lecture notes are freely available at the website). As such, undergraduates would probably find the going a bit tough; at least some knowledge of classical electromagnetism, linear algebra, and Lagrangian mechanics is assumed.

The first three chapters cover Special Relativity and differential geometry, before gravitation is introduced in chapter four. The next four chapters are on applications, including such astronomical topics as black holes and gravitational radiation, though the emphasis here, like elsewhere, is on mathematical formalism and not astrophysical processes. Thus, the book’s title is very descriptive, and the presentation follows the traditional pattern in GR books, introducing differential geometry and tensor calculus before moving on to physics, though the discussion of Special Relativity at the beginning whets the appetite. The chapter on cosmology is perhaps the closest to more-astronomical accounts of the topic. The final chapter, on quantum field theory in curved

\*There is also a list of errata at the website. The few that I checked are corrected in the CUP version, including some not yet corrected in the second printing (so thankfully it is not exactly the same book). The comparison also shows that page and even line numbers are the same as in the original edition.

space-time (necessary to understand Hawking radiation, for example), is unusual in an introductory text. Of course, 'introductory' is relative (pun intended); the book is very mathematical, but a reader with a knowledge of calculus should be able to follow all the derivations (and derivatives!) with no resources other than the book itself, though probably only postgraduate students (and above) would have the necessary physics background. That jibes well with the intent, "to provide an accessible...introduction to general relativity" rather than "a comprehensive reference textbook"<sup>1</sup>.

I spotted no mistakes as such, though it is easy to get the impression (p. 346) that Hubble's Law is valid only at small distances. (I think what he means is that one is restricted to small distances if one wants to derive the recession velocity from the redshift; at least he doesn't mention the special-relativistic Doppler formula in connection with cosmology<sup>2</sup>. On p. 104 he makes it abundantly clear that cosmological redshifts are not due to the conventional Doppler effect, but to me goes overboard by suggesting that "the very notion of their recession should not be taken literally".) The statement on p. 116 that "a greater redshift implies a greater distance" is too general. (The angular-size distance famously has a maximum at finite redshift in many cosmological models, though to be fair since that statement occurs before various cosmological distances are introduced, it can be assumed that the proper distance is meant.) Any book on relativity has to make a choice of metric signature. The one here '-+++' (common among relativists), is not my favourite; Carroll himself notes that "[t]he fact that the interval is negative for a timelike line ... is annoying", and so defines the proper time as the negative of the interval. It is of course common to set  $\hbar$  and  $c$  (and sometimes even  $G$ ) to 1, and that has its justifications. However, in the discussion of the reduced Planck mass ( $m_P/\sqrt{8\pi}$ , where  $m_P = \sqrt{\hbar c/G}$ ) on p. 171, it is noted that half of the square of the latter is the coefficient of the curvature scalar mentioned a few pages previously. That is true in the sense that both are  $1/(16\pi G)$  if  $\hbar = c = 1$ , though  $\hbar$  of course does not appear at all in the purely classical discussion of the curvature scalar and its relation to the action.

There is a chapter on the Schwarzschild solution, containing a section on Schwarzschild black holes, and the chapter on more-general (the hyphen sorely missed in the original) black holes has a section each on charged (Reissner-Nordström) and rotating (Kerr) black holes, but none on the combination of the two, namely Kerr-Newman black holes, the most general type, though they are mentioned in passing in the section on Kerr black holes. Readers of other cosmology books might be annoyed that Carroll uses "Copernican principle" where others use "Cosmological principle". (The latter can be derived from the former and observed isotropy, so in some sense they are equivalent, but I've never seen "perfect Copernican principle" elsewhere.) Readers of this *Magazine* will be familiar with my two pet peeves of missing hyphens and misplaced 'only's (and some share my concerns<sup>3</sup>), so I usually no longer mention them in reviews, but must do so here, as such a misplacement occurs in the final sentence of the main text: "Classical general relativity is the most beautiful physical theory invented to date, but we have every right to expect that a synthesis of GR with other areas of physics will reveal layers of beauty we can only now imagine."

