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MEETING OF THE ROYAL ASTRONOMICAL SOCIETY

Friday 2018 May 11 at $17^h\ 00^m$
in the Geological Society Lecture Theatre, Burlington House

A. M. Cruise, *President*
in the Chair

The President. Thank you very much for reconvening [after the AGM]. I now have some exciting announcements of the various thesis prizes that we offer. I would encourage PhD supervisors to think about sending in nominations for their students, because a prize like this on a CV is really valuable in pushing a student's career forward.

I am pleased to announce that the Michael Penston Prize has been awarded to Dr. Sownak Bose of Durham University for the thesis entitled, 'Beyond ΛCDM: Exploring alternatives to the standard cosmological paradigm'. And the runner-up is Dr. Ivan Cabrera-Ziri from LJMU. [Applause.]

The Keith Runcorn Prize has been awarded to Dr. Jenny Jenkins, University of Cambridge, for the thesis entitled, 'The seismic signature of the Iceland mantle plume from crust- to mid-mantle wind'. There were runners-up here that were considered difficult to differentiate between, so they will both get a runners-up prize. They are Dr. Rohini Giles of the University of Oxford and Dr. Nadine Kalmoni of University College London. [Applause.]

The last set of thesis prizes are from the prize-fund very generously given to us by Patricia Tomkins. This was aimed at theses to do with instrumentation, both in astronomy and geophysics. So, again, people working in instrumentation should consider putting their students forward for these prizes. I am pleased to announce that the prize this year has been awarded to Dr. David Cuadrado Calle of Manchester University for the thesis, 'Design, manufacture, testing, and calibration of monolithic microwave integrated circuits for *ALMA*'. [Applause.]

We hope we will be able to get those thesis prize-winners to come and give talks in the Ordinary Meetings during the course of the year.

The call for nominations for awards and medals will be announced on the new website, so I am not going to give dates now. You will find out on the website how to do it, and the nominations will be *via* the website from now on.

We are expecting the website, as you have heard, to be up and running, perhaps by the end of the month. It is not far away. All Fellows will be notified of how to make those nominations and how to use the portal on the new website.

The announcement, when it comes, will explain to people how to use the portals on the website to nominate for awards and medals, but also how to apply for grants.

The next announcement is that the NAM in 2019 will be held at the University of Lancaster, so I hope we will see lots of you there.

We now come to the programme of talks — two talks only. One is from Professor Steve Miller, who will present to you the second tranche of the RAS 200 programme 'Sky and Earth', where these awards are going to, and what we can expect from them.

Professor S. Miller. This is the fifth report that I have given to successive AGMs on the RAS 200 project. We now have all projects funded. They are up and running, and there is good progress across the board. We also have an evaluation process which is running in parallel. One of the projects, which I think is incredibly moving, is that with the Care for Carers organization, which is based in eastern Scotland and which uses the island of Coll for residential stays for people whose full-time job is to care for relatives and others, but find it difficult to get any break themselves. One of the outcomes of this is a whole series of residential stays for carers, and one of them and their disabled son produced a book called *Coll and the Cosmos*, and we have a copy here.

Last year we partnered the National Youth Agency based in Leicester doing seismology around football stadia. The NYA are going to try to get seismometers for schools to place at all the Premier League football grounds, and there is even a possibility that this might be featured on *Match of the Day* during the 2019/20 season. This is a good example of how the RAS is popularizing science and, in this case, geophysics. Girlguiding has been going ahead with launching a new Astronomy badge in the summer and we are hosting a supporters' event here on June 5. We have had the world premiere of the National Space Centre's re-rendition of the *Planets Suite* — this is a traditional *Planets Suite* and a modern version with 360-degree dome coverage. The premiere was held on February 28. It is quite spectacular, and in some ways very challenging, but very entertaining, and it will be rolled out across the country and then internationally. We are working with the group Beyond Prison Walls. Sheila Kanani, without whom none of this would have been possible [applause], has been working with the Bounce Back organization in Brixton Prison and is pushing what is called Story Book Dads, which has accumulated a supply of astronomy books and encourages prisoners to read to children on visits.

We have made presentations to the wider community, for instance at EWASS/NAM this year, and Megan Argo, who is a member of the steering group, made a presentation at CAT 2018 in Japan. I gave a presentation at the biennial Public Communication of Science and Technology 2018 conference in Otago, New Zealand. I'm pleased to say that STFC has now followed our lead in funding projects in public communication which are bottom-up. Our current goals are to make a presentation at Science in Public later this year, and Robert Massey will give a talk at the IAU General Assembly in Vienna in August. We want more involvement from RAS Fellows in all of these projects in the next year and beyond.

Sue Bowler has done an amazing job in publicizing RAS 200 in *A&G*, and every coming issue will include something about it. We are also looking at the Prince's Trust, which deals with young people who are not in education, training, or employment. They have an annual awards ceremony and we may be able to use RAS 200 to sponsor an award in 2020.

Finally, as you can see, there is a lot going on and I would urge you to get involved. [Applause.]

The President. Steve, thank you. That round of applause was for Steve's efforts on RAS 200 as well. It has been quite a ground-breaking programme for the Society and it is really working very well.

The second talk is curiously entitled the 'Presidential Address', and Professor Zarnecki is going to give it. [Laughter.] It is called, 'Spacecraft I have known and loved: 40 years in space research'.

Professor J. C. Zarnecki. [It is expected that a summary of this talk will appear in a future issue of *A&G*.]

The President. Thank you very much indeed, John. Can I remind you all that we have a drinks reception in the RAS Library, across the way, immediately following this meeting. And finally, I give notice that the next monthly A&G Open Meeting of the Society will be on Friday, 12th of October 2018. I wish you a pleasant, peaceful, and productive summer.

ANALYSIS OF OBSERVATIONS OF EARLIEST VISIBILITY OF THE LUNAR CRESCENT

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Predicting the visibility of thin lunar-crescents following the new moon is difficult and challenging for several technical reasons. The visibility of the earliest new moon has long been used to determine the lunar-crescent calendar and is still used today. Many criteria exist for the first visibility of the lunar crescent. Here, we test the most-commonly-used criteria for thin-lunar-crescent visibility. We used 545 observations, including both positive and negative sightings, made by professional and highly-trained astronomers over a duration of 27 years (1988 – 2015) and from different locations at latitudes between 20°N and 29°N (within Saudi Arabia). We developed a new criterion for lunar-crescent visibility using lunar-crescent width (W) and the arc of vision (ARCV). This new model can be used to predict the visibility of the lunar crescent by naked eye or aided eye, which is fundamental for the lunar-crescent calendar followed by several cultures and religions.

Introduction

Prediction of thin-lunar-crescent visibility following the new moon is fundamental for the lunar-crescent calendar followed by several cultures and religions (*e.g.*, Muslim, Hindu, and Hebrew). Determination of the new lunar Hijri month (Muslim calendar) is based on the visibility of the earliest, thin, new lunar crescent after sunset. Due to the lack of accurate criteria for thin-lunar-crescent visibility, people scan the western horizon at sunset hoping to sight the lunar crescent, which might be impossible. In the absence of positive lunar-crescent sightings, the beginning of the next lunar month is postponed by one day. Therefore, the lunar calendar cannot be based on observations because it is necessary to wait approximately 29 days to determine the start of the next month. This type of observational calendar is highly affected by atmospheric conditions and typically involves error due to human factors such as illusion[1,2].

The problem of lunar-crescent visibility is very old. The Babylonians established criteria for the first visibility of the lunar crescent based on observational data, which states that a thin lunar crescent can be sighted only if the lunar-crescent altitude above the horizon is greater than 12° after sunset[3]. During the 8th to 14th Centuries, several famous Muslim astronomers developed first-visibility criteria for the thin, new lunar crescent after sunset. One criterion stated that the crescent can be observed only if the arc of separation of the Sun and Moon along the celestial equator is larger than 12°. Al-Khwārizmī used this condition to construct tables for thin-lunar-crescent visibility[4]. Another criterion, used by Tabarī, states that the new lunar crescent will not be seen if the Sun depression is less than 9°·5 at moonset[5]. These two criteria are based on one variable, but Al-Battānī used several variables[6] because, when using one condition, the crescent will not be sighted according to one arc but to many arcs. Al-Battānī included the azimuth of the Moon relative to the Sun, the Earth–Moon distance, and the width of the lunar crescent as conditions for thin-lunar-crescent visibility. After being developed by Al-Battānī and others, the Babylonian criteria became common usage and no further development in lunar-crescent visibility occurred until the second half of the 19th Century[3].

New lunar-crescent-visibility criteria were introduced by Fotheringham[7], who collected 76 naked-eye observations of the visibility or non-visibility of the crescent. Fotheringham calculated the arc of vision (ARCV) at sunset time and the relative azimuth (DAZ) with respect to the Sun, as shown in Fig. 1. He found that the formula of the curve fitted the second-degree polynomial based on non-visible observations[7]. The ARCV–DAZ curve introduced by Fotheringham has been used in several similar studies. In 1911, Maunder added a further 48 observations and showed that the dividing curve should be based on visible observations and not non-visible observations[8]. He made a new lunar-crescent criterion using a second-degree polynomial to fit a new dividing (ARCV–DAZ) curve[8]. The Maunder criterion is similar to the so-called Indian criterion, published in the *Indian Astronomical Ephemeris*[9]. In 1977, Bruin published a new approach addressing the earliest-lunar-crescent visibility[6], using new observations on factors such as lunar-crescent width (W), solar depression, and the necessary contrast for naked-eye observations of the lunar crescent. The criterion adopted a minimum lunar-crescent width ($W = 0'\cdot5$), which represents the limit of lunar-crescent visibility[6]. In 1981, Ilyas estimated that Bruin's visibility threshold was an overestimate, and calculated the minimum lunar width as $W = 0'\cdot25$, subsequently determining a new approach based on dividing (ARCV–DAZ) curve, which shows good agreement with Maunder's criterion[10].

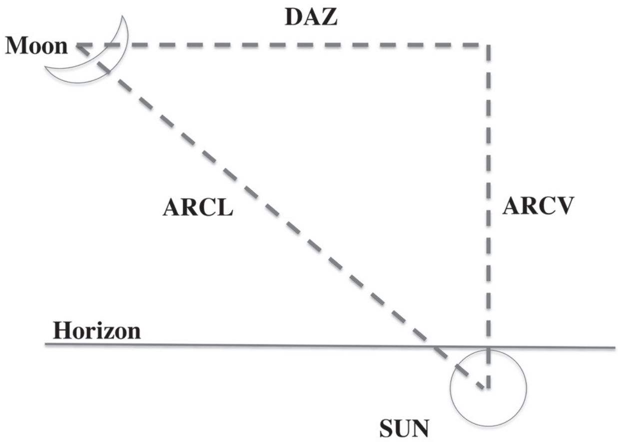

FIG. 1
Schematic showing the position of the Moon after sunset with various celestial arcs.

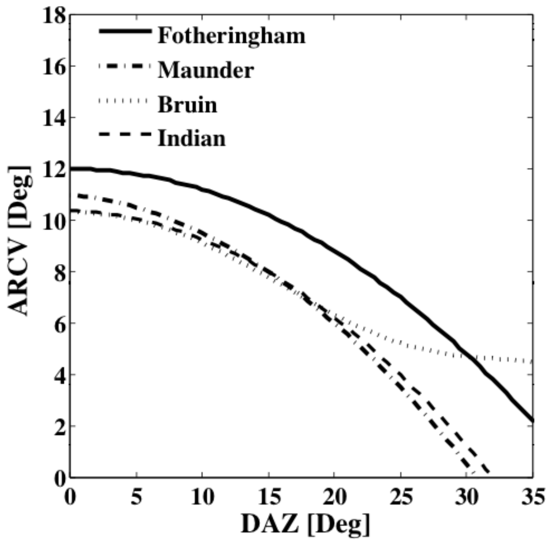

FIG. 2
Fotheringham, Maunder, Bruin, and Indian curves of ARCV = *f*(DAZ).

In Fig. 2, the geometry-based criteria mentioned above have been designed based on the arc of vision (ARCV) and the relative azimuth (DAZ). A hypothetical line, ARCV = f(DAZ), separates the plane into two regions; below the curve represents the invisible lunar crescent and above the curve is the visible lunar crescent. Another important lunar-crescent-visibility condition, recognized as one of the most reliable criteria, is the Danjon limit[11], which states that the lunar crescent disappears and is not visible when the arc of light (ARCL) is less than 7°. In 1998, Yallop[12] improved the Indian criterion using 295 observations over the period 1859 to 1996, and used the topocentric instead of geocentric lunar-crescent width (W). In this study, we test all the criteria for earliest lunar-crescent visibility discussed above by applying them to observations made by highly trained lunar-crescent observers. We also examine the individual conditions such as Moon age, Moon time lag, and the Danjon limit. Then, we propose an improved lunar-crescent criterion based on the (ARCV–DAZ) visibility curve for predicting thin lunar-crescent visibility following the new moon that is suitable for the lunar-crescent calendar.

Observation collection

Observations of the earliest lunar crescent were performed every month from 1988 to 2015. These observations were only made by astronomers at the National Center for Astronomy, who are capable and highly trained to find the earliest lunar crescent following the new moon. The earliest lunar sightings were made after extensive preparation and using a computerized mounted telescope. The position of the Moon was accurately determined with respect to the sunset position. The observations were made in several different locations and all observation reports were written immediately. This data set is fundamental for this study and consists of 288 positive sightings of earliest lunar crescents presented in Table I, and 190 negative sightings in Table II, both made in a clear sky. Fig. 3 shows the percentage of negative and positive sightings and the corresponding observation methods. Because the visibility of the earliest lunar crescent is strongly related to the atmospheric conditions, only observations in clear-sky conditions are considered. For each observation, we calculate the most common observation parameters used to predict the visibility of the earliest lunar crescent. These include the arc of vision (ARCV), which is the Moon's altitude separation from the Sun, the arc of light (ARCL), which is the ecliptic-longitude separation between Moon and Sun, or elongation, and the relative azimuth (DAZ), which is the azimuthal separation of the Moon and Sun. These arcs are illustrated in Fig. 1.

As well as these arcs, we calculated the Moon's age or elapsed time between the new moon conjunction and sunset on the day of observation, the Moon's lag time (LAG), or the elapsed time between sunset and moonset on the day of observation, and the lunar-crescent width, (W), which is the illuminated Moon's surface measured along the Moon's diameter ($W = 0'$ at new moon and $32'$ at full moon). Examples of observations and observation parameters for the early lunar crescent are given in Table III. The ARCV and ARCL distributions for the 288 positive sightings are shown in Figs. 4 and 5, respectively. The solid curves in these figures represent the best Gaussian fits of the distributions. The mean Gaussian fits for the ARCV and ARCL were 13°·31 and 16°·21, respectively, and the standard deviations were 3°·50 and 4°·02. Only four false positive sightings were eliminated from our data collection, which varied from the observations by three standard deviations[13,14].

TABLE I

Positive observations of earliest lunar crescent

T stands for telescope; and N stands for naked-eye.

Lat. °	*Long.* °	*Date* *UT*	*Age* *hrs.*	*Lag* *min.*	*ARCV* °	*ARCL* °	*DAZ* °	*Means*
23·55	46·39	1988/03/19	37·05	93	20·34	20·49	02·55	N
19·52	42·22	1988/04/17	27·49	65	14·15	14·83	04·49	T
23·56	46·93	1988/04/17	27·28	68	14·34	14·70	03·27	T
28·40	36·73	1989/03/08	21·31	56	11·90	11·97	01·11	T
28·40	36·73	1990/02/26	30·61	77	16·36	16·41	01·33	N
26·45	36·38	1990/03/27	20·01	51	10·99	11·67	03·95	T
28·40	36·73	1990/03/27	20·00	53	11·11	11·65	03·54	N
28·40	36·73	1990/04/26	35·62	107	20·88	20·91	01·12	N
26·45	36·38	1990/06/23	21·60	55	10·94	11·84	04·54	T
28·40	36·73	1991/04/15	20·35	54	11·02	11·53	03·41	T
26·45	36·38	1991/05/15	35·64	101	19·98	20·11	02·27	N
28·40	36·73	1992/03/05	26·02	56	11·90	12·49	03·82	N
28·40	36·73	1992/06/02	36·01	89	17·62	19·57	08·65	N
26·45	36·38	1992/07/01	20·94	55	11·42	15·90	01·14	N
21·42	39·83	1993/12/14	29·23	72	14·71	15·31	04·28	N
28·40	36·73	1993/01/23	20·64	46	09·45	09·53	01·23	T
28·40	36·73	1993/02/22	26·39	55	11·62	12·12	03·46	T
21·42	39·83	1993/12/14	29·23	72	14·71	15·31	04·28	N
24·60	46·45	1998/10/21	28·22	53	11·46	12·86	05·87	N
27·52	41·70	1998/12/20	40·20	89	16·95	18·35	07·13	N
26·35	43·95	1999/01/18	22·83	52	10·44	10·65	02·13	T
24·60	46·50	1999/03/18	20·27	48	10·54	11·30	04·11	T
26·35	43·95	1999/10/10	27·12	53	11·41	13·15	06·58	N
24·60	46·45	2000/03/07	34·01	74	16·12	17·00	05·26	N
21·42	39·83	2000/09/28	19·30	44	10·10	10·77	03·75	T
27·52	41·70	2000/12/26	21·08	40	07·69	08·86	04·40	T
21·42	39·83	2001/01/25	25·99	49	10·31	11·23	04·46	T
24·60	46·45	2001/01/25	25·46	48	09·80	11·02	05·05	T
28·40	36·73	2001/02/24	31·14	62	12·77	14·31	06·53	N
28·40	36·73	2001/04/24	24·64	52	10·81	12·42	06·14	N
21·42	39·83	2001/04/24	24·29	51	11·31	12·21	04·62	N
21·42	39·83	2001/06/22	28·13	67	14·09	15·21	05·78	N
27·52	41·70	2001/11/16	31·68	64	12·39	16·21	10·53	N
24·60	46·45	2002/01/14	24·96	48	09·53	11·51	06·49	N
27·52	41·70	2002/02/13	31·37	61	12·52	14·34	07·06	N
26·35	43·95	2002/10/07	27·45	57	12·26	16·00	10·36	N
27·52	41·70	2002/11/05	17·88	36	07·41	09·90	06·58	T
26·35	43·95	2003/02/02	28·16	59	11·85	14·08	07·66	N
27·52	41·70	2003/02/02	28·13	59	11·74	14·14	07·94	N
21·42	39·83	2003/02/02	28·17	60	12·86	14·22	06·50	N
28·40	36·70	2003/02/02	28·16	60	11·76	14·29	08·19	N
24·60	46·45	2003/02/02	28·13	59	12·03	14·01	07·23	N
28·40	36·73	2003/08/28	22·55	49	10·52	12·36	06·52	T
27·52	41·70	2003/09/27	35·93	65	13·79	20·04	14·68	N
21·42	39·83	2003/09/27	36·06	68	15·30	20·30	13·12	N
26·35	43·95	2003/09/27	35·78	65	14·04	19·94	14·31	N
28·40	36·73	2003/09/27	36·26	65	13·67	20·23	15·07	N
27·52	41·70	2003/10/26	25·74	46	09·39	14·55	11·17	T
28·40	36·73	2003/12/24	28·99	65	11·48	16·86	12·43	N
21·42	39·83	2003/12/24	29·03	68	13·05	16·81	10·68	N
26·35	43·95	2003/12/24	28·59	65	11·76	16·61	11·81	N
24·60	46·45	2004/01/23	41·46	103	20·37	22·79	10·45	N
27·52	41·70	2004/01/23	41·69	104	19·89	22·93	11·66	N
26·35	43·95	2004/01/23	41·58	103	20·08	22·87	11·18	N
28·40	36·73	2004/01/23	42·00	105	19·85	23·10	12·06	N
21·42	39·83	2004/05/20	35·04	75	15·35	15·35	00·08	N
24·54	39·63	2004/06/18	19·76	46	09·07	9·07	00·16	T
21·42	39·83	2004/06/19	43·64	61	12·25	19·56	04·11	N

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TABLE I (*continued*)

Lat. °	*Long.* °	*Date* *UT*	*Age* *hrs.*	*Lag* *min.*	*ARCV* °	*ARCL* °	*DAZ* °	*Means*
24·60	46·45	2004/06/19	43·31	95	18·86	19·42	04·73	N
27·52	41·70	2004/08/17	38·42	67	14·49	18·38	11·43	N
28·40	36·73	2004/09/15	25·15	41	08·91	9·05	01·56	T
21·42	39·83	2004/09/16	48·92	78	17·63	21·03	11·66	N
28·40	36·73	2005/01/11	26·88	67	12·19	16·11	10·61	N
24·54	39·63	2005/02/09	16·74	40	8·39	09·88	05·22	T
21·42	39·83	2005/08/06	21·19	64	14·30	16·36	08·03	N
24·60	46·45	2005/08/06	20·83	63	13·69	16·22	08·79	N
26·35	43·95	2005/08/06	21·04	63	13·46	16·33	09·33	N
24·54	39·63	2005/09/05	44·34	61	13·76	13·77	0·40	N
26·35	43·95	2005/11/03	37·33	51	09·65	18·90	16·33	N
27·52	41·70	2005/11/03	37·45	50	09·34	18·98	16·59	N
21·42	39·83	2006/01/01	48·59	89	17·09	20·33	11·19	N
24·54	39·63	2006/01/01	48·50	88	16·34	20·31	12·23	N
24·54	39·63	2006/02/28	14·88	36	07·91	08·11	01·81	T
28·40	36·73	2006/07/26	35·94	64	13·33	16·44	09·70	N
26·35	43·95	2006/12/21	24·27	43	07·83	12·81	10·17	T
27·52	41·70	2006/12/22	48·38	108	18·71	24·82	16·62	N
21·42	39·83	2007/08/14	40·83	60	13·81	19·35	13·69	N
28·40	36·73	2008/08/02	29·81	47	10·02	16·07	12·63	N
27·52	41·70	2008/12/29	50·43	102	19·00	21·89	11·09	N
24·54	39·63	2009/01/27	31·14	65	13·56	13·64	01·53	N
26·35	43·95	2009/01/27	30·80	65	13·34	13·49	02·00	N
27·52	41·70	2009/01/27	30·92	66	13·35	13·55	02·32	N
27·52	41·70	2009/04/26	36·36	101	19·88	19·93	01·41	N
24·60	46·45	2009/07/23	37·14	66	14·62	21·36	15·74	N
26·35	43·95	2009/07/23	37·36	65	14·18	21·51	16·34	N
24·60	46·45	2009/08/21	29·36	36	08·18	14·67	12·22	T
26·35	43·95	2009/10/19	32·99	35	06·99	17·47	16·05	T
26·35	43·95	2009/11/18	42·85	70	12·74	20·57	16·28	N
25·62	45·62	2009/11/18	42·88	70	12·92	20·52	16·07	N
25·62	45·62	2009/12/17	26·13	48	09·09	11·50	07·07	T
25·25	45·25	2009/12/17	26·17	48	09·16	11·51	07·01	T
28·40	36·73	2010/04/15	27·49	65	13·21	13·51	02·85	N
24·54	39·63	2010/04/15	27·24	61	12·85	13·40	03·84	N
24·54	39·63	2010/06/13	28·94	68	13·87	15·22	06·34	N
26·35	43·95	2010/06/13	28·72	67	13·53	15·11	06·79	N
28·40	36·73	2010/06/13	29·28	68	13·50	15·44	07·55	N
25·25	45·25	2010/06/13	28·59	67	13·61	15·03	06·44	N
28·40	36·73	2010/08/11	37·13	48	10·37	18·98	15·99	T
26·37	49·82	2010/08/11	36·21	48	10·74	19·30	16·13	N
24·39	39·63	2010/10/09	44·27	65	13·08	25·29	21·83	N
24·60	46·45	2010/10/09	43·82	63	12·83	25·04	21·69	N
26·35	43·95	2010/10/09	43·97	61	12·23	25·15	22·14	N
25·25	45·25	2010/10/09	43·89	63	12·62	25·09	21·87	N
26·37	49·82	2010/10/09	43·58	61	12·08	24·93	21·98	N
25·62	45·62	2010/10/09	43·86	62	12·47	25·08	21·94	N
27·52	41·70	2010/11/07	33·57	53	10·06	18·09	15·11	T
21·42	39·83	2010/11/07	33·83	59	11·77	18·15	13·92	N
24·39	39·63	2010/11/07	33·78	56	10·99	18·16	14·55	N
24·60	46·45	2010/11/07	33·32	55	10·74	17·92	14·44	N
26·35	43·95	2010/11/07	33·44	54	10·32	18·01	14·84	T
25·25	45·25	2010/11/07	33·38	54	10·59	17·97	14·59	T
24·39	39·63	2010/12/06	20·51	40	07·87	10·20	06·50	T
24·60	46·45	2010/12/06	20·05	39	07·64	09·97	06·42	T
25·62	45·62	2010/12/06	20·07	39	07·52	09·99	06·59	T
24·39	39·63	2011/01/05	29·28	67	13·50	13·75	02·67	N
24·60	46·45	2011/01/05	29·82	66	13·27	13·54	02·68	N
24·39	39·63	2011/04/04	24·80	50	10·70	11·43	04·04	T
21·42	39·83	2011/05/04	32·74	70	14·74	14·76	00·79	N
24·39	39·63	2011/05/04	32·82	72	14·80	14·80	00·09	N

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TABLE I (*continued*)

Lat. °	*Long.* °	*Date* *UT*	*Age* *hrs.*	*Lag* *min.*	*ARCV* °	*ARCL* °	*DAZ* °	*Means*
27·52	41·70	2011/05/04	32·76	74	14·74	14·77	01·00	N
21·42	39·83	2011/07/02	31·46	56	12·10	15·96	10·48	N
24·39	39·63	2011/07/02	31·57	54	11·53	16·05	11·24	N
24·60	46·45	2011/07/02	31·12	53	11·30	15·82	11·14	N
28·40	36·73	2011/07/02	31·91	52	10·76	16·28	12·29	T
25·62	45·62	2011/07/02	31·22	53	11·12	15·88	11·41	N
26·37	49·82	2011/08/30	35·99	41	09·07	09·22	01·70	T
24·60	46·45	2011/09/28	27·60	32	06·98	16·55	15·04	T
21·42	39·83	2011/10/28	48·86	84	16·90	24·63	18·19	N
24·39	39·63	2011/10/28	48·82	82	15·90	24·64	19·07	N
24·60	46·45	2011/10/28	48·36	80	15·63	24·38	18·95	N
28·40	36·73	2011/10/28	48·94	78	14·56	24·75	20·24	N
25·25	45·25	2011/10/28	48·43	80	15·44	24·42	19·16	N
25·62	45·62	2011/10/28	48·40	79	15·30	24·41	19·25	N
26·37	49·82	2011/10/28	48·10	78	14·93	24·25	19·34	N
24·60	46·45	2011/11/26	31·92	73	4·12	17·56	10·55	N
28·40	36·73	2011/11/26	32·45	74	13·57	17·90	11·78	N
25·25	45·25	2011/11/26	31·98	73	14·02	17·60	10·75	N
25·62	45·62	2011/11/26	31·95	73	13·93	17·59	10·84	N
24·39	39·63	2011/12/25	20·57	52	10·49	10·73	02·29	T
24·60	46·45	2011/12/25	20·10	51	10·24	10·48	02·25	T
26·35	43·95	2011/12/25	20·21	52	10·21	10·55	02·65	T
28·40	36·73	2011/12/25	20·61	54	10·30	10·77	03·18	T
25·25	45·25	2011/12/25	20·16	51	10·24	10·52	02·40	T
25·62	45·62	2011/12/25	20·12	51	10·21	10·50	02·48	T
21·42	39·83	2012/01/24	31·43	72	15·80	15·97	02·33	N
24·60	46·45	2012/01/24	30·90	74	15·64	15·70	01·36	N
25·25	45·25	2012/01/24	30·96	74	15·69	15·73	01·15	N
25·62	45·62	2012/01/24	30·93	75	15·68	15·72	01·04	N
24·39	39·63	2012/04/22	32·47	66	13·90	13·90	00·26	N
21·42	39·83	2012/07/20	35·68	48	10·74	17·87	14·36	N
24·60	46·45	2012/07/20	35·33	44	09·74	17·74	14·90	N
24·39	39·63	2012/07/20	35·78	45	09·96	17·95	15·01	N
26·35	43·95	2012/07/20	35·56	43	09·32	17·87	15·31	T
25·62	45·62	2012/07/20	35·42	43	09·49	17·80	15·13	T
21·42	39·83	2012/09/17	37·18	50	11·25	16·73	12·46	N
24·60	46·45	2012/09/17	36·75	46	10·12	16·17	12·68	N
26·35	43·95	2012/09/17	36·92	45	09·64	16·10	12·95	T
25·25	45·25	2012/09/17	36·83	46	09·95	16·15	12·79	T
26·37	49·82	2012/09/17	36·53	44	09·49	15·86	12·77	T
25·62	45·62	2012/09/17	36·81	45	09·83	16·10	12·82	T
24·60	46·45	2012/10/16	26·40	40	08·49	14·85	12·23	T
26·35	43·95	2012/10/16	26·54	39	08·17	14·95	12·57	T
25·25	45·25	2012/10/16	26·47	40	08·38	14·90	12·36	T
25·62	45·62	2012/10/16	26·44	40	08·28	14·89	12·41	T
21·42	39·83	2012/11/15	39·51	97	19·33	23·26	13·19	N
24·39	39·63	2012/11/15	39·45	96	18·55	23·25	14·27	N
24·60	46·45	2012/11/15	38·99	95	18·28	22·98	14·18	N
26·35	43·95	2012/11/15	39·11	95	17·87	23·07	14·84	N
27·52	41·70	2012/11/15	39·22	95	17·60	23·15	15·29	N
28·40	36·73	2012/11/15	39·53	95	17·48	23·34	15·71	N
25·25	45·25	2012/11/15	39·05	95	18·14	23·03	14·43	N
25·62	45·62	2012/11/15	39·02	95	18·03	23·01	14·55	N
26·37	49·82	2012/11/15	38·71	93	17·68	22·84	14·70	N
21·42	39·83	2012/12/14	29·99	82	16·65	17·23	04·51	N
24·39	39·63	2012/12/14	29·90	82	16·31	17·19	05·50	N
24·60	46·45	2012/12/14	29·44	81	16·05	16·92	05·46	N
26·35	43·95	2012/12/14	29·54	82	15·90	16·99	06·06	N
27·52	41·70	2012/12/14	29·65	83	15·82	17·07	06·48	N
25·25	45·25	2012/12/14	29·50	82	16·00	16·96	05·69	N
25·62	45·62	2012/12/14	29·46	82	15·94	16·94	05·80	N
26·35	43·95	2013/01/12	18·80	53	10·93	10·98	01·07	T

TABLE I (*continued*)

Lat. °	*Long.* °	*Date* *UT*	*Age* *hrs.*	*Lag* *min.*	*ARCV* °	*ARCL* °	*DAZ* °	*Means*
25·62	45·62	2013/01/12	18·71	53	10·87	10·94	01·25	T
26·37	49·82	2013/01/12	18·41	52	10·71	10·77	01·13	T
21·42	39·83	2013/02/11	31·94	75	16·72	17·20	04·10	N
24·39	39·63	2013/02/11	31·90	77	16·89	17·17	03·13	N
28·40	36·73	2013/02/11	32·01	81	17·13	17·22	01·79	N
25·25	45·25	2013/02/11	31·51	77	16·72	16·96	02·88	N
25·62	45·62	2013/02/11	31·47	77	16·73	16·95	02·76	N
26·37	49·82	2013/02/11	31·18	77	16·61	16·79	02·54	N
21·42	39·83	2013/04/11	30·06	62	13·61	13·65	01·02	N
21·42	39·83	2013/10/06	38·52	61	13·24	19·63	14·63	N
24·39	39·63	2013/10/06	38·48	59	12·46	19·66	15·33	N
26·35	43·95	2013/10/06	38·92	60	11·82	19·52	15·65	N
27·52	41·70	2013/10/06	38·31	56	11·55	19·61	15·95	N
25·25	45·25	2013/10/06	38·40	57	12·09	19·47	15·38	N
25·62	45·62	2013/10/06	38·40	57	11·98	19·46	15·45	N
26·37	49·82	2013/10/06	38·29	56	11·67	19·32	15·50	N
21·42	39·83	2013/11/04	25·88	54	11·25	13·74	07·93	N
24·39	39·63	2013/11/04	25·83	52	10·79	13·74	08·56	T
24·72	46·67	2013/11/04	25·35	51	10·53	13·47	08·46	T
25·25	45·25	2013/11/04	25·35	51	10·48	13·52	08·60	T
24·39	39·63	2013/12/03	14·18	39	07·92	08·10	01·62	T
21·42	39·83	2014/01/02	27·62	78	16·34	16·34	00·22	N
24·39	39·63	2014/01/02	27·50	79	16·25	16·29	01·20	N
24·72	46·67	2014/01/02	27·03	78	15·97	16·02	01·21	N
26·35	43·95	2014/01/02	27·04	80	15·99	16·09	01·78	N
27·52	41·70	2014/01/02	27·58	81	16·01	16·16	02·20	N
28·40	36·73	2014/01/02	27·58	83	16·13	16·33	02·56	N
25·25	45·25	2014/01/02	27·02	79	16·00	16·06	01·41	N
25·62	45·62	2014/01/02	27·02	79	15·97	16·04	01·52	N
26·37	49·82	2014/01/02	27·58	79	15·78	15·87	01·70	N
24·39	39·63	2014/01/31	17·46	47	10·13	10·56	03·01	T
24·72	46·67	2014/01/31	16·99	46	09·87	10·31	03·00	T
26·35	43·95	2014/01/31	17·13	47	10·04	10·38	02·65	T
25·25	45·25	2014/01/31	17·07	46	09·95	10·35	02·88	T
25·62	45·62	2014/01/31	17·03	47	09·95	10·33	02·81	T
21·42	39·83	2014/03/02	31·42	75	16·99	17·23	02·94	N
24·72	46·67	2014/03/02	30·93	77	16·86	16·96	01·90	N
26·35	43·95	2014/03/02	30·94	78	16·99	17·05	01·37	N
25·25	45·25	2014/03/02	30·94	77	16·92	17·01	01·73	N
25·62	45·62	2014/03/02	30·94	78	16·92	16·99	01·61	N
26·37	49·82	2014/03/02	31·14	77	16·78	16·83	01·39	N
21·42	39·83	2014/03/31	20·84	46	10·42	10·46	00·89	T
24·39	39·63	2014/03/31	20·87	48	10·47	10·48	00·30	T
21·42	39·83	2014/04/30	33·52	73	15·91	16·37	03·91	N
24·39	39·63	2014/04/30	33·60	74	15·71	16·42	04·83	N
28·40	36·73	2014/04/30	33·88	75	15·45	16·58	06·10	N
25·25	45·25	2014/04/30	33·24	73	15·46	16·24	05·05	N
25·62	45·62	2014/04/30	33·23	73	15·41	16·23	05·16	N
21·42	39·83	2014/05/29	21·30	38	08·11	10·37	06·48	T
24·72	46·67	2014/05/29	20·95	36	07·54	10·25	06·97	T
27·52	41·70	2014/05/29	21·37	36	07·33	10·47	07·50	T
25·62	45·62	2014/05/29	21·05	36	07·46	10·30	07·13	T
26·37	49·82	2014/05/29	20·79	35	07·24	10·20	07·20	T
26·35	43·95	2014/07/28	41·35	46	09·94	18·71	15·93	T
21·42	39·83	2014/09/25	33·01	44	10·01	14·90	11·10	N
24·72	46·67	2014/09/25	32·55	42	09·20	14·72	11·55	T
26·35	43·95	2014/09/25	32·73	41	08·93	14·83	11·89	T
27·52	41·70	2014/09/25	32·88	41	08·73	14·91	12·13	T
28·40	36·73	2014/09/25	33·21	41	08·66	15·08	12·39	T
25·62	45·62	2014/09/25	32·62	41	09·04	14·77	11·72	N
26·35	43·95	2014/11/23	25·67	62	12·31	13·41	05·36	N

TABLE I (*concluded*)

Lat. °	*Long.* °	*Date* *UT*	*Age* *hrs.*	*Lag* *min.*	*ARCV* °	*ARCL* °	*DAZ* °	*Means*
27·52	41·70	2014/11/23	25·81	62	12·23	13·47	05·69	N
21·42	39·83	2014/12/23	37·15	98	20·37	20·63	03·35	N
24·72	46·67	2014/12/23	36·58	99	19·83	20·33	04·60	N
26·35	43·95	2014/12/23	36·70	101	19·73	20·40	05·31	N
27·52	41·70	2014/12/23	36·81	101	19·66	20·47	05·82	N
28·40	36·73	2014/12/23	37·11	103	19·70	20·64	06·27	N
25·25	45·25	2014/12/23	36·65	100	19·82	20·37	04·84	N
25·62	45·62	2014/12/23	36·62	100	19·76	20·36	04·98	N
26·37	49·82	2014/12/23	36·31	100	19·53	20·19	05·20	N
21·42	39·83	2015/01/21	25·83	68	14·74	14·83	01·61	N
24·72	46·67	2015/01/21	25·28	69	14·50	14·52	00·72	N
26·35	43·95	2015/01/21	25·41	71	14·59	14·59	00·21	N
27·52	41·70	2015/01/21	25·52	72	14·65	14·65	00·16	N
28·40	36·73	2015/01/21	25·83	73	14·82	14·83	00·48	N
25·25	45·25	2015/01/21	25·36	70	14·55	14·56	00·55	N
25·62	45·62	2015/01/21	25·32	70	14·53	14·54	00·44	N
26·37	49·82	2015/01/21	25·02	70	14·37	14·37	00·28	N
28·40	36·73	2015/02/19	15·65	41	08·73	08·82	01·30	T
21·42	39·83	2015/03/21	29·93	74	16·70	16·70	00·16	N
27·52	41·70	2015/03/21	29·81	77	16·51	16·52	00·57	N
28·40	36·73	2015/03/21	30·14	79	16·67	16·69	00·83	N
21·42	39·83	2015/05/19	35·67	79	17·11	19·05	08·51	N
24·39	39·63	2015/05/19	35·77	79	16·66	19·12	09·53	N
24·72	46·67	2015/05/19	35·31	77	16·37	18·89	09·56	N
26·35	43·95	2015/05/19	35·54	78	16·18	19·02	10·14	N
25·25	45·25	2015/05/19	35·42	78	16·33	18·95	09·75	N
25·62	45·62	2015/05/19	35·41	77	16·25	18·94	09·87	N
26·37	49·82	2015/05/19	35·15	77	15·99	18·82	10·07	N
24·39	39·63	2015/06/17	26·11	42	08·99	13·72	10·41	T
26·35	43·95	2015/06/17	25·89	41	08·49	13·64	10·72	T
27·52	41·70	2015/06/17	26·09	40	08·32	13·75	10·98	T
26·37	49·82	2015/06·/17	25·50	39	8·31	13·46	10·63	T
21·42	39·83	2015/09/14	32·73	44	09·95	10·19	02·23	T
26·37	49·82	2015/09/14	32·09	40	08·83	09·16	02·43	T
21·42	39·83	2015/11/13	44·87	91	18·97	21·05	09·31	N
24·72	46·67	2015/11/13	44·33	90	18·16	20·82	10·35	N
26·35	43·95	2015/11/13	44·47	91	17·89	20·90	10·97	N
27·52	41·70	2015/11/13	44·59	90	17·70	20·96	11·42	N
28·40	36·73	2015/11/13	44·90	91	17·62	21·11	11·83	N
25·62	45·62	2015/11/13	44·38	90	18·01	20·85	10·68	N
26·37	49·82	2015/11/13	44·08	90	17·75	20·71	10·85	N
26·37	49·82	2015/11/13	44·08	90	17·75	20·71	10·85	N

TABLE II

Negative observations of earliest lunar crescent (all means)

Lat. °	*Long.* °	*Date* *UT*	*Age* *hrs.*	*Lag* *min.*	*ARCV* °	*ARCL* °	*DAZ* °
23·56	46·39	1988/03/18	13·04	30	06·70	06·71	00·35
19·15	42·22	1988/04/16	03·49	04	01·01	03·28	03·12
23·56	46·39	1988/04/16	03·27	05	01·14	03·17	02·96
28·40	36·73	1990/02/25	06·60	14	03·01	03·45	01·69
28·40	36·73	1990/04/25	11·61	34	06·83	07·77	03·73
26·45	36·38	1991/05/14	11·63	33	06·64	06·99	02·20
28·40	36·73	1992/06/01	04·13	30	05·95	06·18	01·71
21·42	39·83	1993/12/13	05·22	12	02·59	02·63	00·45
28·40	36·73	1993/02/21	02·38	04	00·87	04·71	04·63

TABLE II (*continued*)

Lat. °	*Long.* °	*Date* *UT*	*Age* *hrs.*	*Lag* *min.*	*ARCV* °	*ARCL* °	*DAZ* °
21·42	39·83	1993/12/13	05·22	12	02·59	02·63	00·45
28·40	36·73	1993/02/21	02·38	04	00·87	04·71	04·63
21·42	39·83	1993/12/13	05·22	12	02·59	02·63	00·45
24·60	46·45	1998/10/20	04·23	16	03·60	03·95	01·62
26·35	43·95	1999/10/09	03·14	16	03·66	04·13	01·90
24·60	46·45	2000/03/06	20·79	18	03·92	05·62	04·03
21·42	39·83	2000/09/27	19·32	03	00·71	01·86	01·72
28·40	36·73	2001/02/23	07·13	09	01·88	04·88	04·50
21·42	39·83	2001/06/21	04·13	05	01·15	01·71	01·26
24·60	46·45	2001/10/16	19·06	02	00·64	05·33	05·29
27·52	41·70	2001/11/15	07·69	19	03·97	04·08	00·93
27·52	41·70	2002/02/12	07·36	08	01·80	05·22	04·90
26·35	43·95	2002/10/06	03·47	16	03·65	03·83	01·13
26·35	43·95	2003/02/01	12·20	00	00·22	05·00	05·00
21·42	39·83	2003/02/01	12·59	04	00·86	04·98	04·91
28·40	36·73	2003/02/01	12·62	01	00·24	05·09	05·09
24·60	46·45	2003/02/01	12·07	01	00·32	04·96	04·95
28·40	36·73	2003/08/27	22·57	12	02·51	04·53	03·77
27·52	41·70	2003/09/26	11·95	27	06·08	06·83	03·12
21·42	39·83	2003/09/26	12·08	28	06·43	06·86	02·42
26·35	43·95	2003/09/26	11·80	27	06·10	06·75	02·91
28·40	36·73	2003/09/26	12·28	28	06·14	07·01	03·38
27·52	41·70	2003/10/25	01·76	04	01·04	01·09	00·30
21·42	39·83	2003/12/23	05·02	02	00·51	04·49	04·46
21·42	39·83	2004/05/19	11·03	21	04·48	04·60	01·07
28·40	36·73	2004/09/14	01·17	09	02·15	02·68	01·60
21·42	39·83	2005/08/05	21·20	29	06·33	06·35	00·45
24·60	46·45	2005/08/05	20·84	29	06·18	06·22	00·75
26·35	43·95	2005/08/05	21·05	30	06·21	06·30	01·05
26·35	43·95	2005/11/02	23·34	08	01·72	06·93	06·72
27·52	41·70	2005/11/02	23·47	07	01·62	07·01	06·82
21·42	39·83	2005/12/31	11·63	19	03·88	07·86	06·83
24·54	39·63	2005/12/31	11·54	18	03·42	07·86	07·08
28·40	36·73	2006/07/25	11·95	29	05·89	06·00	01·16
21·42	39·83	2007/08/13	16·84	26	05·94	07·69	04·89
28·40	36·73	2008/08/01	20·42	08	01·91	02·86	02·12
24·54	39·63	2009/01/26	07·12	11	02·39	02·46	00·56
26·35	43·95	2009/01/26	06·79	11	02·22	02·31	00·65
27·52	41·70	2009/01/26	06·90	11	02·26	02·37	00·72
27·52	41·70	2009/04/25	12·35	33	06·67	07·70	03·85
24·60	46·45	2009/07/22	13·15	22	04·78	07·23	05·43
26·35	43·95	2009/07/22	13·37	22	04·68	07·38	05·71
26·35	43·95	2009/11/17	19·00	18	03·61	09·73	09·04
25·62	45·62	2009/11/17	18·91	19	03·70	09·68	08·96
28·40	36·73	2010/04/14	03·49	07	01·49	04·91	04·68
24·54	39·63	2010/04/14	03·24	04	01·04	04·95	04·84
24·54	39·63	2010/06/12	04·93	11	02·28	02·31	00·39
26·35	43·95	2010/06/12	04·71	11	02·19	02·21	00·34
28·40	36·73	2010/06/12	05·27	12	02·45	02·46	00·05
25·25	45·25	2010/06/12	04·58	10	02·12	02·16	00·44
28·40	36·73	2010/08/10	13·15	07	01·74	08·36	08·18
26·37	49·82	2010/08/10	12·23	078	01·69	07·85	07·66
24·39	39·63	2010/10/08	20·29	17	03·69	12·40	11·84
24·60	46·45	2010/10/08	19·83	16	03·47	12·17	11·67
26·35	43·95	2010/10/08	19·99	14	03·17	12·27	11·86
25·25	45·25	2010/10/08	19·91	15	03·37	12·21	11·75
26·37	49·82	2010/10/08	19·60	14	03·02	12·07	11·69
25·62	45·62	2010/10/08	19·88	15	03·28	12·21	11·76
27·52	41·70	2010/11/06	09·58	01	00·29	06·32	06·31
21·42	39·83	2010/11/06	09·84	05	01·11	06·33	06·23
24·39	39·63	2010/11/06	09·79	03	00·74	06·35	06·31

TABLE II (*continued*)

Lat. °	*Long.* °	*Date* *UT*	*Age* *hrs.*	*Lag* *min.*	*ARCV* °	*ARCL* °	*DAZ* °
24·60	46·45	2010/11/06	09·33	02	00·52	06·18	06·16
26·35	43·95	2010/11/06	09·45	01	00·37	06·25	06·24
25·25	45·25	2010/11/06	09·39	02	00·47	06·21	06·20
24·39	39·63	2011/01/04	12·27	11	02·23	02·24	00·23
24·60	46·45	2011/01/04	11·80	09	02·01	02·03	00·28
21·42	39·83	2011/05/03	18·74	17	03·58	04·50	02·74
24·39	39·63	2011/05/03	18·82	18	03·75	04·50	02·49
27·52	41·70	2011/05/03	18·75	19	03·86	04·46	02·23
21·42	39·83	2011/07/01	21·45	07	01·63	03·71	03·34
24·39	39·63	2011/07/01	21·57	07	01·48	03·81	03·51
24·60	46·45	2011/07/01	21·12	06	01·28	03·61	03·38
28·40	36·73	2011/07/01	21·91	06	01·34	04·02	03·80
25·62	45·62	2011/07/01	21·22	06	01·25	03·67	03·45
21·42	39·83	2011/10/27	18·87	27	05·79	11·00	09·37
24·39	39·63	2011/10/27	18·83	25	05·26	11·01	09·69
24·60	46·45	2011/10/27	18·37	24	05·02	10·76	09·53
28·40	36·73	2011/10/27	18·95	23	04·60	11·13	10·15
25·25	45·25	2011/10/27	18·44	24	04·94	10·81	09·63
25·62	45·62	2011/10/27	18·41	23	04·86	10·80	09·65
26·37	49·82	2011/10/27	18·12	22	04·60	10·65	09·61
21·42	39·83	2011/11/25	08·46	13	02·89	04·31	03·20
24·39	39·63	2011/11/25	08·39	13	02·66	04·30	03·38
24·60	46·45	2011/11/25	07·92	11	02·42	04·06	03·26
28·40	36·73	2011/11/25	08·45	12	02·43	04·39	03·66
25·25	45·25	2011/11/25	07·98	11	02·41	04·10	03·32
25·62	45·62	2011/11/25	07·95	11	02·37	04·08	03·33
21·42	39·83	2012/01/23	07·42	16	03·62	05·02	03·49
24·60	46·45	2012/01/23	06·89	16	03·54	04·81	03·26
25·25	45·25	2012/01/23	06·95	17	03·61	04·83	03·20
25·62	45·62	2012/01/23	06·91	17	03·62	04·81	03·17
21·42	39·83	2012/04/21	08·40	14	03·04	03·89	02·43
24·39	39·63	2012/04/21	08·46	15	03·19	03·88	02·21
21·42	39·83	2012/07/19	11·68	06	01·38	07·03	06·90
24·60	46·45	2012/07/19	11·34	03	00·83	06·95	06·90
24·39	39·63	2012/07/19	11·79	04	01·02	07·12	07·04
26·35	43·95	2012/07/19	11·56	03	00·68	07·06	07·03
25·62	45·62	2012/07/19	11·43	03	00·73	07·00	06·96
21·42	39·83	2012/09/16	13·20	05	01·34	02·85	02·52
24·60	46·45	2012/09/16	12·77	03	00·72	02·33	02·21
26·35	43·95	2012/09/16	12·94	02	00·53	02·26	02·19
25·25	45·25	2012/09/16	12·85	02	00·66	02·31	02·21
26·37	49·82	2012/09/16	12·55	01	00·39	02·06	02·02
25·62	45·62	2012/09/16	12·83	02	00·60	02·27	02·19
24·60	46·45	2012/11/14	15·99	33	06·70	08·81	05·73
26·35	43·95	2012/11/14	16·11	33	06·57	08·90	06·02
27·52	41·70	2012/11/14	16·23	33	06·49	08·98	06·22
28·40	36·73	2012/11/14	16·54	33	06·53	09·17	06·45
25·25	45·25	2012/11/14	16·06	33	06·66	08·85	05·84
25·62	45·62	2012/11/14	16·02	33	06·61	08·84	05·88
26·37	49·82	2012/11/14	15·72	32	06·38	08·67	05·88
21·42	39·83	2012/12/13	05·98	16	03·48	03·56	00·73
24·39	39·63	2012/12/13	05·89	16	03·47	03·50	00·51
24·60	46·45	2012/12/13	05·43	15	03·22	03·28	00·61
26·35	43·95	2012/12/13	05·54	16	03·30	03·33	00·44
27·52	41·70	2012/12/13	05·65	16	03·36	03·38	00·32
25·25	45·25	2012/12/13	05·49	16	03·26	03·30	00·54
25·62	45·62	2012/12/13	05·45	16	03·24	03·28	00·52
21·42	39·83	2013/02/10	07·93	16	03·78	06·09	04·78
24·39	39·63	2013/02/10	07·89	18	04·00	06·04	04·53
28·40	36·73	2013/02/10	08·00	20	04·38	06·03	04·15
25·25	45·25	2013/02/10	07·49	17	03·86	05·91	04·48

TABLE II (*concluded*)

Lat. °	*Long.* °	*Date* *UT*	*Age* *hrs.*	*Lag* *min.*	*ARCV* °	*ARCL* °	*DAZ* °
25·62	45·62	2013/02/10	07·46	17	03·87	05·90	04·45
26·37	49·82	2013/02/10	07·17	17	03·77	05·80	04·41
21·42	39·83	2013/04/10	06·05	09	02·09	02·95	02·08
25·62	45·62	2013/04/10	05·72	09	02·07	02·80	01·88
21·42	39·83	2013/10/05	02·25	15	03·43	07·28	06·43
24·39	39·63	2013/10/05	02·24	14	03·09	07·32	06·64
26·35	43·95	2013/10/05	01·94	12	02·74	07·20	06·66
27·52	41·70	2013/10/05	02·08	12	02·66	07·28	06·78
25·25	45·25	2013/10/05	01·86	12	02·84	07·15	06·56
25·62	45·62	2013/10/05	01·84	12	02·78	07·14	06·57
26·37	49·82	2013/10/05	01·55	12	02·59	07·01	06·52
21·42	39·83	2013/11/03	14·35	00	00·23	00·41	00·34
21·42	39·83	2014/01/01	17·19	12	02·64	04·58	03·74
24·39	39·63	2014/01/01	17·11	13	02·80	04·53	03·56
24·72	46·67	2014/01/01	16·63	12	02·56	04·44	03·63
26·35	43·95	2014/01/01	16·75	13	02·74	04·44	03·49
27·52	41·70	2014/01/01	16·86	14	02·87	04·44	03·39
28·40	36·73	2014/01/01	17·16	15	03·10	04·49	03·25
25·25	45·25	2014/01/01	16·70	12	02·63	04·44	03·58
25·62	45·62	2014/01/01	16·66	12	02·64	04·43	03·56
26·37	49·82	2014/01/01	16·36	12	02·52	04·38	03·58
21·42	39·83	2014/03/01	20·67	14	03·38	04·96	03·63
24·72	46·67	2014/03/01	20·18	14	03·30	04·74	03·41
26·35	43·95	2014/03/01	20·35	15	03·49	04·78	03·28
25·25	45·25	2014/03/01	20·27	15	03·38	04·77	03·37
25·62	45·62	2014/03/01	20·24	15	03·39	04·76	03·34
26·37	49·82	2014/03/01	19·96	14	03·27	04·65	03·31
21·42	39·83	2014/04/29	09·52	17	03·93	04·31	01·76
24·39	39·63	2014/04/29	09·59	18	03·86	04·36	02·03
28·40	36·73	2014/04/29	09·87	18	03·84	04·53	02·41
25·25	45·25	2014/04/29	09·24	17	03·66	04·19	02·06
25·62	45·62	2014/04/29	09·22	17	03·63	04·19	02·09
26·35	43·95	2014/07/27	17·21	08	01·81	08·91	08·72
21·42	39·83	2014/09/24	09·03	05	01·28	04·05	03·84
24·72	46·67	2014/09/24	08·57	04	00·90	03·91	03·81
26·35	43·95	2014/09/24	08·75	03	00·84	04·01	03·92
27·52	41·70	2014/09/24	08·90	03	00·82	04·08	04·00
28·40	36·73	2014/09/24	09·23	04	00·86	04·22	04·14
25·62	45·62	2014/09/24	08·64	03	00·86	03·95	03·86
26·35	43·95	2014/11/22	01·67	10	02·08	02·98	02·13
27·52	41·70	2014/11/22	01·78	10	02·17	02·97	02·03
21·42	39·83	2015/01/20	01·81	04	01·04	04·61	04·50
24·72	46·67	2015/01/20	01·26	04	01·01	04·57	04·46
26·35	43·95	2015/01/20	01·40	05	01·22	04·54	04·37
27·52	41·70	2015/01/20	01·51	06	01·38	04·52	04·31
28·40	36·73	2015/01/20	01·82	07	01·61	04·51	04·21
25·25	45·25	2015/01/20	01·34	04	01·10	04·56	04·43
25·62	45·62	2015/01/20	01·31	05	01·11	04·55	04·42
26·37	49·82	2015/01/20	01·00	04	01·00	04·55	04·44
21·42	39·83	2015/03/20	05·92	11	02·63	02·73	00·74
27·52	41·70	2015/03/20	05·80	11	02·62	02·65	00·38
28·40	36·73	2015/03/20	06·13	13	02·81	02·83	00·29
21·42	39·83	2015/05/18	11·67	21	04·68	07·04	05·27
24·39	39·63	2015/05/18	11·76	21	04·43	07·12	05·58
24·72	46·67	2015/05/18	11·30	19	04·16	06·92	05·54
26·35	43·95	2015/05/18	11·53	19	04·10	07·04	05·73
25·25	45·25	2015/05/18	11·41	19	04·16	06·98	05·61
25·62	45·62	2015/05/18	11·40	19	04·11	06·98	05·64
26·37	49·82	2015/05/18	11·14	18	03·90	06·87	05·66
21·42	39·83	2015/09/13	08·75	06	01·55	03·56	03·20
26·37	49·82	2015/09/13	08·11	04	01·06	03·36	03·19

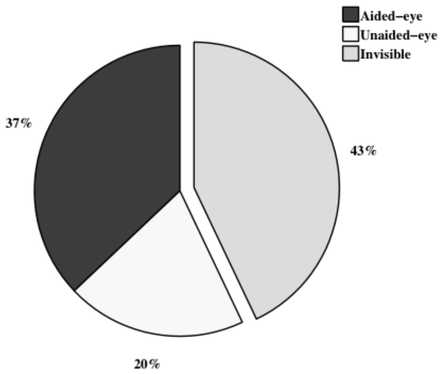

FIG. 3

Percentage of observations where the crescent was invisible (43%), and positive sightings made by optical means (telescope or binoculars, 37%), and by the naked-eye (20%).

TABLE III

Examples of observations and observational parameters

V/I refers to visible or invisible; T stands for telescope; and N stands for naked eye.

No.	*Lat.* °	*Long.* °	*Date* *UT*	*Age* *hrs.*	*Lag* *min.*	*ARCV* °	*ARCL* °	*DAZ* °	*W* ′	*V/I*
026	27·52	41·70	2000/12/26	21·08	40	07·70	08·86	04·40	0·19	V(T)
085	27·52	41·70	2009/01/27	30·92	64	13·35	13·55	02·32	0·44	V(N)
096	26·35	43·95	2009/10/19	33·00	35	06·99	17·47	16·05	0·77	V(T)
099	25·62	45·62	2009/11/18	42·90	70	12·92	20·51	16·07	1·01	V(N)
100	25·62	45·62	2009/12/17	26·13	48	09·08	11·50	07·07	0·32	V(N)
102	28·39	36·73	2010/04/15	27·49	65	13·20	13·51	02·85	0·44	V(N)
104	24·54	39·63	2010/06/13	28·94	68	13·87	15·22	06·34	0·56	V(N)
122	25·62	45·62	2010/12/06	20·93	40	07·87	10·95	06·49	0·25	V(T)
127	24·39	39·63	2011/04/04	25·00	50	10·70	11·42	04·04	0·31	V(N)
137	24·60	46·45	2011/09/28	27·60	32	06·98	16·55	15·04	0·66	V(T)
154	28·40	36·73	2011/12/25	20·61	54	10·30	10·78	03·18	0·53	V(N)
161	21·42	39·82	2012/04/22	32·00	64	13·83	13·87	01·06	0·47	V(N)
167	25·62	45·62	2012/07/20	35·42	43	09·50	17·80	15·13	0·76	V(N)
170	26·35	43·95	2012/09/17	36·92	45	09·64	20·34	18·00	0·99	V(N)
177	25·62	45·62	2012/10/16	26·42	40	08·28	14·88	12·14	0·53	V(N)
442	27·52	41·70	2012/11/14	16·23	33	06·49	08·98	06·22	0·19	I(-)
195	25·62	45·62	2013/01/12	18·71	53	10·87	10·93	01·25	0·29	V(N)
455	24·39	39·63	2013/02/10	07·88	18	04·00	06·04	04·53	0·08	I(-)
204	25·62	45·62	2013/04/11	29·72	63	13·23	13·56	00·05	0·45	V(N)
205	21·42	39·82	2013/05/10	15·37	28	06·07	06·34	01·85	0·10	I(-)
207	24·39	39·63	2013/10/06	38·50	59	12·46	19·65	15·33	0·93	V(N)
217	24·39	39·63	2013/12/03	14·18	39	07·92	08·10	01·62	0·16	V(T)
228	24·72	46·66	2014/01/31	16·98	46	09·86	10·31	02·99	0·25	V(N)
239	24·39	39·63	2014/03/31	20·87	48	10·47	10·40	00·30	0·27	V(N)
488	21·42	39·83	2014/04/29	09·51	18	03·93	04·30	01·76	0·05	I(-)
247	27·52	41·70	2014/05/29	21·37	36	07·33	10·47	07·49	0·27	V(T)
255	28·40	36·72	2014/09/25	33·20	41	08·65	15·07	12·39	0·55	V(N)
257	26·35	43·95	2014/11/23	25·66	62	12·30	13·41	05·36	0·43	V(N)
264	28·39	36·72	2015/02/19	15·65	41	08·72	08·82	01·30	0·19	V(N)
531	24·72	46·66	2015/05/18	11·30	19	04·15	06·92	05·54	0·12	I(-)

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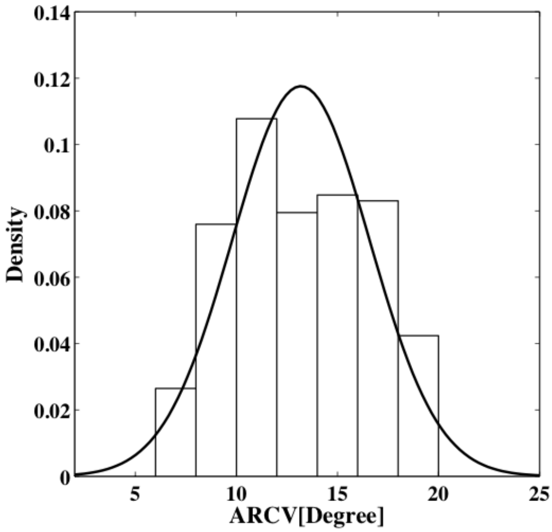

FIG. 4
Arc of vision (ARCV) distribution. The solid curve represents the best Gaussian fit of the distribution.

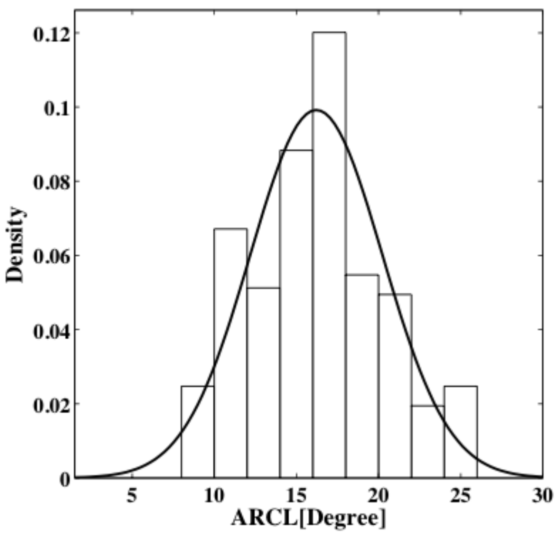

FIG. 5
Arc of light (ARCL) distribution. The solid curve represents the best Gaussian fit of the distribution.