The 13-page index is of reasonable size, though 'Doppler effect' has entries for its use in understanding the equivalence principle and in connection to the CMB dipole, but not for its application (or lack thereof) to cosmology, though the term does appear in the relevant discussion; also, there is no entry for 'Planck mass', but there should be. Useful are ten short appendices which explore

some mathematical topics in greater detail, and the commented bibliography, more than four pages, with books discussing Special and General Relativity at all levels, is more useful in a book such as this than conventional references would have been. (Very occasionally, references are provided as footnotes, usually when specific results are mentioned, when a discussion closely follows a standard textbook, or to point the reader to reviews at arXiv.) Well-done black-and-white figures complement the text. (I would be a curmudgeon if I mentioned that one has lowercase variables used to label curves but uppercase ones in the caption and main text.) The book as a whole is well made, with very few typos. However, while wide margins can be useful in a book such as this, I found it strange that both versos and rectos have margins on the left; normally one would expect them at the outer edges, and if the same, then having them on the right would be more practical for right-handed readers (or, rather, writers).

Compared to the large amount of material in the book, excellent prose, and very good editing, my quibbles above are minor. I recommend the book for those who know little about GR but want to learn more; it is a useful bridge between more-qualitative or even popular introductions and more-advanced textbooks. — PHILLIP HELBIG.

### References

(1) <https://www.preposterousuniverse.com/spacetimeandgeometry/>

(2) P. Helbig, *The Observatory*, **138**, 22, 2018.

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

**What the Stork Brought: African Click-Speakers and the Spread of Humanity's Oldest Beliefs**, by John M. Saul (Old Africa Books, A division of Kifaru Educational and Editorial Consultants LTD, PO Box 2338, Naivasha, 20117, Kenya), 2019. Pp. 109, 24 × 17 cm. Price \$15.99 (about £13) (paperback; ISBN 978 9966 757 52 4).

Virtually all, perhaps all, cultures for which we have any relevant records have had creation myths. A large fraction, perhaps most, involve the Sun, Moon, stars, planets, and perhaps the Milky Way and Magellanic Clouds. Saul's thesis is that there was one, original belief system of this sort, traceable back to the Bushman, Khoi, San, and Hazda speakers of the click-languages of sub-Saharan Africa, or rather their ancestors. Small groups that moved "out of Africa" at various times carried these beliefs with them, and traces are to be found as far away as Australia and the Americas, meaning that the belief system must predate the eras when *Homo Sapiens* first headed in those directions, more, perhaps, than 60 000 years ago.

The long time frame enables precession of the equinoxes, which brings the year-opening Sun into successive areas of the sky (from Gemini to Taurus to Aries, Pisces, and Aquarius in 5000 years or so) to be significant, while Canopus, the stars of Gemini, and a few others were also important, some being identified with animals of the homeland region. For instance, eland, the largest African antelopes, are identified, male with Procyon, and female with Gemini; the Hyades and Pleiades with meerkats; and male and female hartebeest with Aldebaran and Betelgeuse.

Is this at least archaeoastronomy, if we mean by that an effort to let modern astronomical data and anthropological issues illuminate each other? Yes, I think so, at least at the level of "those people there and then had the ability to notice

these phenomena, thought them important, and endeavoured to remember or record them.” And Saul’s volume has some wonderful pictures, of rock paintings and carvings, Acheulean hand-axes, pots, people, Chronos (by Goya), meerkats, eland of course, and one each of slender mongoose, dwarf mongoose, and Egyptian mongoose, which makes three ... . The reader is told there are at least eight different click sounds, of which you might know two, the one generally spelt ‘tsk-tsk’ (I remember North Hollywood butcher Clethro saying that to my mother when a cheque bounced) and the one used to encourage horses forward (which I always thought was pronounced ‘Giddyup’).

Conflict of interest: my copy of *Stork* was a gift from the author, and you must read it for yourself to find out what storks have to do with it all. — VIRGINIA TRIMBLE.

### Here and There

#### GLORIOUS OVERSTATEMENT

..., describing the figure-of-eight diffraction ring around the binary star Zeta Aquarii (separation 1.7 arcminutes) as ‘glorious’. — *JBAA*, 129, 4, 2019.

#### IT’S A SMALL WORLD

An ancient reservoir of diamonds ... has been discovered near the Earth’s core, more than 410 km ... below the surface. — *i*, 2019 August 17, p. 31.