Observation analysis

The data described in previous section and presented in Table I can be used to investigate the various prediction criteria for the first visibility of the lunar crescent following the new moon. We investigate the Moon's age and the lag time (LAG) as individual criteria. We examine the relationship between the Moon's age and lag time (LAG) with the two arcs (ARCV and ARCL). We study the relationships between the three arcs ARCV, ARCL, and DAZ and use these arcs to determine the best lunar-visibility criteria based on the collected data.

The Moon's age

The Moon's age is a simple parameter that has been used to predict lunar-crescent visibility. The youngest lunar crescent reported in our data set is 14·18 hrs, observed by telescope. The world record for the youngest visible lunar crescent by optical aid was 12·12 hrs on 1996 January 20[15]. The minimum Moon age in our data set, from observation 217 in Table III, has an ARCV value of 7°·92, and an ARCL value of 8°·10, which is the minimum ARCL in our data set. Observation 442 in Table III had a Moon age of 16·23 hrs, older than the minimum moon age of observation 217. The ARCV was 6°·49 and the ARCL was 8°·98, which is larger than observation 217; however, observation 442 was a negative sighting. A scatterplot of the age of the youngest visible lunar crescent *versus* ARCV and ARCL indicates a weak relationship between geometry arcs and the lunar-crescent age as shown in Figs. 6 and 7, respectively. These figures show a significant dispersion around the best linear fit and indicate that the minimum Moon age is a simple parameter but insufficient criterion for lunar visibility. The Moon takes a longer time to be visible after the new moon conjunction when it is closer to the ecliptic[6].

Moon lag (*LAG*)

The second most-simple and oldest lunar-visibility criterion is the Moon lag time (LAG). The minimum interval of time between the sunset and moonset (LAG) was 32 minutes (observation 137 in Table III), made by telescope, and the shortest interval ever recorded for a visible lunar crescent by optical aid was 21 min.[15]. As for Moon age, observation 442 had a longer Moon lag time (33 min.) but again, was a negative sighting. A scatterplot of LAG *versus* ARCV in Fig. 8 shows that a large number of observations have a linear relationship. There is some dispersion around the best-fit line, which indicates that a lunar crescent with a particular lag time may or may not be visible depending on the ARCV value.

We note that, the longer the LAG, the higher the altitude (ARCV) of the lunar crescent and the darker the sky. A scatterplot of LAG *versus* ARCL in Fig. 9 shows a significant dispersion around the best linear fit, which indicates a weak relationship between ARCL and LAG. Fig. 8 shows that LAG is a relatively applicable parameter.

The Danjon limit (*ARCL*)

The third direct criterion is the critical angular separation or elongation between the Moon and Sun at sunset or the arc of light (ARCL). This is very well known as the Danjon limit. According to the Danjon limit, the lunar crescent cannot be seen with the naked-eye if the angular separation between the Moon

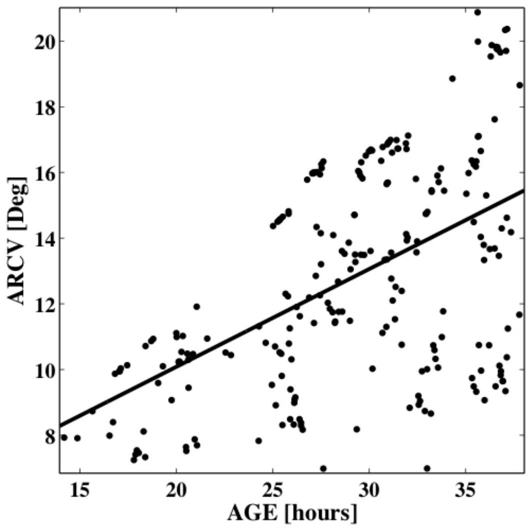

FIG. 6
Arc of vision (ARCV) *versus* lunar-crescent age. The solid line represents the best linear fit.

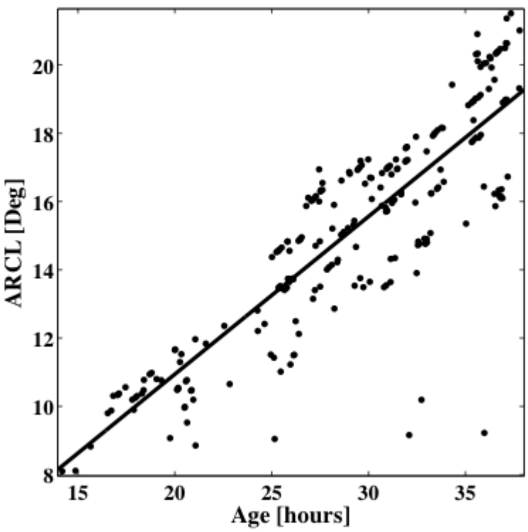

FIG. 7
Arc of light (ARCL) *versus* lunar-crescent age. The solid line represents the best linear fit.

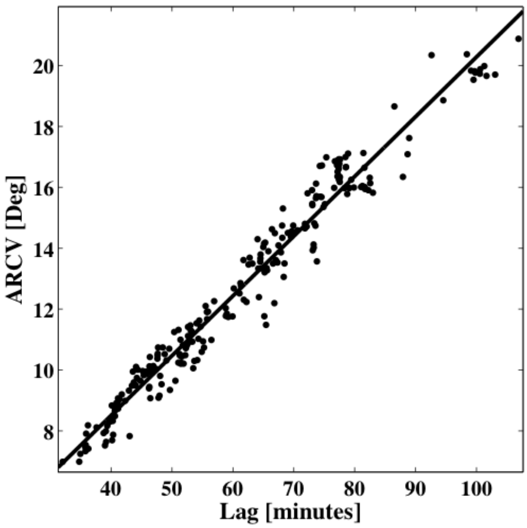

FIG. 8
Arc of vision (ARCV) *versus* (LAG). The solid line represents the best linear fit.

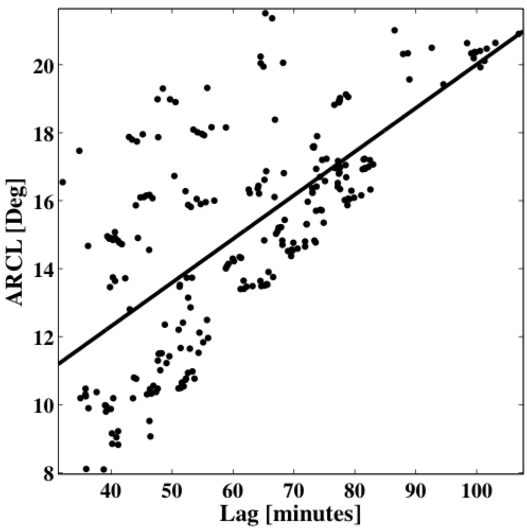

FIG. 9
Arc of vision (ARCL) *versus* (LAG). The solid line represents the best linear fit.

and Sun (ARCL) is less than 7°. Equation (1) relates the two independent arcs ARCV and DAZ with the arc of light (ARCL):

$$\cos(\mathrm{ARCL}) = \cos(\mathrm{ARCV})\cos(\mathrm{DAZ}). \qquad (1)$$

where all the arcs are measured in degrees. The Doggett & Schaefer[1] lunar-crescent-sighting campaign reinforced the Danjon limit. In our data set, the minimum recorded ARCL value by naked-eye was 8°·82 in observation 268 (Table III), which is larger than the Danjon limit. Even by aided-eye, the minimum recorded ARCL was 8°·10 in observation 217, which is larger than the Danjon limit. Ilyas[3,16] determined the lower limit of ARCL observed by naked-eye as 10°·5. Our data set contains 27 observations with ARCL < 10°·5, indicating that Ilyas's criterion is certainly overestimated (perhaps due to data collected with non-computerized mounted telescopes). In 2004, Odeh[15] claimed that he found one observation where the lunar crescent was seen for ARCL = 6°·40. Observations that exceed the Danjon limit are rare and care should be taken to investigate their validity.

The visibility curve (DAZ–ARCV)

The dividing (DAZ–ARCV) curve or lunar-visibility curve is used to separate regions of positive and negative lunar-crescent sightings based on the two arcs DAZ and ARCV, illustrated in Fig. 2. In 1910, Fotheringham used a collection of 76 lunar-crescent sightings, most observed in 1883 in Athens and Troy[7], to calculate the arc of vision (ARCV) and relative azimuth (DAZ). He found that the crescent was visible only when ARCV was above a critical value that depends on DAZ. The formula for lunar-crescent visibility is given by

$$\mathrm{ARCV} = 12 - 0{\cdot}008(\mathrm{DAZ}^2), \qquad (2)$$

where ARCV is the minimum Moon altitude at sunset in degrees and DAZ is the difference in azimuth in degrees[7]. Equation (2) is shown in Fig. 2, where the solid curve is the dividing line between visible (above the curve) and invisible (below the curve) lunar crescents. In 1911, Maunder added 47 observations to the collection and only used positive sightings and the quadratic equation to represent the data[8]. The Maunder criterion for lunar-crescent visibility is given by

$$\mathrm{ARCV} > 11 - 0{\cdot}05(\mathrm{DAZ}) - 0{\cdot}01(\mathrm{DAZ}^2), \qquad (3)$$

where ARCV and DAZ are in degrees. The dot-dash curve in Fig. 2 reveals that the Maunder dividing curve is lower than that of Fotheringham[8]. The Maunder criterion (equation (3)) is slightly modified in the *Indian Astronomical Ephemeris*. The Indian formula is based on the Maunder criterion, which fits DAZ to ARCV and produces the following equation:

$$\mathrm{ARCV} > 10{\cdot}3743 - 0{\cdot}0137(\mathrm{DAZ}) - 0{\cdot}0097(\mathrm{DAZ}^2), \qquad (4)$$

where ARCV and DAZ are in degrees[3,12]. This formula is used in the *Indian Astronomical Ephemeris*[9] and shown in Fig. 2 as the dashed curve, which indicates that the Indian criterion is slightly different to the Maunder criterion.

Our data set was used to design a crescent-visibility curve that separates visible and non-visible lunar-crescent regions characterized by the two arcs ARCV and DAZ. This method follows that of Fotheringham[7]. The data set is divided into two parts: one for observations by naked-eye; and one for observations by aided eye. For unaided observations, a scatterplot is produced in the ARCV–DAZ plane (Fig. 10), where lunar-crescent observations are divided into two clear regions. The crosses in Fig. 10 represent all invisible observations and the solid

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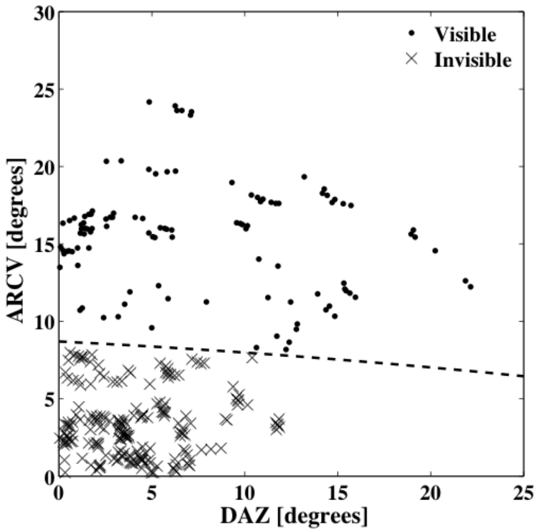

FIG. 10

Hypothetical curve dividing unaided-eye lunar-crescent observations into two regions: visible (above the curve) and invisible (below the curve).

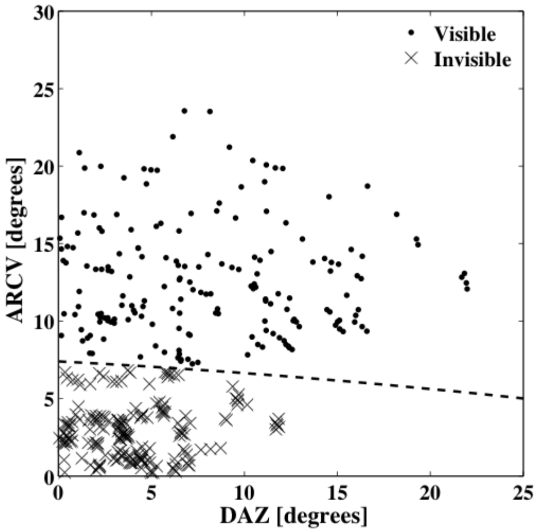

FIG. 11

Hypothetical curve dividing aided-eye lunar-crescent observations into two regions: visible (above the curve) and invisible (below the curve).

points represent all visible observations by naked-eye. A visual inspection of that figure led to the insertion of a hypothetical line separating the data into two regions of points representing visible and invisible lunar-crescent observations. The best hypothetical curve is given by the formula

$$\text{ARCV} = 8{\cdot}7 - 0{\cdot}0594(\text{DAZ}) - 0{\cdot}00121(\text{DAZ}^2), \qquad (5)$$

where ARCV and DAZ are in degrees. Similarly, we perform the same procedure for aided-eye observations (Fig. 11). The hypothetical curve in that figure is given by the formula

$$\text{ARCV} = 7{\cdot}40 - 0{\cdot}0624(\text{DAZ}) - 0{\cdot}0013(\text{DAZ}^2). \qquad (6)$$

Equations (5) and (6) are based only on visual inspection using the best hypothetical curve. The ARCV–DAZ dividing curve reveals that the critical arc of vision (ARCV) of the thin crescent after sunset can be small when the azimuthal distance (DAZ) between the Moon and Sun is large. Thus, for the lunar crescent to be visible, the western sky should be sufficiently dark. Positive (negative) lunar-crescent sightings above (below) the (ARCV–DAZ) dividing curve depend mainly on the contrast between sky-brightness and thin-lunar-crescent illumination. A small contrast can be the difference between visible and non-visible sightings. The contrast increases to the width of the lunar-crescent (W), which is related to the arc of light (ARCL), and therefore to the arc of vision (ARCV) and the azimuthal distance (DAZ) (see equation (1)), according to the following formula

$$W = SD(1 - \cos(\text{ARCL})), \qquad (7)$$

where SD is the semi-diameter of the Moon, which is related to the Moon's parallax π by $SD = 0{\cdot}27255\pi$. In this study, we adopted an SD value of 16′. For the western sky, the contrast is determined by ARCV and W. The minimum contrast resulting in a visible lunar crescent depends on the direct relationship between ARCV and W. Using equation (5) for the best hypothetical curve for naked-eye observations, for any given DAZ, the ARCV can be obtained. The critical contrast between visible and not visible is deduced in Table IV using equations (5), (1), and (7). In Fig. 12, a third-degree polynomial is fitted to the data in Table IV. The resulting critical ARCV required for the critical contrast for naked-eye lunar-crescent sightings is shown by equation (8):

$$\text{ARCV} > 9{\cdot}34 - 4{\cdot}51W + 3{\cdot}3W^2 - 1{\cdot}01W^3. \qquad (8)$$

TABLE IV

ARCV and W for certain values of DAZ by using Equation (5)

DAZ (°)	0	5	10	15	20	25
ARCV (°)	8·70	8·37	7·89	7·53	7·02	6·45
W (′)	0·18	0·23	0·39	0·67	1·07	1·59

The same procedure is performed for aided lunar-crescent sightings, using the hypothetical line equation for aided lunar-crescent observations (equation (6)). ARCV is calculated for certain values of DAZ shown in Table V. The critical W for visibility is deduced in that table using equations (6), (1), and (7). In Fig. 13, a third-degree polynomial is fitted to the data given in Table V. The resulting critical ARCV required for the critical contrast for aided-eye lunar-crescent sightings is shown by equation (9):

$$\text{ARCV} > 7{\cdot}83 - 4{\cdot}35W + 3{\cdot}22W^2 - 1{\cdot}02W^3. \qquad (9)$$

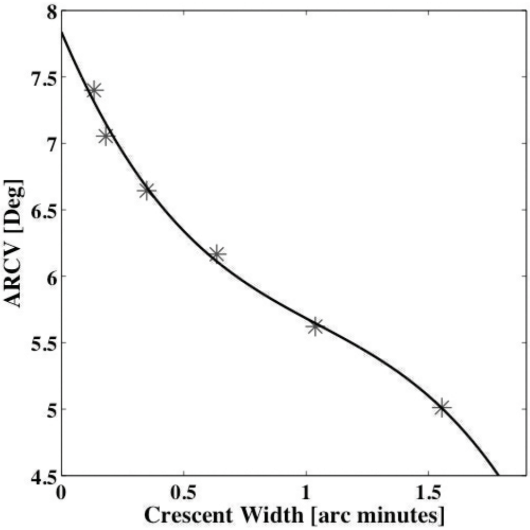

FIG. 12
Third-degree polynomial fitted to the data given in Table IV.

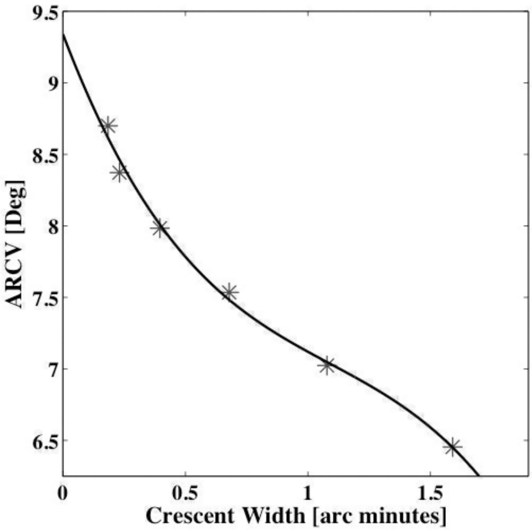

FIG. 13
Third-degree polynomial fitted to the data given in Table V.

TABLE V

ARCV and W for certain values of DAZ by using Equation (6)

DAZ (°)	0	5	10	15	20	25
ARCV (°)	7·40	7·05	6·64	6·16	5·62	5·01
W (′)	0·13	0·18	0·34	0·63	1·03	1·55

The new critical ARCV values in equations (8) and (9) were determined using the visibility curve (DAZ–ARCV). After a visual inspection of the naked-eye and aided-eye scatterplots (Figs. 10 & 11), a hypothetical line ARCV = *f*(DAZ) was inserted, separating regions of positive and negative sightings of the youngest lunar crescent. Equations for these hypothetical lines were used to deduce the numerical values for ARCV and *W* (Tables (IV & V)). These values were then fitted using a third-degree polynomial in the lunar-crescent width (*W*) equations (8, 9).

Discussion

We used a large set of observations of the youngest lunar crescent to investigate several criteria for visibility of the first thin lunar crescent following a new-moon conjunction. We first analyzed Moon age as an individual criterion that has been used since the Babylonians[3]. The youngest lunar crescent observed by telescope in our data set was 14·18 hrs. Our minimum Moon age is older than found by Schaefer *et al.*[17] during their 1987–1990 campaign (13·47 hrs), and older than the world record (12·12 hrs)[15]. It is clear, therefore, that the youngest Moon age after the lunar–solar conjunction is not sufficient for determining thin-lunar-crescent visibility (Figs. 6 & 7). When the Moon is near the ecliptic, it takes longer to increase its brightness and become visible. The second criterion we investigated was Moon lag time (LAG). We found that the Moon lag time is not related to the arc of light (ARCL) (Fig. 9) and that observations with a larger LAG include negative sightings, such as observation 442 in Table III. Fig. 9 shows that LAG does not contribute to greater contrast.

The third criterion we investigated was the Danjon limit, which states[11] that the arc of light (ARCL) required for the lunar crescent to be visible must be greater than 7°. However, a re-examination of Danjon's data by Ilyas[10] showed that, if one point below 10° were removed from Danjon's data, the limit increases to 10°·5. McNally[18] explained that the Danjon limit was due to atmospheric effects or turbulence, and found that the angular size of the lunar crescent vanishes for arc of light (ARCL) values of ≈ 5°. This explanation was rejected by Schaefer[19], who proposed that the lunar cusps are not visible because the brightness per unit length is below the eye's detection threshold, and who concluded that the Danjon limit is quite solid. Fatoohi *et al.*[20] reported an increase in the Danjon limit to 7°·5, and the 7° suggested by Danjon[11] and accepted by Scheafer[19] appears to overestimate the 10°·5 limit of Ilyas[10].

We found that lunar crescents within the Danjon limit at ARCL ≤ 7° were not detected by naked-eye or aided-eye observations. In our data set, the minimum ARCL observed by naked-eye was 8°·82 and that observed by aided-eye was 8°·10. Our results agree with those of Fatoohi *et al.*[20]. After investigating the main parameters commonly used as criteria for early lunar-crescent visibility, we followed the procedure used by Fotheringham[7] and others to determine the critical visibility curve (Figs. 10 & 11). We found new criteria for early new-moon visibility by naked-eye and aided-eye observations (equations (8, 9)). This method using the DAZ–ARCV curve was also used by Yallop[12], who used the Indian formula given in the *Indian Astronomical Ephemeris*[9], whereby numerical values for the arc of vision and the lunar-crescent width (ARCV, W) are fitted using a third-degree polynomial. Then Yallop developed his two-parameter criterion into a single-parameter criterion for visibility of the lunar crescent, in which the q-values are defined as

$$q = (\text{ARCV} - (11{\cdot}871 - 6{\cdot}3226W + 0{\cdot}7319W^2 - 0{\cdot}1018W^3))/10. \qquad (10)$$

The division by 10 in equation (10) confines[12] the values of q between –1 and 1. When q-values are $-0{\cdot}232 \geq q > -0{\cdot}293$, the lunar crescent is not visible with a telescope[12].

We investigated Yallop's criterion by applying it to our data collection. Yallop's criterion (equation (10)) is easy to convert to arc of vision (ARCV) in terms of the azimuthal distance (DAZ). We then used our aided-eye lunar-crescent observations to produce a scatterplot in the ARCV–DAZ as shown in Fig. 14, where the solid curve represents the Yallop criterion and the invisible region is below the solid curve. Clearly, Yallop's criterion lies above some observations from our data collection, and uses semi-topocentric values for the lunar-crescent width (W)[12]. We investigated his criterion using our data of both semi-topocentric (W') and geocentric lunar-crescent width (W) as shown in Fig. 15. There is little difference between the two values of the lunar-crescent width. The dashed line in Fig. 15 is the q-value ($q = -0{\cdot}232$) in Yallop's criterion, which is not visible by telescope. We found some of our observations by aided-eye lie below that line, in the invisible region, based on Yallop's criterion (Table VI). From Figs. 14 & 15, Yallop's criterion is not consistent with our data for lunar-crescent observations, and does not consider how the semi-topocentric W improved the fit to the observations[12]. In 2004 Odeh continued the work of Yallop and found a new criterion based on ARCV–DAZ curve and used 737 observations[15]. Odeh fitted numerical values using a third-degree polynomial, which provides the following criterion:

$$V = \text{ARCV} - (7{\cdot}1651 - 6{\cdot}3226W + 0{\cdot}7319W^2 - 0{\cdot}1018W^3). \qquad (11)$$

When we compare Odeh's model (equation (11)) with that of Yallop (equation (10)), Odeh's numerical values of the coefficient are similar up to the fifth digit to the Yallop's model, but Yallop's division by 10 confines the values of q between –1 and 1. We investigated Odeh's criterion based on the ARCV–DAZ visibility curve, and found that the dashed curve in Fig. 14 is below some observations classified as invisible in our data set. According to the ARCV–DAZ plane (Fig. 14), Odeh's is the same as Yallop's but shifted down. This similarity is questionable because both used different data sets of early lunar-crescent observations. Odeh's used topocentric values for the lunar-crescent width (W) and arc of vision (ARCV), but did not discuss how the topocentric variables improve the criterion. Moreover, we found that the third-degree polynomial fit for lunar-crescent width (W) with the arc of vision (ARCV) given in Table V, page 43, of ref. 20 is not consistent with his model (equation (11)).

Therefore, we propose that the criterion presented in this study for early crescent visibility is the latest criterion based on accurate observations taken by highly trained astronomers. Our two models (equations (8 and 9)) are thoroughly described and suitable for determining the lunar-crescent calendar

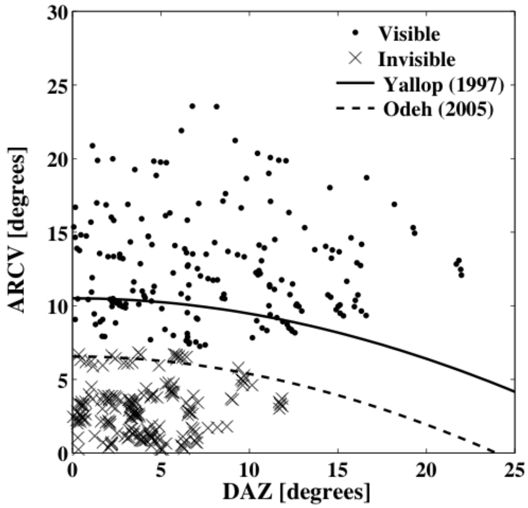

Fig. 14
Yallop and Odeh models in the ARCV–DAZ plane with our eye-aided observation data.

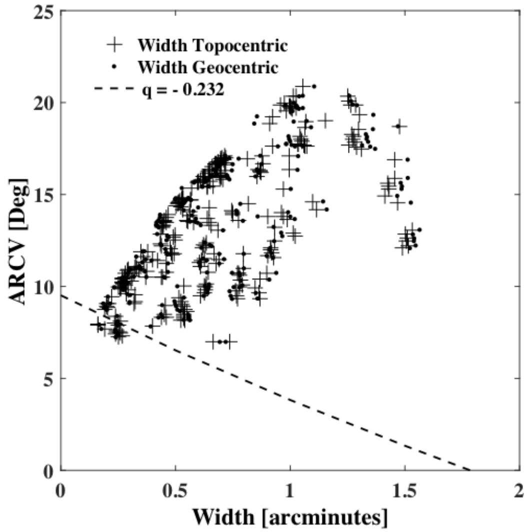

Fig. 15
Application of the Yallop criterion to the geocentric and semi-topocentric lunar-crescent width.

TABLE VI

Observations not in agreement with Yallop's criterion

No.	*Lat.* °	*Long.* °	*Date* *UT*	*ARCV* °	*ARCL* °	*DAZ* °	*W* ′	*q*
026	27·52	41·70	2000/12/26	07·70	08·86	04·40	00·18	−0·31
038	27·52	41·70	2002/11/05	07·41	09·90	06·58	00·25	−0·29
064	27·52	41·70	2005/02/09	07·98	09·80	05·70	00·24	−0·24
075	24·54	39·63	2006/02/28	07·91	08·12	01·81	00·17	−0·29
115	24·39	39·63	2010/12/06	07·87	10·20	06·50	00·25	−0·24
116	24·60	46·45	2010/12/06	07·63	09·97	06·42	00·24	−0·27
117	25·62	45·62	2010/12/06	07·52	09·99	06·60	00·24	−0·28
217	24·39	39·63	2013/12/03	07·92	08·10	01·62	00·17	−0·29
246	24·72	46·67	2014/05/29	07·54	10·25	06·97	00·24	−0·28
247	27·52	41·70	2014/05/29	07·33	10·47	07·49	00·25	−0·30
248	25·62	45·62	2014/05/29	07·46	10·31	07·13	00·24	−0·29
249	26·37	49·82	2014/05/29	07·24	10·20	07·20	00·24	−0·31

for civil purposes. The criteria involve both naked-eye and aided-eye sightings; however, they are not applicable on a global scale because our observations were made at latitudes between 20° N and 29° N.

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COOL DWARFS IN WIDE MULTIPLE SYSTEMS

PAPER 6: A CURIOUS QUINTUPLE SYSTEM OF A COMPACT SUN-LIKE TRIPLE AND A CLOSE PAIR OF AN M DWARF AND A VERY COOL WHITE DWARF AT A WIDE SEPARATION

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The system WDS 16329+0315 is an old, nearby, quintuple physical system in the thick Galactic disc formed by a close, but resolved, triple primary of solar metallicity, namely HD 149162, and a very wide, common-proper-motion, secondary pair, formed by the mid-M dwarf G 17-23 and the white dwarf LSPM J1633+0311S. We present an exhaustive astrometric and photometric data compilation of the system, including *Gaia* DR2 parallaxes and proper motions, and the first analysis of the nature of the faintest component. LSPM J1633+0311S (HD 149162 C) is a very cool white dwarf with an effective temperature of only about 5500 K, near the coolest end of the grid of theoretical models.

The WDS 16329+0315 system

HD 149162 is the brightest member of the multiple stellar system WDS 16329+0315. The star was first classified in 1947 as a dK0 single-line spectroscopic binary[1]. The first careful study of the spectroscopic binary, hereafter Aa,Ab, was carried out by Johnson & Mayor[2]. They calculated an orbital period $P = 225{\cdot}7 \pm 1{\cdot}1$ d and a moderate eccentricity $e = 0{\cdot}282 \pm 0{\cdot}002$, and kinematically classified it as an old-disc K1V-type binary. They computed the mass of the primary, Aa, at 0·8–0·9 $M_\odot$ from the spectroscopic mass function and at 0·76 $M_\odot$ from Geneva photometry, and of the 'secondary', Ab, at over 1 $M_\odot$. To explain this contradictory result and the significant X-ray, ultraviolet, and Ca II *H&K* emission, they proposed the secondary to be, in turn, a neutron star, a white-dwarf–M-dwarf tight binary, or a pair of emission-line M dwarfs.

Subsequent kinematic studies and orbital solutions also supported the idea of the system being part of the old disc, and the Ab component being more massive than Aa[3,4,5]. For example, HD 149162 was one of the 235 stars for which Lindegren *et al.*[4] published orbital solutions from *Hipparcos* data. Next, Horch *et al.*[6] used the *Gemini North* telescope and the *Differential Speckle Survey Instrument* for studying the mass–luminosity relation in metal-poor stars. As part of their analysis, they resolved the components Aa and Ab, which were separated by only $\rho = 0{\cdot}007$–$0{\cdot}020$ arcsec. All the orbital solutions published in the literature for the pair Aa,Ab are listed in Table I. Both astrometric and spectroscopic analyses point to an orbital period of about 0·62 yr with a moderate eccentricity of about 0·31.

TABLE I

Orbital solution parameters of pair WDS 16329+0315 Aa,Ab

From spectroscopy

Ref.	P [d]	T_0 [MJD]	e	ω [deg]	$a \sin i$ [Gm]	$f(M)$ [$M_\odot$]
2	225·70±0·10	45282·1±0·3	0·282±0·002	17·6±0·5	71·10±0·30	0·289±0·003
3	226· 30±1·30	47319·1±1·4	0·324±0·012	19·5±2·3	69·34±0·94	0·260±0·010
5	226·08±0·18	47319·3±1·1	0·3114±0·0087	20·4±1·7	69·76±0·78	0·2647±0·0089

From astrometry

Ref.	P [d]	T_0 [MJD]	e	ω [deg]	a [mas]	i [deg]
4	225·70	45282·1	0·282	17·60	9·87±1·62	109·47±15·28
6	226·08	47319·5	0·3114	203·62	14·80±2·00	112±26

Horch *et al.*[6] also discovered a third, fainter source, hereafter Ac, at $\rho \sim 0{\cdot}284$ arcsec from Aa, and measured magnitude differences through two narrow filters centred on 692 nm and 880 nm. The observed differences agreed with Ab and Ac being k6 V and m5 V main-sequence stars, respectively (a lower case letter in spectral type stands for a determination based on photometry only). Strikingly, given its angular separation, Ac cannot be one of the M-dwarf companion candidates proposed by Johnson & Mayor[2]. The *Washington Double Star Catalogue* (*WDS*[7]) tabulates the triple system with the discoverer code DSG 7.

There has been a long discussion in the literature on the actual iron abundance (the most-used proxy of metallicity) of HD 149162 Aa, which is the only component visible in spectroscopic analyses. The iron abundance, [Fe/H], has been reported in the wide range from –1·39 to –0·04[2,3,8], which made Lindegren *et al.*[4] include it in their sample. However, Montes *et al.*[9] settled the issue and measured a solar metallicity ([Fe/H] $= -0{\cdot}01 \pm 0{\cdot}04$). Montes *et al.*[9] also derived accurate Galactocentric space velocities, *UVW*, for Aa, and assigned it to the Galactic thick disc, in accordance with previous classifications and the lack of identified activity (*i.e.*, youth) features, such as Hα or X-ray emission. This points towards a relatively old systemic age.

Lépine & Bongiorno[10] found a wide, common-proper-motion companion to HD 149162, at an angular separation of $\rho = 252{\cdot}0$ arcsec and position angle $\theta = 138$ deg, namely G 17–23, hereafter B. This pair is catalogued by *WDS* as LEP 98. In the second half of the 20th Century, this M3·0 V star[11] was thought to be isolated[12]. As a relatively bright intermediate M dwarf, B was a potential target for exoplanet search by *CARMENES*[11,13], which originally attracted our attention.

Besides, Lépine & Shara[14] tabulated a faint source at 6·30 arcsec to the southeast of B with exactly the same proper motions. This component, namely LSPM J1633+0331S, hereafter C, has been poorly investigated: before Montes *et al.*[9], only coordinates, proper motions, and *J*, *H*, and *Ks* magnitudes had been reported[13]. The pair B,C is catalogued by *WDS* as DAM 649.

Table II summarizes the known parameters of the quintuple system. Fig. 1 shows an image of the system as visualized with *Aladin*[15].

Data compilation and analysis

First of all, we compiled equatorial coordinates (right ascension and declination) for the Aa, B, and C components with their astrometric epochs, from the following catalogues: AC2000·2[16], USNO-A2[17], GSC2·3[18], 2MASS[19], CMC15[20], AllWISE[21], and *Gaia* DR1[22]. In addition, we measured coordinates for the B

TABLE II

Fundamental parameters of WDS 16329+0315 Aa,Ab,Ac, B, and C

Component	*Aa,Ab,Ac*	*B*	*C*	*Ref.*
Name	HD 149162	G 17-23	LSPM J1633+0311S	*Simbad*
Alt. name	BD+03 3215	NLTT 43046	…	
α [h:m:s]	16:32:51·631	16:33:02·799	16:33:03·088	*Gaia* DR2[26]
δ [d:m:s]	+03:14:45·64	+03:11:37·28	+03:11:32·63	
μ_α cosδ [mas/yr]	−374·95±0·52	−368·92±0·08	−369·28±0·24	
μ_δ [mas/yr]	−180·81±0·44	−186·07±0·06	−189·64±0·16	
d [pc]	41·65±0·62	45·38±0·10	45·57±0·30	
B_P [mag]	9·0635±0·0011	14·8338±0·0016	18·1523±0·0082	
G [mag]	8·5731±0·0003	13·4083±0·0003	17·8064±0·0013	
R_P [mag]	7·9516±0·0013	12·2391±0·0012	17·1870±0·0149	
g [mag]	…	15·171±0·005	18·185±0·008	*Pan STARRS*[27]
r [mag]	…	13·978±0·003	17·756±0·005	
i [mag]	8·393±0·108	12·706±0·012	17·594±0·012	
z [mag]	8·386±0·001	12·144±0·014	17·524±0·008	
y [mag]	8·236±0·115	11·830±0·005	17·398±0·018	
J [mag]	7·159±0·024	10·625±0·026	16·314±0·279	2MASS[19]
H [mag]	6·700±0·055	10·011±0·023	15·918±0·352	
K_s [mag]	6·561±0·018	9·775±0·021	…	
Sp. type	K1V+k6V+m5V	M3·0V	D:	2, 6, 11, 9
T_{eff} [K]	5252±53	3400±50	5500±50	9, this work
log g	4·33±0·13	4·5 (fixed)	9·5±0·5	
[Fe/H]	−0·01±0·04	0·00 (fixed)	…	
V_r [km/s]	−51·33±0·15	…	…	
U [km/s]	−41·79±0·12	…	…	
V [km/s]	−94·4±3·3	…	…	
W [km/s]	+14·8±1·7	…	…	
Population	Thick disc	…	…	
M [$M_\odot$]	(0·77+0·64+0·15)±0·02	0·40	0·54	6, this work

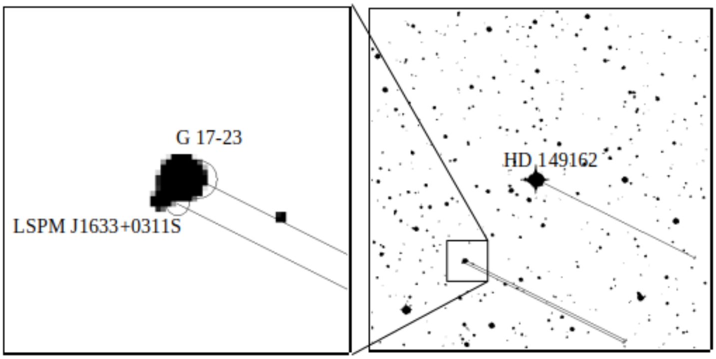

FIG. 1

Inverted Digital Sky Survey R_F photographic images of the system WDS 16329+0315 made with *Aladin*. Left: B and C components, approximately 2 × 2 arcmin^2. Right: Aa,Ab,Ac (unresolved) and B,C (unresolved), approximately 30 × 30 arcmin^2. Names are labelled. Vectors indicate *Simbad* proper motions. North is up and East to the left.

and C components on eight digitized photographic plates downloaded from the Digital Sky Survey and *SuperCOSMOS*[23]. The plates used had exposure times between 12 and 95 min, and different emulsion–filter combinations from the blue to the near infrared. With these coordinates, we derived precise angular separations and position angles between Aa and B components and between B and C components for each astrometric epoch with the Virtual Observatory tool TOPCAT[24]. We list these measurements, along with average values, in Table III.

TABLE III

Astrometric follow-up of pairs WDS 16329+0315 Aa-B and B-C

Pair	*Epoch*	ρ [arcsec]	θ [arcsec]	*Origin*
Aa,B (LEP 79)	1950·294	252·74±0·10	138·47±0·01	USNO-A2[17]
	1993·530	253·16±0·14	137·78±0·01	GSC2·3[18]
	1999·938	252·16±0·46	138·26±0·09	CMC15[20]
	2000·350	252·01±0·06	138·39±0·012	2MASS[19]
	2010·556	252·01±0·04	138·40±0·01	AllWISE[21]
	2015·000	252·03±0·43	138·39±0·01	*Gaia*-DR1[22]
	Average	252·35±0·21	138·28±0·04	
B,C (DAM 649)	1950·294	5·88±0·13	127·37±0·25	POSSI-Red XE565
	1983·452	5·99±0·05	133·50±0·02	Quick-V-Northern N565
	1990·384	6·36±0·05	135·02±0·01	POSSII-Blue XJ800
	1993·390	6·08±0·05	135·04±0·01	POSSII-Red XP800
	1993·475	5·98±0·05	138·41±0·04	POSSII-Blue XJ801
	1993·530	5·80±0·05	134·72±0·01	POSSII-Red XP801
	1997·292	5·79±0·05	135·12±0·01	POSSII-IR XI800
	1997·440	5·66±0·05	136·15±0·01	POSSII-IR XI801
	2000·350	6·26±0·20	138·51±0·172	2MASS[19]
	2015·000	6·39±0·31	137·44±0·18	*Gaia* DR1[22]
	Average	6·01±0·11	135·19±0·07	

We also calculated proper motions for the three stars with simple linear regressions in the epoch-α and epoch-δ planes[25]. In total, we used seven different astrometric epochs for the Aa component with a time baseline of 105 years. For the B and C components, the time baseline of the astrometric follow-up was shorter, 65 years, but contained more data points: 13 and 10, respectively. The three stars share the same proper motion within uncertainties, and are very similar to the new values in the *Gaia* Second Data Release (*Gaia* DR2[26]) listed in Table II and to pre-*Gaia* DR2 values from the literature, as shown in Table IV.

TABLE IV

Calculated and pre-Gaia DR2 proper motions of WDS 16329+0315 Aa,Ab,Ac, B, and C

Component	$\mu_\alpha \cos\delta$ [*mas/a*]	μ_δ [*mas/a*]	*Epochs*	$\mu_\alpha \cos\delta_{lit}$ [*mas/a*]	$\mu_{\delta lit}$ [*mas/a*]	*Origin*
Aa,Ab,Ac	−370·9±1·4	−186·8±1·5	7	−369·81±0·07	−185·50±0·05	TGAS[22]
B	−374·9±4·9	−179·9±3·3	13	−383·38±2·31	−172·58±2·31	HSOY[45]
C	−380·4±5·8	−197·5±5·3	10	−374	−189	ref. 14

Finally, we collected magnitudes for the three components resolved by all-sky surveys at 11 different wavelengths from 490 nm to 2300 nm. The compiled magnitudes were g, r, i, z, and y from *Pan-STARRS*[27], B_P, G and R_P from *Gaia*-DR2[26], and J, H, and K_s from 2MASS[18]. These values are presented in Table II. For component B only, we also collected B and V magnitudes from APASS9[28], and *W1-4* magnitudes from AllWISE[21], which amounted to 17 photometric pass-bands for the M dwarf.

Results, discussion, and conclusions

As expected from the common proper motion, the three stars resolved by *Gaia* (A, B, and C) also have similar parallactic distances (Table II). However, the close multiplicity of Aa,Ab,Ac affects the *Gaia* measures, as the triple star has a larger parallax uncertainty than B and C, in spite of being several magnitudes brighter (but fainter than the *Gaia* bright end at $G \sim 6$ mag). Therefore, we assumed that the multiple system is located at $d = 45{\cdot}48 \pm 0{\cdot}16$ pc, which is the distance obtained from the weighted mean of the parallaxes of B and C only. Compare this value with $d = 46{\cdot}3 \pm 1{\cdot}9$ pc, which was tabulated for Aa,Ab,Ac by the *Tycho–Gaia Astrometric Catalogue* (*TGAS*[22]).

The average angular separations ρ and position angles θ for the pairs Aa,B and B,C listed in Table III, $\rho = 252{\cdot}35 \pm 0{\cdot}21$ arcsec and $\theta = 138{\cdot}28 \pm 0{\cdot}04$ deg, and $\rho = 6{\cdot}01 \pm 0{\cdot}11$ arcsec and $\theta = 135{\cdot}19 \pm 0{\cdot}07$ deg, respectively, match (and slightly improve) the ones provided by *WDS*. Together with the assumed heliocentric distance to the system, these angular separations, and those measured by Horch *et al.*[6] with speckle, translate into projected physical separations $s = 13{\cdot}02 \pm 0{\cdot}06$ AU (Aa–Ac), $s = 11570 \pm 40$ AU (Aa,B), $s = 276 \pm 5$ AU (B,C). With the orbital parameters in Table I, the true physical separation between Aa and Ab varies between $r = 0{\cdot}47 \pm 0{\cdot}06$ AU at periastron and $r = 0{\cdot}89 \pm 0{\cdot}12$ AU at apastron. All in all, WDS 16329+0315 is a hierarchical quintuple system with different physical separations ranging in six orders of magnitude (from 10^{-1} AU to 10^5 AU).

Interestingly, component C (LSPM J1633+0311S), which has never been investigated spectroscopically, is 4·4 mag fainter in the G band than component B, which is an M3·0 dwarf[11]. Since they are located at the same distance, this would make C a very-red late-M dwarf. However, C is *bluer* than B in all colours. This is illustrated by the colour–magnitude diagram shown in Fig. 2. Because of its faint absolute magnitude and blue colours, we considered component C to be a white-dwarf or hot-subdwarf candidate. Montes *et al.*[9] assigned a "D:" (white dwarf) spectral type to LSPM J1633+0311S based on information provided in *this* work.

With the photometry compiled in Table II, the widely-used Koester *et al.*[29] theoretical models of white dwarfs and the Virtual Observatory Spectral Energy Distribution Analyzer (VOSA[30]), we derived an effective temperature of 5500 ± 50 K, a surface gravity $\log g = 9{\cdot}5 \pm 0{\cdot}5$, and a bolometric luminosity $L = (122 \pm 8) \times 10^{-6}\ L_\odot$ for C. The low effective temperature, near the coolest end of the Koester *et al.*[29] grid of models at 5000 K, high surface gravity, and low luminosity agree with what is expected for a very cool white dwarf[31–34] and the most recent findings with *Gaia* DR1[35,36] and *Gaia* DR2[36–38]. The low temperature is, however, not compatible with C being a hot subdwarf. Although we do not know the nature of the stellar progenitor or the cooling evolution of C, its cool temperature supports the old systemic age stated above. Besides, we proceeded similarly with B, but with BT-Settl CIFIST[40] models of low-mass stars and additional optical APASS9 and mid-infrared *WISE* photometry; again, the

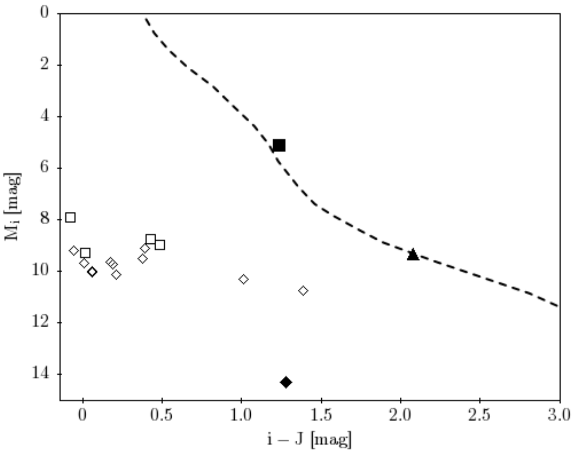

FIG. 2

Optical-near infrared colour–magnitude diagram of the system WDS 16329+0315. Large black filled symbols: components Aa,Ab,Ac (square; slightly above the isochrone because of unresolved multiplicity), B (triangle), and C (rhomb). Small open symbols: the brightest white dwarfs (rhombs) and hot subdwarfs (squares) in the *Tycho-2* catalogue[34]. Dashed line: 10 Gyr-old BT-Settl CIFIST Lyon isochrone[45].

derived temperature, gravity, and luminosity, $L = (164 \pm 2) \times 10^{-4}\, L_\odot$, match the typical parameters of an M3·0V dwarf[41].

Finally, we estimated the temporal scales of variation in the system. Components Aa (K1V) and Ab (k6V), with masses of 0·77 $M_\odot$ and 0·64 $M_\odot$ according to Horch *et al.*[6], orbit around their common centre of gravity every 0·619 yr (Table I). For Ac (m5V) and B (M3·0V), we assumed masses of 0·18 and 0·40 $M_\odot$ from typical masses for intermediate M dwarfs[42–44], and from the *J*-band absolute magnitude, parallactic distance to the system, and the BT-Settl Lyon models[40] for ages between 1 and 10 Gyr. For component C, we adopted the typical mass for a white dwarf at 0·54 $M_\odot$[31]. Next, we computed *reduced orbital periods*, $P^\star$, from Kepler's third law of planetary motion $G\,(M_1{+}M_2)\,P^2 = 4\pi\, a^3$, where the semi-major axis a was replaced by the mean projected physical separation s, as in Caballero[25]. Resulting periods were 37 yr (Aa,Ab-Ac), 4700 yr (B,C), and 810 000 yr (Aa,Ab,Ac-B,C). The indirect effect of Ac on the spectrum of Aa, or even the relative proper motion of Ac with respect to Aa and Ab, should be measured within a few years, which will shed light on the nature of the low-mass-star companions to the K1V star. However, we need low- and high-resolution spectroscopy for studying in further detail the new very cool white dwarf LSPM J1633+0311S, which we baptize here as HD 149162 C.

Acknowledgements

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SPECTROSCOPIC BINARY ORBITS FROM PHOTOELECTRIC RADIAL VELOCITIES

PAPER 263: HR 978 (HD 20277)

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HR 978 is a 6^m late-G star at the southern border of Perseus, nearly 40 minutes of time preceding, and just 18 minutes of arc north of, the third-magnitude B star ζ Per. In the *Bright Star Catalogue* its spectral type is listed as G8 IV, and its photometry is given as $V = 6^m{\cdot}06$, $(B-V) = 0^m{\cdot}99$, $(U-B) = 0^m{\cdot}68$, but low-amplitude photometric variations have subsequently been suspected. A generous number of radial-velocity observations shows it to be a spectroscopic binary in an orbit of low eccentricity with a period just short of 3 years.

Introduction

HR 978 is a 6^m star to be found near the southern boundary of Perseus, about a third of the way from ζ Per westwards towards the compact constellation Triangulum. Its broad-band magnitudes are given in the Abstract above. As befits a bright star, its radial velocity was measured a long time ago. The *Simbad* bibliography recalls five publications (two of which duplicate data), the earliest of which dates from 1942, and gives just the mean velocity from each; the means exhibit a spread of 5·5 km s^{-1}, but no suggestion is made that the velocity is truly variable. The bibliography is headed not as HR 978 but as "V* V573 Per – Semi-regular pulsating Star". However, no pulsational periodicity has been noticed in the radial velocities referred to below.

The star has been credited with photometric variations having an 'amplitude' of $0^m{\cdot}08$, but it is often not clear whether 'amplitude' is intended to represent the extreme range of variation, or half of it, or even the r.m.s. spread of the measured magnitudes. In the present case the 'amplitude' has evidently been copied from an *IBVS* paper[1], *On the Variability of the G0-G9 Stars*. That paper lists some 50 stars of such types, with columns for 'SE (mag)' and 'Amp (mag)', which for HR 978 have entries of 0·0030 and 0·08, respectively. The text says that those columns list standard error and amplitude, but does not define what it intends to mean by 'amplitude', and leaves unsaid that they refer to magnitudes measured by *Hipparcos*. To obtain a mean with a standard error of 0·003 magnitude in the face of an amplitude of variation 27 times greater would seem to require there to be at least of the order of 27-squared (729) independent measurements if 'amplitude' is intended to mean what a more careful specification might call the 'semi-amplitude', but only a quarter as many (say 183) if the full range is intended*. If one applies to *Simbad* to learn more about 'V 573 Per', one is given a "depth of primary minimum" of $0^m{\cdot}08$, and also a specific magnitude range of 6·11 to 6·19, so in *that* place it is clear that $0^m{\cdot}08$ is the *full range* of the variation, whose nature and origin seem not to have been assigned.

*But the *Hipparcos* catalogue itself informs us that there were 62 measurements, so either the time-scale of the variations is much longer than the typical time interval between the measurements, or else the writer of the present paper has somehow misdirected himself in some way.

There was a time (albeit about thirty years ago) when 'optical flashes' were seen in the constellation Perseus by quite a number of independent people. They seem not to have continued to occur, but at the time the evidence was convincing enough for a paper[2] with 15 authors to be published on the subject in the *Astrophysical Journal*. A table in that paper reports 25 visually estimated positions of such flashes, which are plotted on a chart of the relevant area of sky as circles generally a few degrees in radius and mostly mutually overlapping; the chart also marks a flash that was captured photographically and whose position (near the centre of the distribution of the visual observations) is close to that of HR 978. It is hard to believe that that is anything but a coincidence, although the position of the star (as, no doubt, of many other objects) is within the error circles of many of the sightings. As far as the writer is aware, no explanation of the flashes has ever been advanced.

Radial Velocities of HR 978 (HD 20277)

Radial-velocity observations of HR 978 began at Cambridge in 1993, but many had been obtained previously by others. In fact the lack of unanimity of the existing measurements was one of the considerations that prompted the writer's interest in the star in the first place. The earliest of those measurements were made in the 1930s at the David Dunlap Observatory near Toronto and published[3] under the name of the Director, Young, in 1942; he gave the results of five spectrographic plates, probably ones having a dispersion of 66 Å mm^{-1} at $H\gamma$. The mean velocity was +17·5 km s^{-1} with a 'probable error' of 1·8 km s^{-1}; the average 'probable error' of individual plates was reported as 1·6 km s^{-1}. The velocities seem not to have been published individually and so cannot feature in Table I below. By far the earliest ones in Table I (though zero-weighted in the solution of the orbit of HR 978) are three that were obtained at Mount Wilson in the 1930s; R. E. Wilson[4], writing in 1950, noted the existence then of *five* such velocities, but when Abt[5] so public-spiritedly went through the Mount Wilson files and in 1970 published the velocities that had been determined there but had not been accessible to the astronomical public up till then, he found only the three that now appear at the head of Table I.

A contribution to the problem of HR 978 — or (terminologically more exactly) to its solution — came from a fresh direction in 1986, when Beavers & Eitter published[6] in the *ApJ Supplements* a list of 18 radial velocities obtained in 1977–83 with their photoelectric spectrometer at the coudé focus of the 24-inch *Mather* reflector at the Fick Observatory in Ames, Idaho. The observations were graded A, B, or C at source, and are so annotated in the *Velocity* column in Table 1; in the solution of the orbit here they have been given a global weighting of 0·1, multiplied by the (Fick-specified) factors of 1, 0·5, and 0·2 for qualities A, B, and C, respectively. They have an overall duration of rather more than two cycles of the orbit of the star, but their distribution in phase is none too satisfactory, and it is doubtful whether a claim could properly be made that the orbit is really determinable from them alone. An effort to use them in a straightforward solution of the orbit, however — started from elements approximating to those that we now know the star to have — yields a period of 1080 ± 9 days, which is extraordinarily close to the value (1079·9 ± 0·8 days) finally determined below; but some of the other elements ($K = 9 \pm 5$ km s^{-1} and $e = 0{\cdot}44 \pm 0{\cdot}22$) hardly inspire great confidence.

The star was placed on the Cambridge observing programme in 1993, when for a time there was no operational spectrometer at the home site, and the writer is much indebted to Dr. M. Mayor for the use of the latter's *Coravel*

TABLE I

Radial-velocity observations of HR 978

Date (UT)	*MJD*	*Velocity* *km s⁻¹*	*Phase*	*(O – C)* *km s⁻¹*
1934 Dec. 18·24*	27789·24	+23·8	$\overline{14}$·388	+5·2
1935 Dec. 5·30*	28141·30	28·0	$\overline{14}$·714	+4·9
1937 Jan. 27·13*	28560·13	15·7	$\overline{13}$·102	+1·2
1977 Jan. 2·14	43145·14	21·1B	0·608	−1·5
Sept. 26·42	412·42	21·4B	·855	+0·3
1978 Jan. 11·14	43519·14	19·9B	0·954	+1·9
25·08	533·08	15·9A	·967	−1·7
Oct. 10·32	791·32	13·1A	1·206	−1·8
Nov. 8·26	820·26	15·7A	·233	+0·4
1980 Oct. 5·31	44517·31	21·7B	1·878	+1·2
Nov. 22·23	565·23	19·6A	·923	+0·5
Dec. 19·18	592·18	16·4A	·947	−1·8
31·12	604·12	16·4A	·959	−1·4
1981 Dec. 29·16	44967·16	15·9B	2·295	−0·6
1982 Jan. 26·09	44995·09	18·2C	2·321	+1·1
Feb. 2·09	45002·09	18·5B	·327	+1·3
Nov. 18·25	291·25	23·7A	·595	+1·2
Dec. 17·19	320·19	25·4B	·622	+2·6
1983 Oct. 28·31	45635·31	21·5B	2·913	+2·1
Nov. 18·27	656·27	19·4B	·933	+0·7
21·23	659·23	19·4A	·936	+0·8
1984 Nov. 9·00†	46013·01	15·9	3·263	0·0
11·07†	015·07	15·9	·265	0·0
Dec. 11·86‡	045·87	17·6	·294	+1·1
1985 Aug. 24·11†	46301·11	21·1	3·530	−0·5
Sept. 26·07†	334·07	22·1	·561	+0·1
1987 Nov. 17·07‡	47116·07	16·5	4·285	+0·2
1988 Oct. 25·07†	47459·07	22·7	4·602	+0·1
31·00†	465·00	22·6	·608	0·0
1989 Dec. 11·91†	47871·91	17·0	4·985	0·0
1990 Aug. 30·10†	48133·10	15·3	5·226	+0·1
1991 Jan. 5·86†	48261·86	17·7	5·346	0·0
1992 Dec. 10·06†	48966·06	16·4	5·998	−0·1
1993 Feb. 18·89§	49036·89	15·1	6·063	+0·2
Mar. 22·78§	068·78	14·6	·093	+0·1
Nov. 4·24‡	295·24	16·7	·303	0·0
25·96†	316·96	17·4	·323	+0·3
Dec. 26·90†	347·90	17·3	·351	−0·5
1994 Jan. 9·80§	49361·80	18·1	6·364	0·0
Feb. 15·81§	398·81	+19·1	·398	+0·2

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TABLE I (*continued*)

Date (UT)		*MJD*	*Velocity* *km s⁻¹*	*Phase*	*(O–C)* *km s⁻¹*
1994	July 31·15§	49564·15	+22·2	6·552	+0·3
	Dec. 10·93§	696·93	23·3	·675	+0·2
1995	Jan. 1·86§	49718·86	23·4	6·695	+0·3
	Dec. 31·72§	50082·72	16·0	7·032	+0·4
1996	Feb. 13·82†	50126·83	14·3	7·073	−0·5
	Mar. 30·81§	172·81	14·5	·115	+0·1
	Nov. 20·98	407·98	16·4	·333	−1·0
	Dec. 1·94†	418·94	17·9	·343	+0·3
1997	Jan. 26·82§	50474·82	19·3	7·395	+0·5
	Feb. 2·82†	481·82	19·0	·401	+0·1
	Mar. 6·82	513·82	20·3	·431	+0·7
	July 22·13§	651·13	21·4	·558	−0·6
	Sept. 11·01§	702·01	22·3	·605	−0·3
	Oct. 19·11†	740·11	22·9	·641	0·0
	Dec. 20·90§	802·90	23·5	·699	+0·4
1998	Jan. 20·81†	50833·81	22·7	7·727	−0·4
	July 11·12§	51005·12	20·5	·886	+0·2
	Oct. 21·03†	107·03	16·9	·980	−0·2
1999	Dec. 28·91	51540·91	18·0	8·382	−0·5
2000	Jan. 17·79	51560·79	19·6	8·401	+0·7
	Feb. 25·78	599·78	19·9	·437	+0·2
	Aug. 29·13	785·13	22·6	·608	0·0
	Sept. 21·11	808·11	22·7	·630	−0·1
	Oct. 17·09	834·09	23·0	·654	0·0
	Nov. 14·04	862·04	22·8	·679	−0·3
	Dec. 9·97	887·97	23·4	·703	+0·3
2001	Jan. 7·90	51916·90	23·0	8·730	−0·1
	Feb. 14·82	954·82	23·1	·765	+0·3
	Oct. 4·12	52186·12	17·0	·980	−0·1
	Nov. 1·03	214·03	15·9	9·005	−0·4
	Dec. 22·00	265·00	15·5	·053	+0·4
2002	Jan. 17·88	52291·88	14·8	9·077	+0·1
	Feb. 14·78	319·78	14·6	·103	+0·1
	Mar. 7·84	340·84	14·7	·123	+0·3
	Sept. 2·16	519·16	16·3	·288	−0·1
	Oct. 4·11	551·11	16·8	·318	−0·2
	Nov. 11·01	589·01	17·9	·353	+0·1
2003	Jan. 11·93	52650·93	19·1	9·410	0·0
	Feb. 19·86	689·86	19·8	·446	−0·1
	Mar. 15·87	713·87	20·7	·468	+0·3
	Apr. 6·81	735·81	20·9	·489	+0·1
	Aug. 30·18	881·18	22·5	·623	−0·3
	Sept. 20·11	902·11	22·9	·643	0·0
	Oct. 18·10	930·10	23·1	·668	0·0
	Nov. 13·04	956·04	23·3	·693	+0·2
	Dec. 12·01	985·01	23·1	·719	0·0
2004	Jan. 29·86	53033·86	22·9	9·765	+0·1
	Mar. 30·81	094·81	21·7	·821	−0·2
	Aug. 20·16	237·16	18·2	·953	+0·2
	Sept. 26·16	274·16	16·6	·987	−0·3
	Oct. 22·12	300·12	+16·5	10·011	+0·3

TABLE I (*concluded*)

Date (UT)	*MJD*	*Velocity* *km s⁻¹*	*Phase*	*(O – C)* *km s⁻¹*
2004 Nov. 26·95	53335·95	+15·4	10·044	+0·1
Dec. 17·92	356·92	14·7	·064	–0·2
2005 Mar. 17·85	53446·85	13·7	10·147	–0·7
Apr. 6·81	466·81	14·2	·165	–0·3
Sept. 28·16	641·16	17·1	·327	–0·1
Nov. 29·96	703·96	18·4	·385	–0·2
2006 Apr. 1·80	53826·80	20·8	10·499	–0·2
2007 Feb. 6·86	54137·86	22·5	10·787	0·0
26·85	157·85	22·5	·805	+0·3
Apr. 1·82	191·82	21·7	·837	+0·1
July 27·12	308·12	18·4	·945	+0·1
2008 Feb. 26·81	54522·81	14·7	11·143	+0·3
Apr. 10·80	566·80	14·8	·184	+0·2
Nov. 26·03	796·03	18·9	·396	+0·1
2009 Dec. 6·94	55171·94	22·8	11·744	–0·2
2013 Apr. 2·81	56384·81	20·4	12·868	–0·4
2017 Jan. 9·94	57762·94	+14·5	14·144	+0·1

*Young[3]; weight 0
1977–1983: Fick observation[6]; see text
† Observed by others with OHP *Coravel*; wt. 1
‡ Observed with ESO *Coravel*; weight 0
§ Observed by RFG with OHP *Coravel*; wt. 1
No annotation: Cambridge *Coravel*; wt. 1

spectrometer at Haute-Provence. The writer's 16 observations with that instrument are supplemented by 17 that were made with it by others in 1984–1998 and were very kindly forwarded by Dr. Mayor. Two others were obtained with the ESO *Coravel* (one of them by the writer); the *other* one gave a residual greater than 1 km s^{-1} — uncharacteristically bad for a *Coravel* observation — so both the ESO data have been zero-weighted in the solution below of the orbit of HR 978.

Starting in 1999, a new *Coravel* spectrometer has been routinely operating at Cambridge; the writer has made 50 observations of HR 978 with it, in addition to two that were obtained (one in 1996 and one in 1997) during an experimental phase before it was in continuous use. The velocities obtained with the *Coravel* spectrometers at Cambridge and Haute-Provence have been accorded full (unit) weight in the solution of the orbit, but (having been reduced by different people and in different manners) the initially-obtained velocities have needed zero-point adjustments of –0·5 and +0·8 km s^{-1}, respectively, in the solution of the orbit. The correction to the Haute-Provence data is the same as has been found appropriate in previous papers in this series.

The final results of the considerable efforts that have been made in different places to elucidate the nature of HR 978 are to be seen in the informal table of orbital elements here, and in the diagram of the corresponding velocity curve that appears as Fig. 1.

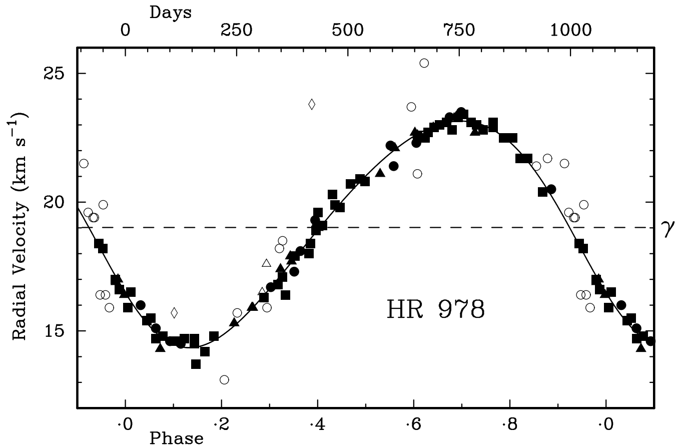

FIG. 1

The earliest radial-velocity measurements were made at Mt. Wilson and belatedly published by Abt[5]. There are two of them plotted as open diamonds; a third one is not plotted, as it falls off the top of the diagram. All three were attributed weight zero in the solution of the orbit. Next, there are 18 velocities published by Beavers & Eitter[6] from Ames and plotted as open circles; they were given weights of 0·1 multiplied by factors of 1, 0·5, or 0·2 according to whether their authors graded them A, B, or C. From 1984 to 1998 nearly all the data came from the Haute-Provence *Coravel*. Those from 1993 onwards were made by the present writer on a guest-investigator basis through the kindness of the owner of the instrument, Dr. Mayor, and are plotted as filled triangles; the earlier ones, starting in 1984 and plotted as filled circles, were made by other observers and helpfully forwarded by Dr. Mayor for the benefit of this paper. Two measurements made by the writer with the ESO *Coravel*, but rejected in the solution of the orbit, are plotted as open triangles. From 1999 onwards all the observations have been made by the writer with the Cambridge *Coravel* and are plotted as filled squares.

P	=	1079·9 ± 0·8 days	$(T)_8$	=	MJD 54809 ± 9
γ	=	+19·02 ± 0·04 km s^{-1}	$a_1 \sin i$	=	64·9 ± 0·7 Gm
K	=	4·40 ± 0·05 km s^{-1}	$f(m)$	=	0·00936 ± 0·00032 $M_\odot$
e	=	0·119 ± 0·012			
ω	=	121 ± 6 degrees	R.m.s residual (wt. 1) = 0·30 km s^{-1}		

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CORRESPONDENCE

To the Editors of 'The Observatory'

On Deciding if One R.M.S. Error is Significantly Larger than Another

In a recent article[1], Griffin notes that in the double-lined binary HD 63107 one star has a larger r.m.s. error in its results than the other but finds no obvious reason for this. A standard statistical test, the F test[2], suggests that this difference is not significant, so it can be dismissed as a random statistical fluctuation.

Let the r.m.s. errors be σ and τ, with $\tau > \sigma$, and calculate $F = \tau^2/\sigma^2$.

It is necessary to find the number of degrees of freedom in the numerator and denominator, which is the number of observations less the number of *independent* parameters that have been estimated. In this case, the number is the same for numerator and denominator, namely 33 less P, γ, K, e, ω, T, and $a \sin i$, or 26. In other cases, there may be fewer observations of the secondary than of the primary.

For 26 and 26 degrees of freedom, the 5% point of the F distribution is 1·93.[3] With the rounded published values, $\tau = 0{\cdot}35$, $\sigma = 0{\cdot}26$, $F = 1{\cdot}81 < 1{\cdot}93$, so the hypothesis that $\tau > \sigma$ is not supported at a significance level of 5%. It would, however, be advisable to recalculate F using the exact values of σ and τ in case that makes a difference.

Yours faithfully,
LISA BUDD

Email: Lisa.Budd@gmail.com

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(3) Enter =F.INV.RT(0·05,26,26) into a spreadsheet.

The Big Bang: Who Really First Suggested It?

Steuart Campbell[1] suggests that Edgar Allan Poe should be credited with the idea of the Big Bang. While it is now generally well known that Poe was the first to explain Olbers' paradox correctly, that is technically different from his Big Bang theory, despite the impressive list of similarities with modern cosmology which Campbell lists. (Campbell also admits that Poe's intuitive concept is a bit vague.) The main difference is that Poe's explanation of Olbers' paradox is identical to the modern one, while his cosmology, though strikingly similar in many respects, is more speculation than science, although it turned out to be at least superficially right. As Campbell notes, Friedmann was the first to discuss something like an initial singularity in a scientific context, and Lemaître the first to speculate about the physics of the early Universe. So, depending on the definition of Big Bang, the honour should go to Friedmann or Lemaître, at least in a scientific context. (Broadening the definition can push the limit back even farther, though it is a stretch to equate the Bible's "Let there be light" with the epoch of recombination or even with the Big Bang itself.)

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Reference

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The Speed of Gravity in the Lights of LIGO and Mercury

Most of the fun in these things lies in doing the arithmetic for yourself and deciding whether the answer feels likely. The *LIGO*–gamma-ray event of 2017 August 17 is the best opportunity since we all pulled out our envelope backs to see what we could estimate from the arrival times of the neutrinos from SN 1987A. Oh? You were in kindergarten in 1987? Never mind. The Appendix lets you pretend you were there then.

The LIGO result

Let's start with *LIGO*, both because it's easier than Mercury and because the official numbers were just published in 2017[1,2], making them easy to find. If a source emits both photons and gravitational waves, which travel at speeds c and v_g for a distance d, the difference in arrival times will be t, given by

$$t = d/v_g - d/c. \qquad (1)$$

The *Fermi* satellite photons lagged the *LIGO* event by 1·7 seconds, and the best estimate of the distance was 40 Mpc. Equation (1) then gives you … . Go on, do it! We all found v_g smaller than c by 4·25 parts in 10^{-16}, if the photons and the waves left the source at the same time.

The *LIGO* folks[1,2] allowed for the source possibly being as close as 26 Mpc and the electromagnetic and gravitational waves leaving the source at slightly different times, to conclude that

$$c - v_g = (-5 \times 10^{-15} \text{ to } +7 \times 10^{-16})\ c. \qquad (2)$$

There is a corresponding limit on the mass of the graviton that comes from a relativistic particle having a total energy, E, given by

$$E = mc^2 / (1 - v^2/c^2)^{1/2}. \qquad (3)$$

Now, you already have the limit on v, so all you need is the energy, E. Well, gravitons are also waves, for which

$$E = hf \qquad (4)$$

and the measured frequencies, f, were in the range 50–400 Hz. Carry on to get something like

$$m \leq 1{\cdot}2 \times 10^{-22}\ \text{eV}/c^2 \approx 2 \times 10^{-54}\ \text{grams}. \qquad (5)$$

Is this the smallest mass we have ever seen? It is not. Fritz Zwicky[3] claimed that the range of the gravitational force is only about 10 Mpc, because there is no clustering of clusters of galaxies. I heard him say it in a seminar talk at Caltech before I had ever heard of the Yukawa argument for the mass of a particle carrying the nuclear force (a prediction of mesons of some sort as then understood)*.

Now use a form of the Heisenberg uncertainty principle

$$\Delta E\ \Delta t \geq h/2\pi \qquad (6)$$

and require that Δt be long enough for the particle to travel a distance of 10 Mpc to discover that if $E = mc^2$ then

$$m \leq 10^{-63} \text{ grams.} \qquad (7)$$

This was an actual value for Zwicky[3,4], but a limit if you think there is a second-order clustering of galaxies. Others claimed to find super-clustering in the Zwicky catalogues, including Igor Karachentsev[5] and Emil Herzog. The latter said so at a Caltech colloquium in about 1966 with Zwicky in the audience. Herzog was offered 'political asylum' at UCLA by George Abell, whose catalogues[6] definitely show super-clustering.

I think the *LIGO* graviton mass has to be very much an upper limit, or the range of the gravitational force would be something like 4000 AU, and the Oort Cloud would be well on its way out of the Milky Way, which would be well on its way to … oh, never mind.

Now about Mercury

Why Mercury? Because a number of commentators have commented that the *LIGO* result for the pair of merging neutron stars[1] was the first quantitative determination of the speed of gravity[7]. But my husband told me in the mid-1970s that we know that speed to be the same as the speed of light to 5% or so because of the Mercuric … Mercurial … Mercurian perihelion advance†.

LIGO and, I think, most of the arguments in ref. 7 concern Special Relativistic contexts. But back in 1905, in the lead-up to what eventually became General Relativity, Henri Poincaré wrote[8], " … *la propagation de la gravitation n'est pas instante, mait se fait avec la vitesse de la lumière*."

If all one has met is the Schwarzschild solution, one might reasonably suppose that deviations from Newtonian results would be of order $2GM/Rc^2$. Start by evaluating this at the distance from the Sun to Mercury (0·387 AU semi-major axis). Convert from radians to arcsec by multiplying by 206 265 (a number

* Cecil Powell won the 1950 Nobel Prize in Physics for finding the right sort of meson. Even Powell felt badly enough about the omission of Giuseppe Occhialini from that prize to nominate him two years later. Two women named Marietta, Blau and Kurz, are also part of that story.

† Is this the sort of thing on which to take one's husband's word? Well, mine was Joseph Weber and typically reliable in such matters. Truthfully, I only 'did the numbers' for myself a few weeks ago as part of trying to find a few calculations that could be done approximately by undergraduate non-physics students in a seminar on 'The Impact of World War I on the Sciences'. If you have never taught such a course, you may not share my worry "Are we who perhaps had our last history courses in secondary school as far away from 21st-Century historical research as these students are from 20th- or 21st-Century physics, given that they had their last, and probably only, physics course in secondary school?"

written upon my heart, like Calais on Mary Tudor's) per 0·24-year orbit period (about 0″·01 at this point). There are some 420 periods in a century, leading to about 4″·3 per century. Are we off by a power of 10? Well, only sort of.

The time has come to abandon simple approximations and let Jim Hartle[9] do the integration along the path of Mercury correctly. There are several integrals. One looks like a mess but always comes out 2π. Another really is a mess, but the outcome is

$$\Delta\varphi = 6\pi GM/c^2 a(1-e^2) \text{ per orbit.} \quad (8)$$

Keep in mind that *GM* is much better known than either separately and that the path is an ellipse of eccentricity *e* or there wouldn't be a perihelion to advance. We get 42″·98 per century as the relativistic prediction.

What do the observations say? The perihelion advance from a perfectly closed orbit is some 5599″ per century. Most of this is our own fault for living on a non-inertial coordinate system called Earth, whose own rotation axis and therefore its celestial coordinates rotate or precess with a period of about 26 000 years. Get rid of that (about 5025″ per century), and there are still some 574″ per century not accounted for. At this point, Hartle hands us over to Irwin Shapiro, a connoisseur of Solar System tests of GR and owner of his very own Shapiro delay*. The potential felt by Mercury is not just the nearly-spherical one of the Sun. Venus and Earth count most, but also Jupiter. They introduce another 565″ per century[10], leaving a modern residual of 42″·98 per century[10], so close to the predicted number that you cannot insert even an anecdote between them.

The historical situation was not quite so tidy. Urbain J. J. Le Verrier was the first to collect enough good observations of the position of Mercury to attempt the full Newtonian fit to the four inner planets. He used both daytime meridian-crossing times and some solar transits of Mercury, announcing in 1859 a 38″ per century residual[11,12].

Our own Learned Astronomer, Simon Newcomb, who devoted a large part of his career to determining the most accurate possible parameters for the motions of the planets and satellites of the Solar System, confirmed the effect and gradually improved the value to about 43″ per century, the target Einstein had to shoot for. Thus he worried that his original *Entwurf*[13] theory of gravity accounted for only 17″ per century. It was also, he felt, inadequately Machian for rotating frames and did not provide unique field equations from a variational principle[14].

Gerald M. Clemence (1908–1974), Newcomb's eventual successor as director of the US Nautical Almanac Office, thought accurate ephemerides were important not only for navigation and prediction of eclipses, occultations, and such, but also to allow comparison of observations with theory, to improve astronomical constants and the actual theories of motion. Much of his work, like Newcomb's, is buried fairly deeply in USNO papers, but a version for the unwashed† appeared in 1947[15]. His numbers are 43″·03 per century for the relativistic prediction (remember this includes having to know the length of the

*Insert your own optional witticism about the relative probabilities of you and Shapiro being delayed in arrival for some event, given that you probably flew and he declines to.

† Other interesting tidbits in the paper include use of analysis by Jan Oort[16] and thanks to Jan Schilt and Martin Schwarzschild of Columbia, who were elsewhere described as "director and directee", being the only astronomers there at the time.

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AU and the speed of light, less precise then than now), or rather 43″·03±0″·03, and for the observed precession 42″·56±0″·94 per century. That 1″ out of 43″ in $(vc)^2$ is Joe's 5% in v_g compared to c. Shapiro's number allows you maybe 0·05% in c minus v_g.

Is this the final word (or number) on what we can expect from General Relativity? Not quite (and the issue was a live one around 1972). The Sun might, of his own accord, have a non-spherical potential, if, for instance, the inside were spinning much faster than the outside. Carl Brans and Robert Dicke[17] thought so at one time, as part of an effort to make gravitation still more Machian than the Einstein version. Expecting such oblateness, Dicke found it[18]. Others did not[19]. Dicke stuck to his oblate guns[20], but was eventually overruled[21]. The actual solar oblateness shows up as p-mode splitting in helioseismology studies at a level too small to drag Mercury away from the 42″·98.

So, in summary, the neutron-star-merger event has told us that gravitational waves travel at the speed of light to within a part in 10^{15} or so, Poincaré and Einstein knew the speeds had to be equal, and in between Mercury was telling us equal to within astronomical accuracy.

Yours faithfully,
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2018 August 11

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Appendix: The envelope back of 1987 February

"The first mark of supernovae might be high neutrino flux while the surface of the star has yet no sign of this sudden internal collapse." So wrote Hong-Yee Chiu (b. 1932, Shanghai, China) & Philip Morrison (1915–2005) in 1959[23].* They were proven correct on 1987 February 24 (in at least some time zones). It was SN 1987A not because of its enormous importance but because it was the first one spotted that year, and was indeed a naked-eye object for southern -hemisphere observers.

The neutrino flux was not as high as Chiu & Morrison had thought of — their reference SN was 30 parsecs away and would have showered us with 10^{13} neutrinos cm^{-2} s^{-1} for a few seconds, thus drowning out a solar flux of less than 10^{10} neutrinos cm^{-2} s^{-1}.

On that day in 1987 February, five devices existed capable of detecting MeV neutrinos that found their way to Earth. The most famous, Ray Davis' tank of C_2Cl_4, probably caught one, lost in the noise of a month's accumulation of solar-induced transformations of Cl^{37} to A^{37}. The other four all reported events. See ref. 22 for the details and a majority decision to consider only the Japanese (*Kamiokande*) and American (Irvine–Michigan–Brookhaven) counts.

The first person to do a careful calculation published it, but most of us got out our pencils and papers when all we had heard was that about 20 antineutrinos had been scattered in the IMB and Kamioka detectors (originally built to look for proton decay) over an interval of about 10 seconds, and that the energies were sort of 10 to 20 MeV.

The simplest calculation is the difference in arrival time between a photon and a neutrino of mass m over the distance to the LMC (55 kpc according to that expert Trimble[26], but 50 kpc was used by the neutrino folks). The photon and neutrino speeds are allowed to differ by at most a couple of parts in 10^{11}. (Check it!) And, following the same procedure,

$$mc^2 = E(1 - v^2/c^2)^{1/2}, \qquad (9)$$

the neutrino mass ends up as, at most, some tens of eV, less if you consider a time window around 2 seconds as having included half the neutrino arrival times.

*The paper was submitted on 1960 November 28 and appeared in the December 15 issue, suggesting that the editor thought it important. It was cited a good deal in the 1960s and 1970s, tapering off to the present. The two supernova-neutrino papers that remained longer in their colleagues' memories were those of George Gamow & M. Schoenberg[24] with "a neutrino theory of stellar collapse" meant seriously despite the April 1 date of publication, and of Colgate & White[25], whose 1961 detailed calculation of neutrino transport through dense gas was state of the art until neutrino physics changed.

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REVIEWS

F. G. W. Struve, by Zinaida Novokshanova-Sokolovskaia, 1964; translated with an explanatory note by Michael Meo, 2017. Pp. 388, 18 × 12 cm. (Self-published and available from the translator at 2925 N.E. Weidler St., Portland, OR 97232.)

Friedrich Georg Wilhelm (Vasili Yakovlevich) Struve (1793–1864) is the one who tied with Bessell and Henderson to measure the first stellar parallax, for which he is generally given less credit than Bessell but more than Henderson. The Russian original of this biography was written and published for the 100th anniversary of FGWS's death and 150th anniversary of his founding of the Poulkovo Observatory, which still exists (as Pulkovo), at least as an office address in St. Petersburg. There are nine other male Struves in the index (which is a very extensive one), of which five also appear in the 2nd edition of the *Biographical Encyclopedia of Astronomers*. He was the great-grandfather of the Otto Struve who was briefly the first director of the National Radio Astronomy Observatory. Author Sokolovskaia also wrote the F. G. W. Struve entry in the *Dictionary of Scientific Biography*, and the Russian edition of the present volume included a complete bibliography, though Meo lists only the papers that are actually mentioned in the text.

A couple of traits make the volume somewhat difficult reading. First, the author already had dozens of footnotes per chapter. These have been gathered at the ends of each chapter, while footnotes added by the translator (398 of them) are actually on page bottoms. Second, the index correctly refers to footnotes by number, but the text pages are typically off by one or two, and yes there are footnotes to the footnotes. Amounts of money from long ago and far away are always a puzzle. Struve was, for instance, given 500 gold pieces (*chernovets*) to travel for three months in Germany to purchase equipment for the observatory at Dorpat (Tartu), which he directed from 1820 to 1839 when he moved to take over the construction of Poulkovo. The amount alloted for those purchases was 2969 silver roubles. He persuaded the university also to acquire a 9-inch Fraunhofer refractor, briefly the largest in the world, soon bettered by a 15-inch for Pulkovo (and many others), which was largely used by his son and successor Otto Wilhelm, one of the 12 of FGW's 18 children (by two wives) to survive him, the youngest dying in 1917.

Interesting factoids abound. FGW did not become a Russian citizen until 1842. He was frequently addressed as "Citizen Struve" (and speaks of a student as "Citizen Preiss"). The class came between the nobility and the peasants (but with somewhat permeable border). Fans of *The Scarlet Pimpernel* inevitably think of the French revolutionary use of *citoyen*, and some of the documents and conversations mentioned in the book were in French, which remained a language of the Russian aristocracy down to the 1917 Revolution.

We astronomers naturally associate FGWS with catalogues of visual binary stars and such, but the observatories and observers of his time and place were also expected to be geodesists. Struve's particular contributions here included measurements of the length of a degree of latitude through Courland, Livonia, and Estonia (yes, the first have, or at least had, languages related to Latvian and Lithuanian; Estonian is delightfully unrelated to anything else you are likely to speak) and organization of an expedition to measure the difference in levels between the Black and Caspian Seas. (Remember the former is, tenuously, connected to the Seven Seas, the latter landlocked.)

The triangulation of Livonia employed a baseline 12·5 *versts* long, and I wish I had had this volume to hand when a visiting student from what was then the USSR was prepared to exercise violence in denying that the *verst* was an old Russian unit of length. (They had always used the metric system!!) The levelling device for the sea measurement was five toises long, and they requested 30 000 roubles to fund the project.

In summary, there is much to be learned from this volume, but it will help a good deal if you bring a fair amount of accumulated knowledge along. Alan Batten's *Resolute and Undertaking Characters: The Lives of Wilhelm and Otto Struve* (Reidel, 1988) would be a good place to start.

Conflict of interest statement: My copy of Struve was a gift from the translator, to whom hearty thanks, upon the advice of Kevin Krisciunas. — VIRGINIA TRIMBLE.

William E. Wilson (1851–1908): The Work and Family of a Westmeath Astronomer, by Ian Elliott & Charles Mollan (Charles Mollan), 2018. Pp. 184, 25 × 17·5 cm. Price £25/$35 (hardbound; ISBN 978 1 5272 1226 8).

This slim, scholarly volume is a tribute to more than just William E. Wilson: it commences with a chapter about his father, moves to short biographies of members of the family, and concludes with sketches about contemporary Irish astronomers or other scientists of note. The material has been carefully researched, and is accompanied by commendable reproductions of nearly 50 archived photographs and a dozen figures, constituting a pleasing, high-quality production. The subject of the title actually occupies less than half of the book; that is probably an accurate reflection, since equipment and instruments were only basic, 'astrophysics' had hardly commenced as a branch of the science, and most of what it contained was somewhat speculative. However, the members of his wider family, particularly the Edgeworths, also had leanings towards astronomy. The 19 contemporaries whose careers are outlined in the concluding section includes such worthies as Lord Kelvin, Laurence Parsons, Howard Grubb, Agnes Clerke, Robert Ball, George Minchin, Gabriel Stokes, John Tyndall, and Mary and William Huggins, all of whom have been honoured in some lasting way in their respective sub-fields of astronomy.

Wilson was a 'gentleman astronomer', inheriting wealth and status that rendered him free to indulge in his hobbies without needing to earn his way. As an amateur astronomer he certainly made his mark, being described as a man "of insatiable and original curiosity, considerable dexterity, confident of his ability and opinions, and with a need to be appreciated by those whom he admired". His inquisitive mind also settled on a wide range of other hobbies, becoming a strong advocate (for instance) for the "tricycle built for two". His rather short life coincided with the start of great advances in all the sciences, especially astronomy, when there seemed to be everything to discover but little equipment to aid even the most persistent observer. Wilson gloried in inventing neat devices, patenting several, and applying them in heroic attempts to investigate, *inter alia*, the surface temperature of the Sun and absolute stellar photometry. Though he did not obtain any academic qualifications, memberships of learned societies enabled him to publish in the top astronomical journals, and the fame which his research won led to the award of an honorary D.Sc. from Dublin University. The telling of those events is liberally sprinkled with anecdotes, both personal and professional, gently oiled with irresistible dashes of humour, and well seasoned with Irish pride.

The book was actually written by the second author; Elliott had unfortunately died before the large amount of materials that he had researched were transformed into a readable text, but Mollan was unwilling to let such research lapse without attempting the final steps which Elliott must have been near to commencing. It definitely deserves a place in every library of science history. — ELIZABETH GRIFFIN.

The Life of Arthur Stanley Eddington, by A. Vibert Douglas (independently republished, 2018). Pp. 306, 30 × 21 cm. Price £13·72 (paperback; ISBN 978 1 973 32074 6).

Sir Arthur Eddington, O.M., stood shoulder to shoulder with other greats in the scientific revolution of the early 20th Century (almost literally; there are stiffly posed photos of him in the company of William Bragg, Albert Einstein, Ernest Rutherford, Meghnad Saha, and Willem de Sitter, among others, reproduced in this book). As well as being a pioneer in the development of the quantitative understanding of stellar astrophysics, he is also — and perhaps more widely — remembered as an early exponent of General Relativity, and for his celebrated measurement of the gravitational deflection of starlight at the 1919 total solar eclipse. He was, additionally, one of the first scientists to write 'popular' science books for general readerships.

After his death in 1944, his sister, with whom he lived all his life, passed a number of letters and journals to his "intimate friend of forty years", C. J. A. Trimble*, who gathered further material, with the intention that he would write a "life of Sir Arthur from the more human or general point of view complementary to an appreciation by another hand of his scientific work"[1]. The 'another' was (Alice) Vibert Douglas, herself a minor celebrity in Canadian astrophysics†; in the event, the entire task fell to her, and the biography was finally published in 1956.

The newly republished edition is a slightly odd beast, available (only?) through Amazon, from an anonymous "independent publisher". It is not a reprint; my guess would be that someone has used OCR software to render the text machine-readable (as well as scanning the 15 plates in the original), and has used that to generate a new printed version. If so, then the process has been done rather carefully (I didn't find any typographical errors, and footnotes, Greek characters, italic text, *etc.*, seem all to be correctly represented). However, it's hardly a thing of beauty, printed in what appears to be 16-point Arial ('the go-to font for amateurs and thoughtless designers'); consequently, although the A4 acreage is ~1·7× that of the original, the text still requires ~1·5× as many pages. There are also some odd layout anomalies which look as though they've arisen through attempts to maintain the full-page 'plates' (now printed on ordinary stock) near their original locations in the text. Compared to the original, the new version has gained an opening portrait of Dr. Douglas, and her short essay on 'Forty Minutes with Einstein', but, sadly, has lost the index, and the listing of chapter page numbers in the contents page (presumably both

*It is a sign of past times that it required moderate effort to discover that Trimble's given name was 'Charles'. Virginia tells me there is no direct relationship.

†She served as president of the RASC, as the first Canadian president of the International Federation of University Women, and as the Canadian representative at the 1954 UNESCO conference in Montevideo. In 1967, she was named one of ten 'Women of the Century' by the Canadian National Council of Jewish Women.

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a consequence of the repagination, although the effort required to update the contents summary would've been minimal).

I refer the interested reader to the substantial reviews of the original publication by W. M. Smart[2] (who knew Eddington personally) and G. J. Whitrow[3] (who was taught mathematics by Trimble) for basic content and contemporary perspectives, but add the observation that Douglas studied under Eddington, and her treatment is at times almost reverential. Consequently, the exposition, while providing a reasonably thorough overview, is definitely of its time, and is not analytical or searching in the way that a modern-day biography might be. For example, the dedication to Trimble piqued a prurient curiosity on the nature of their relationship (Eddington never married), which is now unlikely ever to be addressed satisfactorily. And to read the Preface, one might imagine quite an avuncular figure — difficult to reconcile, at this distance, with the vigour of the intellectual debates that Eddington held with Chandrasekhar, Jeans, and Milne. I concur with Stanley[4]: this 60-year-old biography is "useful for the facts about major events in Eddington's life, but is far from comprehensive and not at all critical". And another salutary quotation, from Chandrasekhar: "Miss Douglas' biography of Eddington is full of mistakes; and she misuses some of the material I had given to Trimble who was to have written the biography but died before he had embarked on the project" (*cf.* ref. 5).

The historical perspective that this book provides is perhaps most valuable in reminding today's worker of the context in which Eddington set out on his research career: the basic composition of stars (dominated by hydrogen), the order of magnitude of relevant opacities, even the fundamental nature of stellar energy sources — all unknown. Anyone who has taught, or remembers taking, mid-level courses in stellar astrophysics will know who to blame for the Eddington limit, the Eddington approximation, and the Eddington standard model; seen in the light of what little was known before his work, Eddington's achievements are all the more remarkable. — IAN D. HOWARTH.

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Northern Star: J. S. Plaskett, by R. Peter Broughton (University of Toronto Press), 2018. Pp. 539, 23·5 × 16·5 cm. Price £50/Can$90 (hardbound; ISBN 978 1 4426 3017 8).

It was a little over 30 years ago, in a programme to exploit high-resolution data from *IUE* for the measurement of radial velocities of hot stars, that I first encountered that mysterious and massive object, HD 47129, which for many years held the heavy-weight title among stars. But the real saga of that object began almost a century ago with the first orbital determination by John Stanley Plaskett in 1922 using the new 72-inch telescope of the also-new Dominion Astrophysical Observatory in Victoria, British Columbia.

So, having 'met' Plaskett's Star back in 1987 (see, in these pages, **107**, 68), it was time to get acquainted with the man, and the opportunity has now arisen through this splendid biography by Peter Broughton. But it's not just the tale of a very influential, self-made astronomer but of the rise of astronomy, and particularly astrophysics, in Canada.

Starting with Plaskett's origins in an area of southern Ontario (with names strangely familiar to me — Oxford County, Woodstock, and Stratford) we follow his path through school and on to the University of Toronto where he developed the practical skills that would serve him well in his astronomical career. And then on to the Dominion Observatory in Ottawa, where he cultivated the assertive powers that would enable him to tackle the 'Establishment' for the benefit of astronomy (and of JSP!).

Astrophysics, rather than more traditional astronomy, was what drove Plaskett, and it was not long before he was campaigning for the wherewithal to push the frontiers of his research on the spectra (and especially radial velocities) of the O and B stars that marked out the spiral arms of the Milky Way. The creation of the DAO is covered here in detail and its exploitation by Plaskett, Harper, Pearce, Petrie, Beals, *et al.* show how it was punching above its weight in the 1920s and '30s. But Plaskett was not content simply to present his results quietly to the astronomical community — he was in constant touch with the media and a regular public speaker — all to the benefit of Canadian astronomy.

Indeed, Plaskett's legacy is covered nicely in this well-produced volume, and that, of course, includes his son, Harry, who became the Savilian Professor at Oxford. The first of the Appendices lists his many publications; copious Notes follow — 90 pages of them — and a comprehensive Index concludes the book. A number of monochrome photos help bring the story to life. I found not a single typo, but strangely, on page 227, the plot of Plaskett's Star's radial velocities and orbital curve from *PDAO*, **2**, 157, is dated at 1924 whereas I found it to be 1922. — DAVID STICKLAND.

The Invention of Science: A New History of the Scientific Revolution, by David Wootton (Harper), 2015. Pp. 768, 22·5 × 14·5 cm. Price $35 (about £26) (hardbound; ISBN 978 0 06 175952 9).

There was a Scientific Revolution*, and this is an absolutely fascinating book about it. It is, what is more, our book, for author David calls Tycho Brahe's nova stella of 1572 the first crucial scientific discovery. And the invention of modern science was complete when Newton published his *Opticks* in 1704, pointing out that white light is made of all the colours of the rainbow. The first discovery was that of America (yes, the 1492 one, with argument permitted on whether it was made by Columbus or the watchman atop the mast who first saw land). Astronomy was the first science after 1572 because it had a research programme, a community of experts, and was prepared to question every long-established certainty.

In between come all our old friends, Galileo and Kepler, Torricelli with his barometer, a few thermometers, van Leeuwenhoek and Hooke with their microscopes (but not so much of them, and the reason is explained), and Gilbert on the Earth's magnetism. But the (glorious, and this is not an expensive volume) colour plates include four annunciations (three to Mary, one to Anne), illustrating the development of painting. Next door in the text is double-entry book-keeping, found at least as far back as the 13th Century, which in its glory required three sets of books, all honest.

My QWERTY typewriter appears on p. 520, along with geocentrism

*A deliberate rewrite of Steven Shapin's *The Scientific Revolution* (University of Chicago Press, 1996) which begins by saying "There was no scientific revolution, and this is a book about it."

for the Catholic church after 1611, as examples of economic or institutional investment in a bad solution that allows it to persist, along with very many other topics whose relationship to science and revolution require some thought. Wootton has obviously given these a great deal of thought, along with just about everything else you might conceive as belonging to the story. So much of the book focusses on the invention of new words and changes in word meaning that go with the development of science that I expected to be able to find somewhere the dictum that the first step in learning is to call things by their right names. Aristotle, perhaps, but not Wootten-indexed Aristotle anyhow.

Again this is a fascinating book, to which no review can do justice, though this review is late by *The Observatory*'s standards (not by history-of-science standards) because I discovered *Invention* in a review in *American Journal of Physics* written by Dennis Danielson (whose own books are a delight to read), said to myself "Anything Dennis likes must be worth reading", bought it, and immediately succumbed.

Yes, the format of footnotes and citations (not even on separate lines) is annoying, but *per aspera ad astra*. — VIRGINIA TRIMBLE.

Universe in Creation: a New Understanding of the Big Bang and the Emergence of Life, by Roy R. Gould (Harvard University Press), 2018. Pp. 277, 20·5 × 14 cm. Price £17·95/$24·95 (paperback; ISBN 978 0 674 97607 8).

I found this 'popular' book very difficult to review and the result is that I didn't much like it, although others may. Part of the problem may well lie in the obviously very different views on the parts of author and reviewer of the logical and philosophical issues raised by current cosmology, but it seems to this reader that the book promises 'Life, the Universe and Everything', while delivering something well short of those rather immodest claims.

The book's theme is the question, attributed here to J. A. Wheeler although surely going back to well before his time, of whether the laws of nature are 'written', somehow, in such fashion as to make the appearance of sentient life in the Universe somewhere, sometime, inevitable. The trouble with such a question is that it is far from self-evident either that it can be stated with sufficient precision to make it a fit subject for rigorous inquiry, or, that having done so, it is in principle answerable: such fundamental logical and philosophical doubts are not significantly addressed in the book under review.

The exposition is divided into three sections: Part 1 on the creation and expansion of the Universe, its description by General Relativity, and the Big Bang; Part 2 on the spontaneous appearance of structure in the physical world; and Part 3 on the question of whether the origin of life was merely a chance event. It will therefore immediately occur to some readers at least that the book inhabits much the same realms of discourse as the influential works of Barrow & Tipler[1] and of Ward & Brownlee[2], so it is decidedly disquieting to find that these are both dismissed with but a single passing reference each, the first in note 5 to page 89 and the second not until three-quarters of the way through the present book, in note 17 to p. 184. That disquiet is not allayed by finding no mention of the 'Rare Earth' hypothesis, or even of 'SETI', in the relevant Chapter 16, 'Who's There?'.

Minor irritations occur throughout the book, including overuse of exclamation marks and meaningless phrases such as "nearly infinite" (pp. 89, 164, 178, 259)

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and [How could] "the universe know" (p. 11 & elsewhere). It would take up too much space here to address all the more-major bones of contention, so a representative selection must suffice. The history of early attempts to find the AU given on pp. 20 *et seq.* is seriously in error: Copernicus, in Book 5 of the *De Revolutionibus* of 1543, already had the proportions of the planetary orbits correct to within 4% at worst and mostly far better, so such knowledge did not have to wait for the time of Halley, nor was he the first to instigate a successful determination of the scale of the whole system; the first such parallax measurement was that of Cassini I and Richer at the 1672 opposition of Mars nearly a century before the famous 18th-Century transits, and they came within 8% of the true value. Nor is it the case, as asserted here on pp. 56–7, that it was Karl Schwarzschild, rather than the author of General Relativity, who was the first to calculate the precession of the orbit of Mercury in the new theory. The story of how Einstein's successful solving of this problem on 1915 November 18 paralysed him with euphoria for the next three days and gave the final prompt for his presentation of the full field equations of GR to the Prussian Academy just a week later[3] is one of the most famous in the history of the subject and too well-attested to brook such revisionist denial. Schwarzschild did not write the crucial letter to Einstein until December 22.

More serious are some basic points of scientific principle. While there may or may not be something in the author's much-vaunted "new understanding of the Big Bang", involving the Universe "expanding inwards" — presumably just a rather whacky 'take' on metric expansion, although too little explanation is given here to be sure (pp. 60–64) — the exposition does not inspire confidence in his grasp of the subject. For instance, on p. 62 we find M 51, 'The Whirlpool', being cited as the illustrative case of Hubble's Law…Oh dear… To see just how nonsensical this is, compare M 51's radial velocity of 461 km/sec with those of the brighter individual galaxies of the Virgo Cluster, which range from –280 to +1545 km/sec: even in an expanding universe there is such a thing as peculiar motion — don't they teach that in 'Cosmology 101'? And that is not all, as hinted before, to speak only of the astronomy and cosmology in the book.

Finally, the biological dimension. Chapter 12 is the crux of the argument regarding the origin of life and the probability of that event, but it seems to this reader to be laced with hand-waving and non-sequiturs, and not at all to address the fundamental question raised in its first paragraph: given only the operation of blind chance, how could anything as complex as RNA ever have originated from pre-biotic chemistry? The reviewer's final rough note on finishing the book was "So where does that get us? Where is the 'New Understanding' promised in the subtitle?" It fails to convince. — CHRISTOPHER TAYLOR.

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Signatures of the Artist: The Vital Imperfections that Make our Universe Habitable, by Steven E. Vigdor (Oxford University Press), 2018. Pp. 345, 22·5 × 15 cm. Price £25 (hardbound; ISBN 978 0 19 881482 5).

Curiosity knows no bounds, particularly when it concerns our world, our Universe, our origins, or our uniqueness. It inspired the authors of the

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book of *Genesis*, and — several thousand years later — it drives SETI, wins funding for colossal particle accelerators, and supports many researchers, not just in theoretical and observational cosmology but also in particle physics and molecular biology. Whether or not it actually matters to us in practice — whether it makes any difference to how we conduct our lives and our world — we still want to know. And even if we can in fact never know, we still want to go on trying to find out. This book puts all that into factual perspective.

Vigdor's main goal — and which he achieves extremely well — is to present us with a fair, unbiassed assessment of the boundaries that science has now reached, and to discuss the probabilities involved, from three fundamental approaches: how particle physics determined the immediate conditions and next steps of the infant Universe after some Big Bang launched it, how cosmology addressed its adolescence of expansion (or contraction) and whether it had a multitude of siblings, and how generations of life-bearing matter could arise from non-living chemicals. All of that seems amazing when set in context and balanced against the many odds, yet what seems most amazing of all is that, despite the evident universal perfections and interdependencies of Mother Nature, it was the *a*symmetries, the *im*perfections, the slips, the violations of hard and fast laws, that were necessary for the Universe *as we know it* to have evolved and to have enabled the creation of life *as we know it*. Those minuscule lapses, or chance fragments, constitute the 'signatures of the Artist' from which the book's title is drawn.

All this Vigdor does from an authoritative background of direct or indirect involvement in much of the experimental work whose results he describes, and from extensive discussions with colleagues in associated fields. In order to approach the subject from a perspective that is broader than the individual fields and thus more accessible to the experience of the non-specialist reader, he balances the topics with a mastery stemming from wide-ranging discussions and very intensive reading: the bibliography lists 374 papers, books, reports, or websites.

Vigdor does not offer suggestions as to the identity or multiplicity of the 'Artist', nor of 'Why' any of the catastrophic events happened; those are the province of less unbiassed thinkers, and would have destroyed the credibility of the purely scientific evidence that he presents. Creationists get mentioned, but so do Fred Hoyle, religion (with a small 'r'), and Richard Dawkins, duly overshadowed by references to Albert Einstein and to the achievements of many other Nobel Laureates. The book is superbly well written, tastefully flavoured with humour and humility, and disarmingly honest. His parting shot is that, whatever our preference as to the identity of the Artist, we must update it to accommodate evolving facts. Sound advice, especially for the younger generation who believe that problems were only recognized yesterday and that tomorrow theirs will be the unfalsifiable solutions. This book should be listed as curriculum reading for students in all the fields mentioned, and featured in all departmental and general-science libraries. — ELIZABETH GRIFFIN.

The Great Silence: The Science and Philosophy of Fermi's Paradox, by Milan M. Ćirković (Oxford University Press), 2018. Pp. 395, 24 × 16·5 cm. Price £25 (hardbound; ISBN 978 0 19 964630 2).

Fermi's paradox dates from 1950, when the great physicist Enrico Fermi asked during lunch with his colleagues at Los Alamos National Laboratory: "Where is everybody?". The paradox arising from this existential question centres on the logical contrast between the high *ex ante* probability of intelligent life elsewhere, and the dumb lifeless Universe we observe. In the summer of 1950, the United States experienced a torrent of UFO sightings, and human spaceflight still lay 11 years in the future. Fred Hoyle, who was visiting Los Alamos at that time and knew Fermi, took this question very seriously. Given the past temporal infinity of the Steady State universe, he asked why we do not perceive traces of arbitrarily old extraterrestrial civilizations. He speculated that civilizations persisting for arbitrarily long times became indistinguishable from their environment.

Milan Ćirković has provided us with an intriguing philosophical analysis of the paradox. His philosophical enquiry into the foundations of astrobiology and the search for extraterrestrial intelligence (SETI) is a reality check on the many assumptions that are necessary in any explorations of the multi-dimensional parameter space defined by the Drake equation. The opening chapter formulates the problem, and Chapter 2 gives its astrophysical background. In the chapter that follows, Ćirković sets out his take on the philosophical background, which leads him to the conclusion that the Drake equation is no more than a mathematical distraction that diverts attention away from the lack of any real theoretical foundation for the SETI industry. Instead of a real theory, the Drake equation is "a fig leaf … which is constraining and impractical." On page 98 Ćirković calls for "…ritual invocation of the Drake equation to stop." To that end, in the next 200 pages, readers will find thorough discussions of many explanatory hypotheses that have been offered as solutions to the paradox. Western philosophy is about the development of thinking styles, which leads the author to introduce a four-fold taxonomy for classifying the protagonists and their solutions. These classifications are: solipsist solutions (the Universe is uncertain and possibly an illusion); 'Rare Earth' solutions (we are unique); neocatastrophism (they existed but got destroyed); and logistic solutions (impossible to maintain an expanding advanced civilization without exhausting resources). Overall, this is a delightful and thought-provoking book that cleared my mind of clutter and confusion concerning Fermi's Paradox and the Drake equation. — SIMON MITTON.

At Least Know This: Essential Science to Enhance Your Life, by Guy P. Harrison (Prometheus), 2018. Pp. 416, 22·5 × 15 cm. Price $19 (about £13) (paperback; ISBN 978 1 63388 405 2).

I think it was the science-fiction writer Kurt Vonnegut who said something along the lines of "the purpose of people is to convert sunlight into human babies". Presumably the purpose of knowledge is to help us in this endeavour. Guy Harrison wants us to know things — 'Essential Science' — for our own good "to enhance our lives". He is quite consistent in this as each new piece of 'essential science' is accompanied by an example of how one's life may be enhanced. Sometimes it is simply that awe in the face of the astonishing Universe will make you feel good — "to ignite feelings of empowerment"; sometimes it is a little more practical — physical exercise will do many good things for your body.

In his introduction Harrison asks "What might happen if every politician and CEO knew that an overwhelming majority of life in Earth today has not even been identified or named much less studied?". Which of us believes that anything significant would happen? Would the out-sourced privatized building inspectors still pass as safe, flammable tower-block cladding; would CEOs not try to drive down labour costs by any marginally legal means possible; would governments of the major powers recognize that threatening mass suicide by nuclear annihilation does not make the world safer? These are clearly things that are worth knowing and that may well enhance or even save your life; as a tower-block tenant, a worker for a multi-national company, or simply a citizen of the World — but Harrison is not about to tell you any of those things. His subtitle sets the limits of this work — Harrison wants to tell you only about the sort of science that will enhance your life — and, like running, maybe it will. He is not going to tell you about the soaring majesty of a powerful orchestral work, or the deep 'in-your-guts' emotional grip of rock music; he will not illuminate the spiritual strangeness of poetry or the weird compelling beauty of abstract art. But are you completely human without all of that artistic cultural stuff? Harrison does in fact address what it means to be human in his chapter 'Who are we', but mostly from the point of view of evolution.

He lays out his stall in terms of the six basic questions that a journalist may be expected to answer when reporting a news event: Who, What, Why, When, Where, and How. He doesn't reply with an equal distribution of answers: 'Who' gets the single chapter on human evolution mentioned above; 'What' gets two chapters; and, as befits the author's mission to explain, 'How' gets three. The other questions are contained within a single chapter each, including probably the most challenging, 'Why' — and it isn't why does any of this matter, but an interesting discussion on why the concept of race fails.

The book is essentially a brisk run through the popular-science bookshelf of your local bookstore — without any of the 'maths is fun' territory. He covers the Universe — its beginning and end; Humanity — evolution, brains, gut biome, the origins of life; and the nature of the physical world with a dash of quantum physics. On that popular-science bookshelf you will find numerous examples of books covering exactly the same ground but mostly as single-subject projects and accordingly covered in greater depth than here. But Harrison does not compromise; he sees no use for religion and is equally damning about the concept of race — one may wish he were slightly more accommodating in the former at least in terms of the social need for ceremony, but can only applaud his view of the latter. *At Least Know This* is a taster compendium of all of those popular-science books, and all of that knowledge whittled down to the few topics that Harrison believes are important to know in order to live a full life. I'm sure that most of us could come up with our own list of important subjects, but although I might not endorse his belief in the beneficial effects of this knowledge, I wouldn't disagree too much with his selection — it is all good stuff and all energetically covered.

This book is a pretty thorough account of what science tells us about the physical world up to the present, told in an inspiring way. For example, Harrison points out that, in terms of number of atoms, a human being is made up mostly of hydrogen, and that every one of those, roughly 5×10^{27} hydrogen atoms, was made at about the moment the Universe came into existence. Now that should cause any reasonable person to pause and reflect and maybe silently say "Wow". The remaining atoms were all made in stars. Harrison says that this gives us a deep personal link to the entirety of the Universe — well, wow indeed! I have to say that I didn't feel the same emotion or conviction on being told that the modern human body, compared to other animals, is an elite endurance machine — but maybe yours is. Harrison has written a good introductory and engaging text told in a brisk, chatty, journalistic style which I could imagine might inspire future generations of scientists. I'm not sure that my feelings of empowerment got ignited but I did feel a small spark of pleasure. — BARRY KENT.

The Nature of Life and Its Potential to Survive, by David S. Stevenson (Springer), 2017. Pp. 456, 23·5 × 15·5 cm. Price £35·99/$44·99 (paperback; ISBN 978 3 319 52910 3).

The title suggests a wide-ranging book and readers will not be disappointed. In the first two chapters, the author surveys the diversity of life on Earth and its habitats, emphasizing the commonality of its genetic heritage. The discussion of genetics extends to CRISPR (Clustered Regularly Interspaced Short Palindromic Repeats), which has become the basis for modern genetic technology. The survey then moves on to the second essential characteristic of life, respiration: the variety of processes by which cells can extract energy needed to function. Most involve coupled reduction and oxidation processes, exploiting a variety of chemical gradients, geological as well as biological. Further basics include photosynthesis ("our planet's most important innovation") and the rise of oxygen, sexual reproduction, and the transition from unicellular to multicellular organisms. Although this transition is not fully understood, it was not a 'one-off', but occurred independently (but at about the same time, suggesting an environmental trigger) in several different lineages. The emergence of sensors in even the most-simple organisms is required for survival and their use requires development of central nervous systems to process the stimuli. The author posits that intelligence, and language to communicate amongst members of the group, are inevitable consequences of growth of complexity — at least amongst creatures that have evolved large enough brains and sufficiently active metabolisms to support them. There is a high density of information in these first chapters, clearly presented and well-illustrated.

Using this foundation, the author goes on to discuss the early history of the Earth, and the delivery of organic molecules by comets and planetesimals. I am not as certain that the high abundance of ^{26}Al can be attributed to a nearby supernova: it could have been formed in a massive star and delivered by its stellar wind. Primitive life began with the external supply of biomolecules and evolved using these, and those provided by hydrothermal activity, until it came to make its own. The author discusses the role of RNA as both catalyst and information store in the early synthesis of proteins. For a possible precursor to RNA, he introduces us to his own, published, proposal based on tRNA. The next chapter discusses evolution in terms of entropy, in particular information, or Shannon, entropy. Organisms, through their genomes, and the environment, through the variety of niches, possess Shannon entropy and drive evolution. This most interesting idea is developed further in the final chapter. As to extraterrestrial life, the author considers most life in the cosmos likely to be microbial, pointing searches to habitats analogous to those in Earth's deep biosphere. He reviews the challenges for life on planets around red dwarfs and the possibilities for the prime Solar System candidates, Mars and Enceladus.

The next two chapters look at the remarkable resilience of life. The mass extinction best known to astronomers, that which wiped out the dinosaurs 65 million years ago, was actually the *least* severe of the five major extinctions experienced by life on Earth. The effects of the Chicxulub event are eclipsed by those of flood basalt volcanism. A sixth major extinction, caused by human activity, is now under way. In the following chapter, the author discusses agents of mass destruction including climate change, nuclear war, over-population, pestilence, and asteroid impacts and concludes that life is so resilient that some can survive all, and humans all but the worst disasters. In the longer term, increasing solar luminosity will initially cause the concentration of CO_2 to fall, leading to failure of photosynthesis and plant life, and ultimately the temperature to rise again making life on Earth impossible.

This book is part of Springer's *Astronomer's Universe* series and is an excellent read for anyone having broad interests. The author writes fluently with a light touch, making for an enjoyable read, spoilt slightly by the scatter of errors left by the light-touch proof reading. Each chapter ends with a conclusion and references, and the book with a Glossary and Index. The breadth and depth of the coverage, weaving together geology, chemistry, and biology, make for a strong recommendation. — PEREDUR WILLIAMS.

Losing the Nobel Prize: A Story of Cosmology, Ambition, and the Perils of Science's Highest Honor, by Brian Keating (Norton), 2018. Pp. 326, 23 × 14·5 cm. Price £19·99/$27·95 ((hardbound; ISBN 978 1 324 00091 4).

BICEP stands for *Background Imaging of Cosmic Extragalactic Polarization*, biceps (coming from Latin meaning two-headed) is a muscle in the upper arm. And this book. while single-authored, is roughly three-headed, the author interweaving his own life with the development, use, and non-discovery of a telescope designed to measure the polarization of the Cosmic Microwave Background radiation and his views about the Nobel Prize in Physics as currently awarded.

Take the Nobel Prize first (aw, go on — take it!). The will establishing the Prize said one person, who had conferred the greatest benefit on mankind, in the previous year; this is probably a reasonable description of Röntgen's Rays in 1901, but, more often, since, it is one to three people, and organizations for the Peace Prize, not all of them beneficial, and the waiting time has stretched (*e.g.*, for the Chandrasekhar limiting mass for white dwarfs and the prediction of the Higgs boson) to 50 years. Dying before a committee reaches its final decision generally also puts one out of the running. Keating would like to change all of these, opening the science prizes to large collaborations (including in principle *BICEP*, which began as about a dozen scientists and at last count had 48), to contributions made over many years and not obviously beneficial (this has already happened in effect) and to the recently deceased. His list of those who might have benefitted from the third change, at least through their heirs and assigns, is Vera Rubin (dark matter from galaxy rotation curves), Ron Drever (third member of the *LIGO* prize-winning teams up to his death in 2016 March), Deborah Jin (pioneer in polar molecular quantum chemistry and production of fermionic condensates), and Mildred Dresselhaus (neat things done with graphene late in an already wonderfully productive career in condensed-matter physics). Keating would also prefer that Nobels be given primarily for serendipitous discoveries rather than things sought and found, so "yes" to Penzias and Wilson, "no" to Davis and Koshiba (solar neutrinos).

The astronomical non-discovery for which Keating would not have won the Nobel Prize (being by then no longer one of four leaders of the team) is B-mode polarization patterns of the irregularities in the CMB. OK? Well, it took a long dinner for Arthur Kosowsky, one of the outstanding theorists on the team, to explain what they thought they had seen to the late Edward Gerjuoy (by then the last living Oppenheimer student) and me at Pittsburgh a few days after the misguided announcement in 2014 March. But let me try.

The CMB is remarkably smooth in temperature (or intensity at any one wavelength) on the sky. The *COBE* satellite recorded fluctuations at an angular scale of about 7° and amplitude less than 10^{-4} (2006 Nobels for John Mather and George Smoot). That such anisotropies should polarize the background radiation was a 1968 prediction by Martin Rees.

Picture the polarization as a bunch of straight lines parallel to the E vector of the radiation. By analogy with the electric field around a current-carrying wire, label the two modes of polarization E modes (straight lines sticking out of a point and produced by density inhomogeneities in the material that last scattered the photons) and B modes (straight lines making a circle but oblique to the circumference) caused by gravitational waves left from inflation. That sort of polarization is expected if the early Universe went through an inflationary phase, but would be hard to account for otherwise. So, find the B modes (whose polarization is an order of magnitude less than that of the E modes, which are already bloody small), and you have 'confirmed' inflation, pleasing a large subset of theoretical cosmologists.

The *BICEP2* folks thought they had seen such a pattern, a factor of two stronger than a limit being set at the same time by the folks working with data from the *Planck* satellite (the 2018 Gruber Cosmology Prize). Well, they had seen the pattern, but gravitational waves left from inflation were not the cause, as *Planck* and other data quickly showed. The Milky Way is pervaded by patterned magnetic fields. Magnetic fields align dust particles. Dust particles scatter photons and do so in an asymmetric way that yields polarized scattered radiation (yes, also in visible light, as Hall and Hiltner showed in 1949 — they were actually looking for polarization due to electron scattering in the atmospheres of B stars, more like the predicted CMB effect than what *BICEP2* had actually found). Yes, *BICEP2* had rediscovered interstellar dust, by a *very* difficult method. Dust also features in several other astronomical topics Keating addresses — the size of the Milky Way and our location in it, the value of the Hubble constant, and so forth.

But let us jump to the present, with multiple groups and observatories now looking again for 'B-mode polarization of the CMB' in various ways. But an important one is the Simons Observatory (named, like Carnegie Observatories and Yerkes for the major funder, the Simons Foundation). It merges two groups, from east and west coasts; Keating is part of the crew, and they are now very much aware of dust, galactic synchrotron radiation, and other sources of radiation that are signal to some, but noise to them.

Lots of interesting tidbits appear along the way (not quite all true). Ansel Adams visited the University of California at San Diego in 1966 and took wonderful pictures of the Burbidges (separately) and Harold Urey. Martin Rees is still predicting (a blurb on Keating's back cover). And the author's favourite example of an earlier-reported major discovery not confirmed is Joseph Weber's work with detectors for gravitational waves (not the sort left from inflation!). *LIGO* is there too, but you will have to read the book for Keating's take on the Nobel winners and losers in that team.

Conflict of interest: my copy of *Losing* was an autographed present from the author. The signature was done with a broad felt-tip, but not (I think) because they won't let him have sharp-pointed tools in there. — VIRGINIA TRIMBLE.

Introduction to Cosmology, 2nd Edition, by Barbara Ryden (Cambridge University Press), 2017. Pp. 276, 25 × 18 cm. Price £37·99/$44·99 (hardbound; ISBN 978 1 107 15483 4).

The first edition of this book won the Chambliss Astronomical Writing Award of the American Astronomical Society; Ryden is now a member of the committee for that award. I knew about the first edition but have never read it, as it appeared in the time after I had learned introductory cosmology and before I started writing reviews for this *Magazine*. Apart from a general update, the second edition has expanded discussions of relativity and dark energy and a new chapter on the role of baryonic matter in structure formation. As is appropriate for an introductory book of moderate length, coverage of a broad range of topics is necessarily lacking more-detailed discussions, but Ryden avoids oversimplification while covering all topics at about the same level, appropriate for an undergraduate course in cosmology, although the last two chapters on structure formation go somewhat beyond that.

There are of course many cosmology textbooks, and even many introductory cosmology textbooks published in only the last few years, but even books at the same level intended for the same readership often have different emphases. This book is probably most similar to that by Heacox[1], reviewed recently in these pages[2], though the latter contains more information on General Relativity and the former somewhat more-detailed discussions of the other topics, including more equations. Both are thus essentially updated and condensed versions of Harrison's classic textbook[3] (my characterization; in neither case do I know if Harrison's book was an inspiration or even if the author was aware of it), which includes much more background material and more-detailed treatments of many topics (such as horizons). This book begins with fundamental observations (dark night sky, homogeneity and isotropy, redshift, *etc.*) and builds up the theory needed to explain them, starting with Newtonian physics and moving through relativity to model universes based on the Robertson–Walker metric with various combinations of matter, radiation, curvature, and the cosmological constant. Those are followed by a discussion of classical observational cosmology before more-modern topics such as dark matter, CMB anisotropies, nucleosynthesis, inflation, and structure formation are covered.

The mixture of narrative and equations is very close to a lecture course, and the book is well written. Complicated topics such as cosmological distances and horizons are presented briefly, but correctly. The editing is much better than average: there are almost no typos, and my only complaints are small matters of style. There are a few black-and-white figures throughout the text. Each chapter ends with a handful of exercises, solutions to which are available to those using the book for a course. I'm happy that there are footnotes rather than endnotes; as is usually the case with a textbook, there are no references in the text and hence no bibliography. However, some suggestions for further reading would have been a nice addition. (The list in the book by Heacox[1] is excellent; it is sufficient to point the reader to that.) The main text is followed by a table of useful constants and a five-page small-print index.

Despite the similarity, this book is perhaps closer to what most students would expect than the book by Heacox, so is perhaps a slightly better recommendation if one is to read only one introductory cosmology book; since I enthusiastically recommended that book, this book is highly recommended as well. My only real complaint about the contents, which applies to many other books and other publications as well, is that, while the rest of the book has been brought up to date where necessary, the discussion of the flatness, horizon, and multipole problems is essentially the same as that of 35–40 years ago. There has been some progress in the evaluation of those problems in the last 15 years or so, so much that a review[4] has recently appeared. While on the observational side updates to textbooks usually include both a re-evaluation of older work and the presentation of new, the former is often lacking with regard to theory. — PHILLIP HELBIG.

References

(1) W. D. Heacox, *The Expanding Universe: A Primer on Relativistic Cosmology*, (Cambridge University Press), 2015.
(2) P. Helbig, *The Observatory*, **136**, 204, 2016.
(3) E. R. Harrison, *Cosmology: The Science of the Universe, 2nd Edition* (Cambridge University Press), 2000.
(4) M. Holman, *Foundations of Physics* (submitted), arXiv:1803.05148.

Cosmology for the Curious, by Delia Perlov & Alex Vilenkin (Springer), 2017. Pp. 372, 23 × 15 cm. Price £31·99/$39·99 (hardbound; ISBN 978 3 319 57038 9).

Authors Perlov and Vilenkin are both at Tufts University, where the latter has been teaching an undergraduate cosmology course that is the basis for this book. It assumes no physics or mathematics beyond American high-school level, and the necessary physics is introduced as it is required (so says the back cover). Each chapter ends with some questions; in the earlier chapters many involve simple calculations, and there are even a few connected with mediocrity and the anthropic principle.

Is this a textbook for an American-style, non-major course in cosmology? Yes, I think so — and very much better than many floating around. Provided you use Chapters 1–14 for 10 or 14 weeks, you can probably get at least half way through the material before anything in it severely angers you. 'History' flies from Pan Gu and the Greeks to Newton in just a couple of pages. But the descriptions of what Friedmann, Lemaître, Slipher, and Hubble contributed to an expanding universe is very well done. The explanation of cosmological redshift is right on the button, nose, or whatever target you prefer. Doppler is indexed, but does not appear on the advertized page (this is actually a problem with the index for other people and some concepts), so his trumpeters cannot be confused with what light waves do.

Oddly, the plot of element abundances ('Why Alchemists did not succeed') does not have gaps at $z = 43$ (Tc) and 61 (Pm), but there has to be something left for the instructor to do. A good selection of 'further reading' is there to help you, though I wish it had included Barrow & Tipler's *The Anthropic Cosmological Principle* (one of the territories for which they provide no suggestions). They have found photos that make Steve Weinberg look young (1979 Nobel) and Brandon Carter (an early anthropicist) look old. Well, I suppose Weinberg was once young, though his portrait seems to be labelled "our first observational evidence for the existence of a multiverse". But Brandon is my age, and, … oh, well, there it is. The second half of the book starts at 'Problems with the Big Bang' and ends with 'Our place in the Universe'. In between the reader, student, or instructor will meet inflation, strings, the Standard Model of particle physics, and some of the second author's own work. Particularly meritorious is the discussion of how there can be a hot, dense phase (to give us helium, the cosmic microwave radiation, and so forth) after the cooling expected from 100 or so doubling times of exponential expansion. The Big Bang is NOT $t = 0$. It is $t = 10^{-35}$ seconds, and the associated temperature and density are large but not infinite.

As astounding as the quality of the science is that the publishers have given us as much colour as needed and as many equations (mostly in the appendices for the calculus-minded) for the price of a good dinner (without wine). I paid for my copy (at a Springer-editor & author's reduced price) and will use it if my department ever lets me teach one of those fun 'Cosmology for Poets' courses again. — VIRGINIA TRIMBLE.

Gravitational Waves: How Einstein's Spacetime Ripples Reveal the Secrets of the Universe, by Brian Clegg (Icon Books), 2018. Pp. 176, 19·7 × 12·8 cm. Price £7·99/$12·95 (paperback; ISBN 978 1 78578 320 3).

From the pen (or keyboard) of a well-known science writer, this is a breezy, popular-science-level introduction to gravitational waves and their detection by *LIGO*. As might be expected of probably one of the few people who has written for *Nature*, *The Times*, *Good Housekeeping*, and *Playboy*, it is well written, engaging, and somewhat different from other books covering roughly the same territory. After a brief account of GW150914, the next few chapters summarize the basics of waves, General Relativity, and the history of the field of (attempted) gravitational-wave detection before *LIGO*. (Although it is impossible to describe the career of Joseph Weber without a tragic component, the account here is reasonably balanced.) Astrophysics is first discussed in more depth in a discussion of neutron stars, built around the story of PSR 1913+16 and the indirect detection of gravitational waves. A welcome surprise is a description of *LIGO* which is more detailed than one might expect from such a small book, covering the observatory itself, the politics of collaboration and leadership, data analysis, and public relations in the shadow of the *BICEP2* disaster. The final, ninth, chapter returns to astrophysics, discussing mainly black holes as those are the sources of most of the gravitational-wave detections so far, and also future possibilities, such as networks of detectors on Earth, *LISA*, pulsar-timing arrays, and so on, as well as indirect detection *via* the CMB. That is followed by a discussion of the value of 'big science'. Finally, the possibilities of using gravitational waves to see further back to the Big Bang and to investigate dark matter are mentioned.

There is not that much astrophysics in the book, but, in one at this level, that would essentially repeat what probably most readers have encountered many times. Also, gravitational waves are a topic which can be described at an introductory level, as here, or in great detail, but an intermediate-level description is difficult. On the other hand, the discussions of the social and political aspects of *LIGO*, gravitational-wave detectors, and science in general are interesting, and mesh well with the more physics-based topics. I didn't notice any factual mistakes, but a few passages are somewhat confusing, at least to me. For example, "[W]e can say that light (sometimes) behaves like a wave, but not that it is a wave. This is in contrast to gravitational waves, which if they were to exist would actually be waves." Also, Janna Levin is described as a "journalist " and a "science writer". The first is perhaps misleading; the second is true; however, she is also a tenured professor of physics. Towards the end of the book, "gravity wave" rather than "gravitational wave" is used, with no explanation. Since 'gravity wave' has another, longer-established meaning (a wave where gravity, rather than, *e.g.*, surface tension, is the restoring force), if it is used at all in the discussion of gravitational waves, this should at least be pointed out, as in the book reviewed in ref. 1. (Describing *LISA*'s distance from the Earth of " ... between 50 and 65 million kilometres, about a quarter again the distance at which the Moon orbits" I put down to carelessness rather than error; that overestimates the size of the Moon's orbit by a factor of 100.)

The chapters are preceded by a time-line, starting with Faraday and ending with GR150914, and followed by suggestions for further reading (grouped by subject) and a six-page, small-print index. There are a handful of black-and-white diagrams and photos throughout the text. The few notes are footnotes rather than endnotes. Except for the usual misplaced "only"s (see ref. 2) and non-hyphenated two-word adjectives ('gravitational wave' being by far the most common), there are essentially no typos nor other editorial mistakes, which, together with the polished prose, makes for an enjoyable read.

I had planned to read this book on the Adriatic coast in Istria (between experiences of more-conventional gravity waves), but finished it before my holiday, both because it is relatively short and because it is an enjoyable read. I'm sure that others will enjoy it as well. —PHILLIP HELBIG.

References

(1) P. Helbig, *The Observatory*, **138**, 255, 2018.
(2) L. Baldwin, *The Observatory*, **136**, 194, 2016.

Shape Dynamics: Relativity and Relationalism, by Flavio Mercati (Oxford University Press), 2018. Pp. 255, 24·5 × 17 cm. Price £70 (hardbound; ISBN 978 0 19 878947 5), £35 (paperback; ISBN 978 0 19 878948 2).

The late film critic Roger Ebert once quipped "It's not what a movie is about, it's how it is about it." In other words, one could make a good movie about a bad topic or *vice versa* (or, of course, both could be bad or both good); as a film critic, to some extent he could write about the presentation independently of the content. So it is with this review, which is concerned more with presentation than with content; Shape Dynamics (SD) is probably unfamiliar to most readers, and even a short appraisal would make this review much too long. Nevertheless, a brief description is necessary. Shape Dynamics is an attempt to base a theory of gravity on fewer and more-fundamental first principles than General Relativity, motivated by a desire to incorporate Mach's Principle to a greater degree than does GR, even though that means giving up the relativity of simultaneity in favour of invariance under spatial conformal transformations. The name comes from the fact that only angles are fundamental, while the local scale factor plays no role. In almost all cases, predictions are the same as those of GR. There appears to be no easy test to distinguish between the two theories; the motivation, however, is more aesthetic than phenomenological (that was also the case with GR, though GR famously had relatively easily testable predictions — and, with the precession of the perihelion of Mercury, a testable postdiction — from the outset). Nevertheless, a net angular momentum of the Universe would rule out SD, and a spatially open universe or one with non-zero total energy would be difficult to reconcile with SD.

Although this book has only one author — who won the Buchalter Prize for Cosmology in 2015 — *Shape Dynamics* is the work of a small collaboration, which Mercati duly acknowledges. This is a very mathematical textbook (704 equations), not an introduction, although there is a summary in one section of the introductory chapter and a couple of chapters on historical motivation. The next nine chapters build up the theory in 100 pages, with the final chapter presenting various solutions in a bit less than 100 pages. A good grounding in classical theoretical mechanics is needed to follow the argument. Although difficult, the presentation is well written and well edited: essentially no typos nor any indication that the author is not a native speaker of English (my only gripes concern minor matters of style, though in that respect as well this book has less to complain about than most which I have reviewed in these pages). The book is obviously a labour of love.

A couple of quotations give a flavour of the contents and style: "... a second-class system like that of case |III.C| can be seen as a gauge-fixing of a first-class system. Doing this often requires enlargement of the phase space with further redundant (constrained) degrees of freedom, ...". (That appears on p. 102, where the author states "I have reached the point at which I can finally introduce SD." The long build-up reminds me of Russell & Whitehead needing 362 pages before being able to state "From this proposition it will follow, when arithmetical addition has been defined, that 1 + 1 = 2."[1]), or "Solution (310) corresponds to ADM in a gauge where the Hubble parameter is a conformal harmonic function. In many cases, such as if the metric is of positive Yamabe class, it reduces to maximal slicing gauge."

The book is well produced and has 52 figures (in colour if necessary) distributed throughout. Notes are thankfully footnotes rather than endnotes, and 126 numbered references point the reader to both background material and more-detailed discussions. The index is short but sufficiently thorough. Who should read this book? Despite the clear presentation, the mathematical difficulty will obviously limit the readership. (The relatively high price is explained by the limited readership; lowering it wouldn't attract any more readers, and those interested in the topic will probably want a copy even at the high price.) Those curious about whether there is something to Shape Dynamics will certainly find an answer here. — PHILLIP HELBIG.

Reference

(1) B. Russell & A. N. Whitehead, *Principia Mathematica* (Cambridge University Press), 1910.

Introduction to Plasma Physics, with Space, Laboratory, and Astrophysical Applications, by Donald A. Gurnett & Amitava Bhattacharjee (Cambridge University Press), 2017. Pp. 521, 25·5 × 18 cm. Price £49·99/$64·99 (hardbound; ISBN 978 1 107 02737 4).

This second edition of Gurnett & Bhattacharjee's *Introduction to Plasma Physics* is a thorough update of the original published in 2005. The layout of the book and its contents are fairly standard for a text on plasma physics, providing a comprehensive treatment, from the basics of single-particle motions, through kinetic theory and magnetohydrodynamics, to instabilities and shocks, and culminating in the last third to a particularly detailed discussion of plasma waves.

The approach of the book is in-depth and exhaustive. The derivations are detailed, with few 'and then a miracle happens' steps, which makes the book suitable for advanced undergraduates as well as researchers. Together with the meticulous mathematics, the physics is described in an intuitive way, which helps build a clear mental picture of plasma phenomena — indeed, despite the heavy material in places, I found the writing style refreshingly direct and readable throughout. As an aid to undergraduate teaching, most chapters finish with a problem section, with questions at a variety of levels, and suggestions for further reading.

As the title suggests, the book makes many references to plasma behaviours in a range of contexts including the laboratory and Solar System and terrestrial plasma environments. While these examples provide a grounding for the theory, they are occasionally introduced somewhat briefly, and require background knowledge on the part of the reader to be illuminating. Indeed, this book will not teach space-plasma physics or laboratory-plasma physics by itself, and for either of those topics a more specialized source would be necessary. However, as an introduction to the general underpinning physics of plasma phenomena, it is an excellent book that I can see myself referring to extensively in future. — STEPHEN MILAN.

First Ten Years of Hinode Solar On-Orbit Observatory, edited by Toshifumi Shimizu, Shinsuke Imada & Masahito Kubo (Springer), 2018. Pp. 305, 24 × 16 cm. Price £129·99/$179 (hardbound; ISBN 978 981 10 7741 8).

The Japanese solar observatory *Hinode* (or Sunrise) was launched in 2006 September with three major instruments on board. The expectations were high, and to a large extent have been fully realized over the period since then. This volume of review papers, mostly by Japanese scientists heavily involved with the *Hinode* project, captures some of the excitement with which the results, including the stunning high-resolution images in optical, soft X-ray, and ultraviolet wavelengths, were first greeted by the solar community. So a step back by the leading *Hinode* scientists to review the first ten years is very timely and will be welcome.

There are 23 reviews in the volume covering observations by the three main instruments: the *Solar Optical Telescope* (*SOT*), the *X-ray Telescope* (*XRT*), and the *EUV Imaging Spectrometer* (*EIS*). The research topics include the small-scale magnetic flux tubes pervading the photosphere (article by Suematsu), MHD waves along various structures like spicules and prominences (Matsumoto), plasma outflows from active regions (Watanabe), and the possible identification of the slow solar wind (Lee *et al.*). The article by Shiota on polar magnetic fields will be of interest ahead of the imminent *Solar Orbiter* launch. Although solar activity has been low during the lifetime of *Hinode*, many observations of flares and tiny nanoflares have been made, and the articles by Reeves and Bamba give a good outline of the discoveries.

A concluding section on the *Hinode* Science Centre and public outreach is a welcome innovation. The gallery of solar images from the *SOT* and *XRT* instruments at the back of the book will certainly provoke much interest. The colour-image quality is good, so that one can readily confirm the 0·2 arcsecond spatial resolution in (*e.g.*) the *SOT* images of granulation.

The one heavy drawback is the book's price tag, much higher than previous *Hinode* conference proceedings. This puts it outside the reach of the research students at whom the book is aimed. It is a great pity as this is a book that ought to be readily accessible to those eager to follow the latest solar spacecraft findings. — KEN PHILLIPS.

Eclipse: Journeys to the Dark Side of the Moon, by Frank Close (Oxford University Press), 2017. Pp. 219, 20·5 × 14 cm. Price £12·99/$21·95 (hardbound; ISBN 978 0 19 879549 0).

A total eclipse of the Sun is one of the most spectacular sights in all of nature. I have always been fascinated by the compulsion that drives some people to travel the world simply to experience totality. I am such an individual and so is the author of *Eclipse: Journeys to the Dark Side of the Moon*. Professor Frank Close explains his lifelong fascination with eclipses which started when he was an 8-year old and his imagination was fired by an inspirational teacher and a partial eclipse of the Sun on 1954 June 30 as seen from his primary school in Peterborough. 'Umbraphilia', if indeed there is such a condition, can be a wallet-draining affliction but also one which gives the sufferer a chance to visit parts of the world that he or she might never otherwise experience. Close's book provides an insight into how this condition has affected him.

This book concentrates more on the places the author has visited in the pursuit of totality. If you were expecting more of a scientific insight into eclipses then this book is probably not for you. If you want more of a travelogue, then this is a gentle introduction to the subject of eclipses. There are a plethora of guides to eclipse chasing that will satisfy those who want to know all the whys and wherefores of predicting and observing eclipses. There are some factual errors in the book, such as the number of synodic months corresponding to 242 Draconic months (the average time interval between successive passages of the Moon through the same node). On page 46, the book gives 233 synodic months instead of the correct value of 223. It must be said that some of the explanations given in the book are a little light on detail, which some readers may find disappointing.

Close's book is mainly organized by his travels to see total eclipses of the Sun in such places as Zambia, Libya, and the South Pacific, and includes a look forward to the American eclipses of 2017 and 2024. There are some insights into the role of the weather in eclipse watching and how to observe these events safely. He also describes how they have been used to date historical events such as the crucifixion of Jesus. Close further provides some eyewitness accounts of eclipses in addition to his own personal recollections. The reader does get a real sense of the lasting impact these eclipses have had on Close and the feeling that being present in the umbral shadow is an experience not to be missed.

As an introduction to eclipses and the places eclipse watching might take you, this is an interesting read. However, this is not what I would call a scientific guide, and those wanting to know more about the mechanics of eclipses should look elsewhere. — STEVE BELL.

Totality: The Great American Eclipses of 2017 and 2024, by Mark Littmann & Fred Espenak (Oxford University Press), 2017, Pp. 347, 24 × 16·5 cm. Price £25/$29·95 (hardbound; ISBN 978 0 19 879569 8).

Two of the most observed solar eclipses of the 21st Century must be those crossing the United States in 2017 and 2024. We have already seen the huge levels of interest generated by the 2017 August 21 total eclipse of the Sun that crossed the United States from Oregon in the north-west to South Carolina in the south-east. No doubt the 2024 April 8 total eclipse of the Sun will have a similar effect when it passes over the eastern Pacific Ocean, northern Mexico, and the United States from Texas in the south west to Maine in the north east, as well as eastern Canada and the north-western Atlantic Ocean. The previous time the mainland United States saw a total eclipse of the Sun was 1979 February 26, almost four decades ago, when the north-western part of the United States experienced totality. Similarly, the last time a total eclipse was seen 'coast to coast' in the mainland United States was a century ago on 1918 June 8, which ran almost parallel to the track of the 2017 eclipse.

Totality: The Great American Eclipses of 2017 and 2024, by Mark Littmann & Fred Espenak, is the complete guide to these two impressive astronomical events. It has to be said that some of the material in the book will be familiar to purchasers of *Totality: Eclipses of the Sun* by Littmann, Espenak & Willcox (OUP, 2017, 3rd Edition). However, the book covers a lot of ground including general aspects of observing a total eclipse of the Sun, what to look for during the eclipse, how to photograph and video the event, and information on weather prospects for both eclipses, details of the paths of totality and timings of both eclipses. It also covers why eclipses happen, early attempts to predict eclipses, and the mythology and folklore of eclipses. The book is copiously illustrated with 220 illustrations, mostly black and white, which enhance the material on eclipse phenomena and how the solar eclipse affects wildlife as well as people. If I have a criticism, it is that there should have been more colour photographs to convey the spectacular nature of a total eclipse of the Sun, especially when you consider Espenak's very extensive photographic accomplishments. A nice touch is the 'Moment of Totality' interludes between the chapters which provide different viewpoints and reflections on the whole eclipse experience. I think Sheridan Williams' contribution sums things up nicely: "After seeing a total eclipse, I have never, never heard anyone say 'I don't see what all the fuss was about'". Additional information such as global maps for all solar eclipses in the interval from 2017 to 2045 are given, lists of all total, annular, and hybrid solar eclipses are provided for 1970 through to 2070, and total eclipses visible in the United States are given for the period 1492 to 2100.

At £25, this book is an extremely useful, affordable guide to both of these magnificent astronomical phenomena. Even though the 2017 total eclipse of the Sun is now just a historical circumstance, the information for the 2024 eclipse is worth the price of the book on its own. Unfortunately, I was not able to go to the 2017 eclipse, but, by all accounts, the traffic jams, the overbooked hotels, and the size of the crowds in many parts of the United States were a price worth paying to see one of nature's most awe-inspiring events. I, for one, will make sure that I am in the path of totality on 2024 April 8. — STEVE BELL.

The Moon, by Bill Leatherbarrow (Reaktion), 2018. Pp. 182, 23 × 18 cm. Price £25 (hardbound; ISBN 978 1 78023 914 9).

I finished reading this book uncertain of its intended readership, so immediately re-read the preface. The primary aim is said to be the description of how our knowledge of the Moon has developed over the years and to depict the current state of lunar science. This accords with the aims of works on the Earth sciences (the generally excellent *Nature and Culture* series) issued by the same publisher, who has now moved to astronomical books. Perhaps unfortunately, cultural aspects are merely touched upon in passing, despite the Moon having had considerable impact on ideas in numerous cultures worldwide over the centuries.

A second aim of this particular book is said to be to encourage amateurs to observe the Moon. I am not sure that it really succeeds in this. Although the way in which the geological (selenological) formations are described is excellent, as is the encouragement of observers to examine different types of lunar features, some of the elementary material seems redundant. Surely, by now, anyone interested in astronomy knows about the causes of lunar phases, the circumstances of eclipses, and the three main forms of amateur telescope? They hardly need descriptions and (rather crude) diagrams.

There are some unfortunate omissions or only partial explanations. For example, although mascons are mentioned, there is no discussion of their significance in terms of their occurrence in connection with certain major impact basins (but not others) nor of the original conceptions that they were the result of flooding by dense mare-type basalts, but that this view cannot explain the overall density anomalies, nor why regions of extensive basalt flooding — in particular Oceanus Procellarum — do not show any positive gravity anomalies. There is, in fact, no full discussion of how the various mare lavas are distinguished nor of how they display a succession of ages.

Although the original proposal by Andreas Hansen in 1854 that the Moon's centre of mass is displaced from its physical centre is mentioned, there is no discussion of the suggestion that the asymmetrical distribution of mass and the consequent gravitational anomaly is the reason for the 'locked' rotation, with one face turned to Earth, nor of the fact that the lunar crust is thicker on the farside.

The description of the formation of the Moon covers the theory that it originated with the collision of a protoplanetary-sized body (known as Theia) and the early Earth. It is hardly the fault of the author or publisher that the latest theories are not covered, because they were published only in 2017 January. These theories suggest that the existing Moon is merely the latest in a series of satellite bodies; that there was one major impact early in the history of the Solar System; and that water played a significant part in the Moon's formation.

The illustrations are not numbered and are, unfortunately, poorly tied to the text. One example of this is found on page 79, where the text states "A prime example of this is the crater Archimedes in the Mare Imbrium". I automatically looked for an image of Archimedes — there is none, nor is even an adequate image of the Mare Imbrium to be found elsewhere in the book.

The author bemoans the fact that the best atlas of the Moon (that by the renowned Czech selenographer, the late Antonín Rukl) is not readily available, even second-hand, but seems unaware that Rukl prepared just a single Moon map, which was published in various sections, ranging from 76 in *Moon, Mars and Venus* (Hamlyn, 1976) and *Atlas of the Moon* (Sky & Telescope, 2004) to 16 (plus mirror-images for catadioptric telescopes) in *Collins Atlas of the Night Sky* (Collins, 2005). The last of these is certainly available, second-hand, at a reasonable price, and paper (not book) versions of Rukl's map may still be obtained from Sky & Telescope.

On a personal note, I am always irritated by the 'pseudo-PC' use of the word 'humankind' instead of 'mankind' — it is unnecessary, according to the definitions in the OED, and should, in any case, be two words 'human kind' , The word is used frequently in the initial chapters. So I nearly cheered when 'mankind' appears later in the book. Somewhat similarly, I do feel that there is an excessive use of exclamation marks — surely not really necessary in work of this type.

In summary then, it is good, but I would have liked more detailed descriptions of the physical nature of lunar features and possibly of the Moon's cultural influences. — STORM DUNLOP.

Jupiter, by William Sheehan & Thomas Hockey (Reaktion), 2018. Pp. 191, 23 × 18 cm. Price £25 (hardbound; ISBN 978 1 78023 908 8).

Thomas Hockey has previously chronicled historical observations of the planet Jupiter in his impressive *Galileo's Planet* (Institute of Physics Publishing, 1999). Here he joins forces with fellow writer and historian Bill Sheehan in this

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popular introduction to the Solar System's largest planet, in a new series of books by Reaktion Books.

Jupiter is very well written and illustrated. The approach is basically historical, with much fascinating detail and many rich insights into the subject. The references are comprehensive. Publication was timed to coincide with the *Juno* mission. There is plenty of contextual detail throughout, with Jupiter's probable origin and its status in the Solar System discussed in detail at the start. A chapter about how the Great Red Spot became Great was particularly interesting to me, illustrated with some previously unseen archival drawings from the 1870s and '80s. In this chapter Sheehan and Hockey also discuss the important role played by amateur astronomers in the understanding of the motions within Jupiter's visible cloud layers. Some minor errors: Rev. T. E. R. Phillips died in 1942, two years before a flying bomb did a lot of damage to Headley Rectory and the Observatory (and not the other way round). And contrary to what is implied, the BAA Jupiter Section did much good work in the 1950s, when Dr. A. F. O'D. Alexander investigated the possible link between visible features and the newly discovered radio emissions.

There are very good descriptions of the other types of Jovian features such as the white South Temperate ovals, the South Tropical Disturbances, and the often violent revivals of the South Equatorial Belt. The Reese 'volcano' hypothesis for the latter phenomena (an early version of which appeared in the BAA *Journal* in 1953) remains an intriguing concept. On page 102 I would have preferred a clear distinction between the quasi-periodic SEB revivals and the occasional outbreaks of white spots between the two components of the SEB.

The moons of Jupiter receive proper attention in Chapter 7. The exciting times of the Comet Crash in 1994 are revived in Chapter 8, and it is now clear that events involving smaller objects are more common than was formerly thought. Sheehan reproduces his own sketches of the 1994 event, which brought back happy memories of those exciting days for me. The book ends with a discussion of *Juno* and its mission aims, and with details of how to make your own observations of Jupiter. Useful Appendices give numerical data, forthcoming conjunction dates with other planets, a list of previous spacecraft missions, and a Glossary.

In summary, *Jupiter* is both eloquent and detailed. I can thoroughly recommend it as the best available introduction to that fascinating world. — Richard McKim.

The Design and Engineering of Curiosity: How the Mars Rover Performs Its Job, by Emily Lakdawalla (Springer), 2018. Pp. 394, 24 × 17 cm. Price £27·99/$39·99 (paperback; ISBN 978 3 319 68144 3).

This book presents an in-depth explanation of how "the most complex machine ever sent to another planet" works. *Curiosity*'s audacious landing procedure disarmed its critics, since when it has proved to be a spectacular success. Its power system, tyres, cameras, robotic arm and drill, spectrometers and weather station all receive attention, while a 40-page Appendix chronicles all its actions till the end of 2017. There are in-depth discussions on wheel design and degradation as well as complete listings of the drill and scoop sampling campaign. Beautifully written and illustrated, Ladawalla's essay is truly encyclopaedic. She informs us that she is now writing a sequel to describe the actual mission results. The author was clearly not responsible for the index, which fails to mention basic terms such as 'camera', 'drill', dust', 'spectrometer', and 'tyre', but does list the word 'anomaly' 34 times, and so it is a bit of an anomaly itself in an otherwise splendid book. — RICHARD MCKIM.

Inventing a Space Mission: the Story of the *Herschel* Space Observatory, by Vincent Minier *et al.* (Springer) 2018. Pp. 280, 24 × 16 cm. Price £109·99/$149·99 (hardbound; ISBN 978 3 319 60023 9).

This is not the book I was expecting from the title. Rather than being an anecdote-heavy, personality-driven, chronological account, this is a study of innovation and project management using *Herschel* as an example. As such it not necessary to understand much about sub-mm astronomy since the project issues are applicable to many large-scale scientific endeavours. Starting from the formation and travails of ESRO, ESA's predecessor, the book details the development of the now iconic Horizon 2000 ESA plan, which included an unspecified large heterodyne sub-mm mission as a cornerstone, even though such a mission was far beyond the then state of the art. Various sections recount the mission's time-lines and target-specific technologies (*e.g.*, the mirror, the detectors, and the cryostat) as examples of the innovation process, complete with dead-ends and even steps backwards. I learned a number of new terms (copetion, sociality, C–K theory) which derive from game and management theory, but which are here applied to the development of a space project. Considerable emphasis is placed on the commitment to a long-term, stable, scientific plan and to the discipline enforced by a 'design-to-cost' philosophy. As such this account should be of interest to systems engineers and project managers as much, if not more, than to astronomers.

There are also discussions of the different philosophies used by the science teams, both for their own internal management and for the use of their guaranteed observing time, and a bibliological vector analysis of author co-citations. The most interesting conclusion for me was that *Herschel* succeeded not because it was a safe-bet but rather because it was so far beyond what was then possible that it drove innovation to do new things, rather than adapt and expand existing well-understood technologies. Indeed the writers conclude that in today's more conservative 'Technology Readiness Level'-driven culture the managed-risk-based approach of *Herschel* would never have been allowed and the mission would, literally, never have got off the ground. — JOHN DAVIES.

Assembling and Supplying the ISS: The Space Shuttle Fulfills Its Mission, by David J. Shayler (Springer), 2017. Pp. 350, 24 × 17 cm. Price £24/$44·99 (paperback; ISBN 978 3 319 40441 7).

The Space Shuttle era is over, but one of the main legacies of the programme continues in the form of the *International Space Station* (*ISS*). Without the development of the heavy-lift, versatile, Shuttle fleet, the largest and most complex human-made structure ever to be placed in orbit would never have materialized.

Between 1998 December and 2011 July, 37 Shuttle missions were flown to the *ISS*, delivering station modules and other hardware, as well as crews and cargo. Once their brief sojourns at the *ISS* were completed, the reusable craft were able to return to Earth with up to eight crew and a payload of used hardware and scientific experiments.

Since the termination of the Shuttle programme after 135 missions — 133 successful — the United States and all of its *ISS* partners have had to rely solely on the Russians to deliver fresh crews to the *Station* and return to Earth with astronauts who have completed their missions. This reliance upon relatively primitive Soyuz spacecraft is not expected to end until the first commercially developed US crew-carrying craft make their debuts — perhaps in 2019.

Author David Shayler, who has studied and reported on human space activities for many years, provides a detailed account of how three of the US Shuttles fulfilled their original promise as space delivery trucks. The book includes summaries of all the Shuttle–*ISS* missions and the crews who flew on those missions.

Shayler also delves behind the scenes, examining the key aspects of each mission, including launch, docking, extra-vehicular activity, the Shuttle robotic manipulator system, and return to Earth. The text is supported by numerous photos and tables. All-in-all, a valuable reference for space buffs who want to look back to what may one day be remembered as a golden age for space transportation — despite the two catastrophic failures that resulted in the deaths of 14 astronauts. — PETER BOND.

Discovering the Cosmos with Small Spacecraft: The American Explorer Program, by Brian Harvey (Springer), 2018. Pp. 281, 24 × 17 cm. Price £31·99/$39·99 (paperback; ISBN 978 3 319 68138 2).

This is a most fascinating book, rich at two levels. It gives a complete rundown of the series of nearly 100 small-sized space missions that constituted — and continue to constitute — the Explorer programme, and it provides useful background information about the purely astronomical ones (as well as studies of the ionosphere, atmosphere, magnetosphere, *etc.*, which were also part of the programme). Many astronomers are probably as unaware as I was of the huge efforts that went into learning how to launch even small spacecraft reliably, or of how the achievements of one mission really did form the cornerstone of the next.

The Explorer programme started in 1958, when the drive for supremacy in space was already high on the political agenda and absorbing much more of the available funds that these tiny space experiments wanted, but Von Braun and Van Allen were key proponents with both vision and drive, and pushed successfully for opportunities to experiment. Happily for astronomy, James Webb (appointed NASA Administrator in 1961) was able to implement his far-sighted ideas of university involvement in a way that ensured an on-going investment in space missions by talented academics. His approach succeeded in selling the value of curiosity to America so convincingly that, in total, 95 successful Explorer missions were launched and returned new science (those that failed for some reason were not included in the numbering sequence). Quite a number of the results acquired by these space missions led to Nobel Prizes. Astronomy continues to benefit from Webb's philosophy; the *Transiting Exoplanet Survey Satellite* (*TESS*) was launched in 2018.

Harvey's descriptions of the science, the technology, and the results flow attractively as he weaves the whole into a comprehensive image of what has been, and continues to be, a uniquely valuable programme for astronomical, atmospheric, planetary, and solar science. He does not shy away from the failures (which were unfortunately not that uncommon in the early years when rocket science was also in its infancy), as progress was best achieved by learning from what went wrong. He maintains a parallel observation of the political side by analyzing the influences for better or for worse as national attitudes, priorities, and budgets were re-cast with disturbing frequency, offers answers to one-time baffling questions such as mission cancellations, and details the spin-offs — both technological and scientific — deriving from very many of the flights. Incidentally, one cannot help noticing how few women were involved at the front line, though the book does not offer any opinion on that.

Without question, this is a history that needed to be told. Harvey does so in a very readable manner, and his book deserves wide popularity with professionals, students, and lay citizens alike. — ELIZABETH GRIFFIN.

Building Habitats on the Moon: Engineering Approaches to Lunar Settlements, by Haym Benaroya (Springer), 2018. Pp. 314, 24 × 17 cm. Price £34·99/$39·99 (paperback; ISBN 978 3 319 68242 6).

Haym Benaroya, a professor of mechanical and aerospace engineering at Rutgers University in the United States, has spent much of his career developing engineering solutions to facilitate future human habitation on the Moon. This book builds on that experience, and develops themes explored in his earlier book *Turning Dust to Gold: Building a Future on the Moon and Mars* (Springer Praxis, 2010). There is some repetition of material from the earlier book, but, as its title suggests, the present volume concentrates more on the engineering aspects of lunar settlement. In particular, engineering concepts related to the structural and thermal design of lunar habitats, radiation and seismic protection, and *in-situ* resource utilization are covered in detail. The chapters covering these topics are all well-referenced, and thus provide a valuable introduction to the relevant literature for the non-specialist. In addition, and as also in *Turning Dust to Gold*, Benaroya punctuates the main text with interviews conducted with independent experts in appropriate fields, which provide insights that add interest and value to the book as a whole.

Purely scientific benefits of future human activities on the Moon are not dealt with in detail, except for a short chapter dedicated to lunar-based astronomy. Benaroya has long been an advocate of this topic, and organized a conference on lunar astronomy over 20 years ago (see *JBIS*, **48**, No. 2, 1995). I was pleased to see this included because I also believe that observational astronomy will be a scientific beneficiary of future human operations on the Moon. Indeed, recent developments in cosmology and low-frequency radio astronomy have strengthened the case for lunar observatories (see, *e.g.*, Joseph Silk's recent article in *Nature*, **553**, 6, 2018). However, while welcome, it was slightly incongruous to see observational astronomy highlighted in this way in a book largely dedicated to engineering, and with no comparably detailed treatment given to other sciences which would also benefit from a human presence on the Moon (for an attempt by myself and colleagues to review these, see *Planetary and Space Science*, **74**, 3, 2012).

In addition to the more technical aspects, the book also considers lunar settlement in the wider context of future space activities. Benaroya concludes, rightly I think, that the Moon is the next logical step for human space exploration, and that dreams of sending people further afield, for example to Mars, will depend on technologies, skills, and operational protocols developed first on the Moon. As he says in his Preface: "[i]f someone gave me as much money as I wanted to make humanity a spacefaring civilisation, I would still choose the Moon as our first goal." This book provides ample justification for that statement, while also succinctly summarizing the technical and engineering capabilities that will be required to make that goal attainable. — IAN CRAWFORD.

Calling Taikong: A Strategy Report and Study of China's Future Space Science Missions, by Ji Wu (Springer), 2018. Pp. 52, 24 × 16 cm. Price £99·99/$139·99 (hardbound; ISBN 978 7 03 049030 8).

To anyone associated with the Chinese space-science programme, the most enduring impression is of breathtaking pace. Paying attention is essential whenever you discuss whatever project you are involved in, as you often discover another ambitious project has appeared. This slim volume provides a helpful summary of the state of the overall Chinese space-science programme as it looked in 2016. The author, Professor Ji Wu, is well placed to provide a summary, being a former director of space science at the National Space Science Center of the Chinese National Academy of Sciences. The report covers the period 2016–2030 and sets out the scientific vision and the proposed set of space missions designed to address it. The science questions, unsurprisingly, are similar to those of other countries, including the origin of the Universe, the origin of life, space-environment studies, and the Solar System, including the Sun.

The central part of the volume discusses mission plans. Some of these are well developed, including some now launched such as *HXMT* — the *Hard X-ray Modulation Telescope*, and others under construction such as the *Einstein Probe*, due for launch in 2022. Other missions are more conceptual but illustrate the broad ambition. China clearly wishes to have a space-science programme able to address a range of topics and to have many launch opportunities. Of particular interest to those outside China is their desire to have missions jointly with other agencies. The *SMILE — Solar Wind Magnetospheric Ionospheric Link Explorer* — mission with ESA is a good example. *SMILE* will have some European and some Chinese instruments on a small spacecraft to be launched by ESA. Although a modest budget by Western standards (roughly €50M from ESA), it can be seen as a collaboration pathfinder, and indeed ESA is already in discussions with China regarding other missions. Some individual countries, France for example, also have collaborative projects. There are important issues regarding technology transfer and data rights which will need to be dealt with, but overall the impression is of a country willing to be collaborative, which can only be a good thing.

An interesting section in Chapter 4 discusses the relative budgets for space agencies. In the West we have seen real pressure on science budgets, not helped by delays in launches. China has had a seemingly unstoppable growth in GDP, mirrored by a growth in their R&D budget. So far, they are also growing their space budget but currently it remains modest compared to others. The figures quoted suggest a total spend in China during 2011–2015 of about 2% that of the USA or eight times less than ESA. If growth continues, however, that will change in future, approaching more like half of ESA's budget in 2026–2030.

No-one should doubt the ambition and drive in China to succeed in space science. Working with Chinese colleagues is both stimulating and astonishing in terms of the schedule and sense of purpose. This volume will impress those unfamiliar with the programme and perhaps even make you jealous of the range of missions available. Whatever happens next will be exciting. While too expensive for individuals, this volume is a useful addition to libraries. — PAUL O'BRIEN.

Formation, Evolution, and Dynamics of Young Solar Systems, edited by Martin Pesch & Oliver Gressel (Springer), 2018. Pp. 374, 24 × 16 cm. Price £129·99/$179·99 (hardbound; ISBN 978 3 319 60608 8).

This is an excellent book with a collection of review articles on our current understanding of the formation of planets and planetary systems presented within an interdisciplinary context. The field of planet formation is currently advancing at a fast pace, driven by observations of unprecedented resolution and sensitivity. Such observations are revealing not only exoplanetary systems of extreme variety but also planet formation as it actually happens within young protoplanetary discs. This is a diverse research area bringing together many fields, from astronomy to planetary science.

The authors of the reviews in this book are leaders in the field, most of them emergent young ones, providing a fresh approach to the discussion of ever-challenging questions. The book covers the entire process of planet formation from protoplanetary discs, which provide the environment in which planets form and grow, to the final outcome of the process, *i.e.*, the expected observed properties of exoplanetary systems. Although there is a clear focus on the theoretical aspects of planet formation, the connection of theory with observations is a recurrent theme throughout these review articles.

The book starts with a critical description of recent observations of protoplanetary discs and continues with discussing current theoretical developments on how these discs evolve and how planets may form in them. Constraints from studies of our own Solar System are discussed within a cosmochemistry context. What I enjoyed most in this book was the description of recent, potentially paradigm-shifting, theories that have been pursued in the last decade: wind-driven disc accretion and quick planet formation *via* pebble accretion are discussed in detail by the people who have been developing those ideas. Interestingly, the book discusses additional constraints for the planet-formation process provided by observations of second-generation planetary systems formed around white dwarfs, *i.e.*, more-evolved stars than our Sun, and in binary stars, which constitute a large fraction of the total stellar population.

This is a book useful to postgraduate students but also to researchers in the field who want to acquire a more holistic understanding of planet formation and expand their research horizons. Each review is written with a clear introduction and in a simple and accessible style, so that the book can be a good read for researchers from other fields who want to delve into the important open questions of planet formation. — DIMITRIS STAMATELLOS.

The Cambridge Photographic Atlas of Galaxies, by M. König & S. Binnewies, translated by P. Helbig (Cambridge University Press), 2017. Pp. 344, 28·5 × 24 cm. Price £44·99/$54·99 (hardbound; ISBN 978 1 107 18948 5).

This is a translation of König and Binnewies' book in German *Bildatlas der Galaxien: Die Astrophysik hinter den Astrofotografien* published by Franckh-Kosmos Verlag. I have not been able to view the original version, but it seems that the translator has done a good job here as the text reads as very accessible English.

The book starts with a very brief chapter on the historical context and classification schemes for galaxies. The rest of the book is the atlas of galaxies, dividing the objects by their general classes. Introducing each section is a useful short chapter on the basic astrophysics around the particular class. The sections are ordered by 'Spirals', 'Barred Spirals', 'Ellipticals', 'Irregulars and Interacting', 'Dwarf', 'Ring', 'Groups and Clusters', and finally 'Active, Quasars and Gravitational Lenses'. Each galaxy has at least one page dedicated to it; with either the picture on the same page as the description or in some cases a full-page image is used. Technical data about the galaxies have been sourced from the NASA/IPAC Extragalactic Database (NED) so should be fairly up to date (as of 2016). All the 'favourite' galaxies seem to be included plus a number that may be less familiar. And there is good coverage of southern-hemisphere objects too.

The pictures used throughout this book are excellent — and whilst they have been taken by amateur astro-photographers they are by no means amateurish. And CUP have done a great job in rendering them well. Many of the images have been taken with large or very large telescopes which are outwith the realm of the average back-yard astronomer. Each image is accompanied by details of the telescope and camera used, the overall exposure time, and the photographer. And a nice touch, which emphasizes the attention to detail in this book, is that the direction of North is indicated with every image. The book is well referenced, providing useful pointers for those wishing to explore in more detail.

This is an excellent book for both reading and dipping into, and more than just a 'coffee-table' publication. It will be a welcome resource for anyone interested in studying, observing, or imaging galaxies, which is rather un-represented in current popular literature. I whole-heartedly recommend it. — CALLUM POTTER.

The Astronomy Book: Big Ideas Simply Explained, by J. Mitton (consultant editor), D. W. Hughes, R. Dinwiddie, P. Johnson & T. Jackson (Dorling Kindersley), 2017. Pp. 352, 24·2 × 20·2 cm. Price £17·99/$17·00 (hardbound; ISBN 978 0 2412 2593 6).

This popular book (no equations) gives an overview of astronomy *via* 100 short chapters (ranging from one to eight pages, though many of the longer chapters begin with a two-page title). It is arranged both chronologically and by subject: each of the seven parts covers a particular span of years and describes the main topics during that time (*e.g.*, 'From Myth to Science 600 BCE–1550 CE', 'The Rise of Astrophysics 1850–1915'). The chapters in each part are preceded by a two-page introduction (and a two-page title). Each chapter contains, in addition to the main text, information on the 'key astronomer(s)' (occasionally, 'key organization' or 'key development') with a timeline divided into 'before' and 'after' (*i.e.*, influences and those influenced) and references to related chapters. In addition, most contain some combination of a pithy quote, a flow chart illustrating the logic behind the basic idea, a photograph or other figure, or a biography of (one of) the key astronomer(s) (with a listing of 'key works'). As such, the book is more like a lecture presentation than a textbook. There is a general introduction before the first part, and the main text is followed by a 'directory' (list of astronomers who didn't make the cut, including Eratosthenes, Huygens, Kapteyn, and Jeans), a glossary, and an index.

The book is well written, though some humour is perhaps unintentional: "He married in 1826 and fathered 12 children. [John] Herschel had numerous interests in addition to astronomy." The production is good and the editing above average. In particular, the illustrations, some familiar and some newly made for the book, are top-notch. I found only a couple of explanations not up to the high standard of the others. The explanation of Hawking radiation is somewhat confusing, though to be fair it is similar to many others and part of the problem is that Hawking himself popularized a too-simple analogy[1]. The discussion of dark matter mentions the possibility of WIMPs as dark-matter particles, though the related discussion of supersymmetry is somewhat confused. Also, I find it strange to mention extra dimensions, the multiverse, *etc.*, as possible explanations for the observations which are usually invoked as evidence for dark matter, while not mentioning MOND at all.

The obvious point of a comparison is a roughly similar, though smaller, book[2] recently reviewed[3] in these pages. That book has fewer topics, though all are covered at the same length, and is similar in style. While I recommend it as well, the book reviewed here has more and much better illustrations, and the historical context and more emphasis on astronomers perhaps make it easier for those encountering the topics for the first time. — PHILLIP HELBIG.

References

(1) http://backreaction.blogspot.com/2015/12/hawking-radiation-is-not-produced-at.html
(2) G. Sparrow, *50 Astronomy Ideas You Really Need to Know* (Quercus), 2016.
(3) P. Helbig, *The Observatory*, **137**, 30, 2017.

OTHER BOOKS RECEIVED

Optimal Spacecraft Trajectories, by John E. Prussing (Oxford University Press), 2018. Pp. 140, 23·5 × 15·5 cm. Price £60 (hardbound; ISBN 978 0 19 881108 4), £30 (paperback; ISBN 978 0 19 881111 4).

This text-book and reference work is aimed at graduates in astronautics and others involved in space missions trying to optimize spacecraft payloads by keeping fuel consumption during flights to a minimum through careful trajectory planning. Problems are provided to test students' understanding.

Practical Astrodynamics, Volumes 1 & 2, by Alessandro de Iaco Veris (Springer), 2018. Pp. 1308, 24 × 16 cm. Price £129·99/$179·99 (hardbound; ISBN 978 3 319 62219 4).

This pair of substantial volumes presents a comprehensive treatment of the theory of all aspects of spacecraft control, and will make an essential companion for any practising flight engineer at a space agency.

ASTRONOMICAL CENTENARIES FOR 2019

Compiled by Kenelm England

The following is a list of astronomical events, whose centenaries fall in 2019. For events before 1600 the main source has been Barry Hetherington's *A Chronicle of Pre-Telescopic Astronomy* (Wiley, 1996). For the 17th to 19th Centuries, lists of astronomical events came from wikipedia and other on-line sources, supplemented by astronomical texts. Discoveries of comets, asteroids, novae, and other objects for 1919 appeared in the February issue of *Monthly Notices of the Royal Astronomical Society* in the following year. There were also references from *Popular Astronomy*, *Journal of the British Astronomical Association*, and *Publications of the Astronomical Society of the Pacific*. Professional discoveries and observations were followed up in *Astronomische Nachrichten*. Details of individual astronomers were supplemented by articles published in *Biographical Encyclopedia of Astronomers* (Springer, 2007). Gary Kronk's *Cometography* Volumes 1–3 (Cambridge, 1999–2007) provided details on all the comets. Finally NASA's Five Millennium Canons of Eclipses and planetary tables were consulted for information on eclipses and planetary events.

1919

January 4: Roscoe Frank Sanford (Mount Wilson Observatory) discovered a nova ($17^{m}\cdot0$) in the Andromeda Galaxy [Nova N12 in M31].

January: Edward Emerson Barnard published *On the Dark Markings of the Sky*, including a catalogue of 182 dark nebulae.

February 3: Death of Edward Charles Pickering. Born in 1846, he became Director of the Harvard College Observatory. He laid the foundations of stellar photometry and spectroscopy with a dedicated group of mainly women astronomers, the Harvard Computers. He also established the Observatory's photographic plate library.

February 13: Roscoe Frank Sanford (Mount Wilson Observatory) discovered a nova ($17^{m}\cdot4$) in the Andromeda Galaxy [Nova N13 in M31].

February 25: A supernova ($11^{m}\cdot5$) appeared in the giant elliptical galaxy Messier 87 (NGC 4486), discovered on archive plates by Innokenti Andreyevich Balanovski (Pulkovo Observatory) in 1922 January. Photographs from Harvard and Pulkovo showed it fading to $12^{m}\cdot4$ on March 3 and $12^{m}\cdot2$ on March 22. It was fainter than $19^{m}\cdot5$ in 1920 [SN 1919A; most likely Type Ia].

March 11: Ida Elizabeth Woods (Harvard College Observatory) discovered a nova in Sagittarius (7^{m}). The nova had outbursts to magnitude 10 in 1901, 1973, and 1991 [V1017 Sagittarii].

March 19: Karl Wilhelm Reinmuth (Heidelberg Observatory) discovered asteroid 1919 FD. It was the sixth Trojan asteroid to be found, lying in the L_4 position, and was named (911) Agamemnon.

May 29: There was a total solar eclipse visible from South America, the South Atlantic, and Central Africa [Saros 136]. Arthur Stanley Eddington was the driving force behind the RAS expedition to photograph background stars during the eclipse to test predictions made by Einstein's theory of General Relativity. Attempts to make those observations during the great American eclipse of 1918 had failed due to poor weather. Eddington was located at the island of Príncipe in the Gulf of Guinea and successfully photographed the background stars. Meanwhile, Andrew Claude de la Cherois Crommelin and Charles Rundle Davidson also photographed the eclipse from Sobral in Brazil. Both groups detected the predicted bending of starlight by the Sun's gravitational field.

July 4: Max Wolf (Heidelberg Observatory) reported a nova in Aquila (11^{m}). The star slowly faded but varied irregularly for several years. More recent studies showed that it was not a true nova but perhaps a 'born-again' star [V605 Aquilae].

July 9: Birth of Olin Jeuck Eggen. He was an American astronomer, who observed stars in the Milky Way; died 1998.

July 18–28: Constitutive Assembly of the International Research Council in Brussels.

July 21: Gretchen Mary Ritchie (Mount Wilson Observatory) discovered a nova in the Andromeda Galaxy. It was $15^{m}\cdot 9$ and remained visible for the rest of the month [Nova N14 in M31].

July 21: John Charles Duncan (Mount Wilson Observatory) discovered a nova in the Andromeda Galaxy. It was $17^{m}\cdot 2$ and reached $17^{m}\cdot 0$ on the 23rd., before fading slowly to $18^{m}\cdot 0$ on August 24 [Nova N15 in M 31].

July 26: Birth of James Lovelock. He is a British scientist, who proposed the *Gaia hypothesis* that the Earth, including its biology, works as a system.

July 28: Foundation of the International Astronomical Union at the Constitutive Assembly of the International Research Council in Brussels.

July 30: Max Wolf (Heidelberg Observatory) recovered periodic comet Kopff, discovered in 1906 but missed in 1913. It was 11^{m} in Aquila and remained so during August before slowly fading. It was last seen on December 11 [Comet 22P/1919 O1 (Kopff)].

August 1: Harlow Shapley (Mount Wilson Observatory) discovered a nova in the Andromeda Galaxy. It was just visible at $18^{m}\cdot 5$ on the 2nd. [Nova N16 in M31].

August 12: Birth of Eleanor Margaret Burbidge (née Peachey). She studied the nucleosynthesis of elements in stars and was part of the influential B^2FH team who wrote *Synthesis of the Elements in Stars* in 1957. She worked on the physics of galaxies and quasars; married to the astronomer Geoffrey Ronald Burbidge (1925–2010).

August 20: Joel Hastings Metcalf (Camp Idlewild, Vermont, USA) discovered an 8^{m} comet in the morning sky in Pegasus. It was independently discovered by several observers over the next few mornings. The comet was widely observed in September, as it could just be seen with the naked eye and had a tail 4° long. It was at its brightest early in October, before fading rapidly, and was last seen on November 18. Orbits calculated at the end of August showed that it was the return of Brorsen's comet of 1847 [Comet 23P/1919 Q1 (Brorsen–Metcalf)].

August 20: Joanna Crighton Stevens Mackie (Harvard College Observatory) reported finding a nova ($9^{m}\cdot 4$) in Ophiuchus on photographic plates. It brightened to $7^{m}\cdot 5$ on September 13 and then faded slowly to $9^{m}\cdot 5$ in October [V849 Ophiuchi].

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August 23: Joel Hastings Metcalf (Cape Idlewild, Vermont, USA) discovered a second comet in Bootes, when it was about 9^m. Alphonse Borrelly (Marseille Observatory) also discovered the comet later that day. The comet slowly brightened during September and October, as it travelled south. It was last seen on 1920 February 17 [Comet C/1919 Q2 (Metcalf)].

September 18: Joanna Crighton Stevens Mackie (Harvard College Observatory) reported finding a nova in Sagitta on archive plates taken in 1913 November. It reached $7^{m}\cdot2$ on the 22nd, and was visible for six weeks. It did not appear on any other plates. Later, outbursts were found in 1946, 1978, and 2001 and is designated a dwarf nova [WZ Sagittae].

September 20: Comet 107P/Wilson–Harrington passed only 0·0525 AU from the Earth; not observed [encounter discovered in 1992].

September 23: Death of Annibale Ricco. Born in 1844, he worked at several Italian observatories. He studied sunspots and prominences, deducing the presence of the solar wind, and observed four solar eclipses. He was briefly Vice-President of the International Astronomical Union.

October 25: T. Sasaki (Kyoto Observatory) discovered a 9^m comet in Capricornus but it turned out to be the return of comet 15P/Finlay. The comet had been missed in 1913 and no ephemeris had been published for 1919. It remained about 9^m during November and then faded rapidly. It was last seen on 1920 March 9, when it was 18^m [Comet 15P].

October 30: Milton La Salle Humason (Mount Wilson Observatory) discovered a nova ($15^{m}\cdot7$) in the Andromeda Galaxy. It faded rapidly to $16^{m}\cdot5$ on October 31 and disappeared on November 30 [Nova N17 in M31].

October 30: Ephemerides had been calculated for the first predicted return of comet 24P/Schaumasse. It was recovered by Gaston Jules Fayet (Nice Observatory) in Virgo, 7° from the predicted position. The comet was about magnitude 12–13 and was last seen on 1920 January 2 [Comet 24P/1919 U1 (Schaumasse)].

November 6: At the joint Royal Society/RAS meeting, results from the eclipse expedition of May 29 were announced, confirming that starlight had been bent by the Sun's gravitational field in accordance with Einstein's theory of General Relativity.

November 11: Death of James Law Challis. Born in 1833, the son of the noted astronomer James Challis, he lectured on astronomy and was Fellow of the RAS.

November 26: A brilliant fireball travelled across southern Michigan and northern Indiana in the United States, followed by a loud noise 3 minutes later. There was considerable physical damage over a wide area and some disruption to electrical systems [similar to the Chelyabinsk meteor of 2013].

November 26: Birth of Frederik Pohl. He was a prolific American science-fiction writer; died 2013.

December 6: Joanna Crighton Stevens Mackie (Harvard College Observatory) discovered a nova in Lyra ($6^{m}\cdot5$). The star was fainter than $16^{m}\cdot5$ on the 4th. It faded steadily to $8^{m}\cdot5$ by the beginning of 1920 [HR Lyrae].

December 6: A nova was discovered in the Triangulum Galaxy Messier 33 ($17^{m}\cdot2$) [Nova N1 in M33].

December 10: While searching for comet 17P/Holmes, Wilhelm Heinrich Walter Baade (Hamburg Observatory) found a nebulous object on two photographs. This was probably a comet, but bad weather prevented any follow-up observations.

December 19: James Francis Skjellerup (Cape Town, South Africa) discovered a 9^m comet in Libra, while observing the variable RS Librae. The comet was only observed until December 24, as it moved into the twilight horizon. Searches for the comet after perihelion found nothing [Comet C/1919 Y1 (Skjellerup)].

December: Robert Hutchings Goddard published *A Method of Reaching Extreme Altitudes*, a seminal book on rockets and their use to study the Earth's upper atmosphere and beyond, including the Moon.

1819

January 3: Birth of Charles Piazzi Smyth. The son of the astronomer William Henry Smyth, he observed Halley's Comet in 1835 and the Great Comet of 1843. He was Astronomer Royal for Scotland (1846-88), investigated observing conditions on Tenerife and made extensive studies of the Great Pyramid at Giza; died 1900.

April 26: Mars and Saturn were only 45 arcminutes apart.

April 28: Venus and Saturn were only 38 arcminutes apart.

June 5: Birth of John Couch Adams. He was a British mathematician, who calculated the position of a possible planet beyond Uranus in 1845, later to be the planet Neptune. He became President of the RAS and Lowndean Professor of Astronomy at the University of Cambridge; died 1892.

June 12: Jean Louis Pons (Marseille, France) discovered a small, tailless comet in the western sky in Leo. He observed it during June, when it was just below naked-eye visibility. The comet was last seen on July 19, as it entered evening twilight. The comet's orbit was distinctly elliptical, but the orbital period was very uncertain. The comet was accidentally re-discovered in 1858, revealing that it had an orbital period of 5·55 years. It was known as Winnecke's comet during the 19th Century [Comet 7P/1819 L1 (Pons–Winnecke)].

June 13: Soon after sunrise a fireball appeared over Jonzac in Aquitaine, France, and explosions were heard. A shower of stones landed, including two weighing 3 kg and 2 kg. The meteorites are noted as eucrites, probably originating from the asteroid Vesta.

June 17: Johann Wilhelm Pastorff (Buchholz, Saxony) reported seeing two small, black spots on the Sun. He interpreted them as an intra-Mercury planet with a small moon transiting the Sun.

June 26: Franz von Gruithuisen (Munich, Bavaria) reported seeing two small, black spots on the Sun, similar to Pastorff's observation.

July 1: Johann Georg Tralles (Berlin, Germany) made the first observation of a spectacular comet in evening twilight. It was easily visible with the naked eye and discovered independently by several observers over the next few days. It had a bright coma and a 10° tail, found to be polarized, and was bright enough to be seen in full moonlight. The comet faded as it moved through Lynx to Ursa Major in August. At the end of the month it faded rapidly and could only be followed in telescopes until October 25. Calculations showed that the comet had passed across the Sun's disc at perihelion shortly before discovery [Comet C/1819 N1 (Great)].

July 20: Death of John Playfair. Born in 1748, he was a British geologist who followed James Hutton's view of 'Deep Time' for the geological history of the Earth. He was Professor, first of Mathematics and then of Natural Philosophy, at Edinburgh University.

November 9: Birth of Annibale de Gasparis. He was an Italian astronomer who became Professor of Astronomy and Director of the Naples Observatory. He discovered eight asteroids: (10) Hygiea, (11) Parthenope, (13) Egeria, (15) Eunomia, (16) Psyche, (24) Themis, (63) Ausonia, and (83) Beatrix; died 1892.

November 21: Johann Wilhelm Pastorff (Buchholz, Saxony) reported seeing two small, black spots on the Sun again. These observations supported the view that a small planet, Vulcan, orbited the Sun closer than Mercury; later disproved.

November 28: Jean Jacques Blanpain (Marseille, France) discovered a comet in the morning sky in Virgo. It had a small coma but no tail. Blanpain only observed the comet until December 2. Then Jean Louis Pons (Marlia, Italy) found the comet on December 5, and it was followed by several astronomers with difficulty until 1820 January 25. The comet's orbit was distinctly elliptical with a period of about 5 years. The comet remained lost until it was accidentally re-discovered as an asteroid in 2003 [Comet 289P/1819 W1 (Blanpain)].

Johann Franz Encke published his study of the orbit of comet 1818 in *Correspondance Astronomique*. He identified it with comets seen in 1786, 1795, and 1805 and predicted that it would return in 1822 [Comet 2P/Encke].

Ernst Florens Friedrich Chladni published *Ueber Feuer-Meteore und über die mit denselben herabgefallenen Massen* (*On the Fiery Meteors and on the Masses that fell down with them*), summarizing all that was known about meteorites.

1719

March 19: A brilliant fireball appeared over Hereford, England. It was brighter than the Moon and seen across Northern Europe. Edmond Halley estimated that it was 150 miles (240 km) high.

August 20: Birth of Christian Mayer. He was a German astronomer who observed the transits of Venus in 1761 and 1769. He observed possible double stars and produced a catalogue of 80 double stars in 1778. He suggested that they could be physically connected; died 1783.

August 25: Mars was closest to the Earth (0.3740 AU), the nearest approach until 2003.

September 7: Death of John Harris. Born in 1666, he lectured on astronomy and was secretary of the Royal Society. He wrote *Astronomical dialogues between a gentleman and a lady*, published in 1719.

December 31: Death of John Flamsteed. Born in 1646, he became the first Astronomer Royal in 1675 and established the Royal Observatory at Greenwich. He studied the motion of the Moon and drew up star maps and a catalogue of 2935 stars, published posthumously in 1725 as *Historia Coelestis Britannica*. This included a pre-discovery observation of Uranus in Taurus. Flamsteed numbers are still in use for many of the brighter stars.

1619

February–March: Chinese astronomers observed a comet in the southeast before sunrise. The tail was sharply curved and about 100° long. It must have been a short-lived apparition, as no European observer saw the comet. It is likely to have passed very close to the Sun but was not a member of the Kreutz sungrazer comet group. The Chinese also saw two bright meteors on the same night.

September: Death of Hans Lippershey. Born in about 1570, he was a Dutch spectacle-maker in Middelburg, Zealand, who constructed a refracting telescope and applied for a patent in 1608; buried September 29. As well as its military applications, it was the single greatest development for astronomy and in the hands of Galileo revolutionized the science.

Johannes Kepler published *De Cometis Libelli Tres* (*Three Pamphlets About Comets*), describing the observations of the comets of 1607 (Halley) and 1618.

Johannes Kepler published *Harmonices Mundi* (*The Harmonies of the World*), including his third law of planetary motion.

Orazio Grassi published *De tribus cometis ann. Mdcxvii disputatio astronomica* (*An astronomical argument on the three comets of the year 1618*), which argued against the views of Copernicus but included observations of the comets, placing them beyond the Moon (as Tycho did).

Mario Guiducci published *Discorso delle comete* (*Discourse on Comets*), mainly written by Galileo, as a rebuttal of Grassi's views, placing comets as atmospheric phenomena.

John Bainbridge published *An astronomicall Description of the late comet of 1618*, describing observations of the third comet of the year.

1519

January 1: Piero di Dino published a star map of the southern sky.

May 2: Death of Leonardo da Vinci. Born in 1452, he became the most famous artist and scientist of Renaissance Italy. He drew naked-eye observations of the Moon, showing geographical features that he thought of as land and sea. He recognized Earthshine as sunlight reflected from the Earth onto the Moon.

July 5: Korean astronomers observed stars scattered like fireballs, a prominent meteor-shower display.

1419

June 12: Japanese astronomers observed a comet with a long tail in the northeast just after midnight, as it appeared in the morning sky before sunrise.

Death of Mikulas of Kadan. Born about 1350, he was an imperial clockmaker, who co-designed the Prague astronomical clock.

1319

January 12: Death of Kamal al-Din Hasan ibn Ali ibn Hasan al-Farisi. Born in 1267, he was a Persian scholar who wrote on mathematics, optics, and the refraction of light.

May 31: Korean astronomers observed a comet moving from Perseus to Cassiopeia. It moved to the northeast on June 4 and was near Corona Borealis on July 1, before disappearing on July 9.

1119

June 28: An aurora appeared.

July 31: Mars was closest to the Earth (0·3734 AU).

August: An aurora appeared.

September 28: Florence of Worcester recorded a comet.

Zhu Yu published *Pingzhou Ketan* (*Pingzhou Table Talks*), a book on naval technology, including the magnetic compass and its use for navigation.

1019

February 6: Korean astronomers observed a comet in the morning sky near Ophiuchus. This report could be dated to 1020.

April 8: Abu Rayhan Muhammad ibn Ahmad al-Biruni observed the Sun rise in eclipse from Langhan, Afghanistan. The Sun was one-third covered by the Moon and near the end of the eclipse. The eclipse was annular in Siberia [Saros 113].

July 30: Chinese observers discovered a comet in Ursa Major. It moved north to Leo and then more quickly to the west. It was last seen on September 4, when it was in Hydra.

September 17: Abu Rayhan Muhammad ibn Ahmad al-Biruni observed a lunar eclipse from Ghazni, Afghanistan, and wrote a detailed report. [Saros 92.]

919

February 17: Saturn was occulted by the Moon.

An aurora was observed from Russia.

719

A Persian astronomer from Chaghariyan (Tocharistan) known as Ta Mu She arrived in China to exchange astronomical information and ideas. He was part of an official diplomatic delegation.

619

Stephen of Alexandria published *A Commentary to Ptolemy's Handy Tables* for the latitude of Constantinople.

Fu Jen-chun compiled a new calendar *Mao-yin-li* for China, using the motions of the Sun and the Moon.

519

October–December: A comet appeared. This may be part of a record concerning the comet of 520.

419

February 17: Chinese and Korean astronomers observed a comet near β Leonis.

319

May 6: At Constantinople 'there was a darkness at the 9th hour of the day (mid-afternoon).' There was a total solar eclipse, which passed across Southern England (including London), the northern frontier of the Roman Empire, and the north coast of the Black Sea [Saros 72]. Totality reached Georgia and may explain a story about Mirian III King of Iberia. While out hunting, the land became dark and the king thought that he had become blind. On praying, light returned and as a result Mirian was converted to Christianity.

219

The emperor Elagabalus placed the Sacred Stone of Emesa in its own temple in Rome. Almost certainly a meteorite, it was returned to Emesa in Syria in 222.

119

A papyrus from Oxyrhynchus in Egypt converted Roman and Alexandrian calendars.

AD 19

There is a very uncertain report of a comet seen from China.

82 BC

At Rome Lucius Marcius Censorinus and the other moneyers issued denarii with the bust of Venus on the obverse and Venus in a two-horse chariot on the reverse.

182 BC

Spring: Chinese observers saw a star visible in daytime. Venus was favourably placed in the morning sky from February to April and was at Greatest Western Elongation on March 10.

282 BC

August 6: A total solar eclipse was visible across Spain, Northern Italy, the Northern Balkans, and the north coast of the Black Sea. Surprisingly, there are no references in Ancient Greek sources [Saros 60].

382 BC

June 18: Babylonian astronomers made detailed observations of a partial lunar eclipse [Saros 43].

July 3: Chinese astronomers observed a total solar eclipse, when stars became visible. The path of totality crossed the northern part of China [Saros 69].

December 13: Babylonian astronomers made detailed observations of a total lunar eclipse [Saros 48].

482 BC

September–October: Chinese astronomers observed a comet in the east before sunrise.

OBITUARY

Allan James Willis (*1951–2018*)

I first met Allan over 40 years ago when I joined the British project team just before the launch on 1978 January 26 of the *International Ultraviolet Explorer* (*IUE*). That team was led by Professor Sir Robert Wilson of University College London, and in many respects, Allan was his 'scientific son', having been one of Bob's first PhD students. His thesis topic, begun in 1970, was an analysis of optical and UV observations of Wolf-Rayet stars, including the brightest one, γ^2 Velorum. This led to him becoming a pundit on UV astronomy, something that I (as a pretty old-fashioned optical astronomer) was keen to tap into for my work as a Resident Astronomer on *IUE* at the ESA 'Vilspa' tracking station near Madrid.

Very soon Allan became a good friend and was often out at our villa in Las Matas for a meal, a dip in the pool, or a flamenco show at Arco de Cuchilleros in Madrid. He also got me involved in his scientific endeavours with hot stars, and we collaborated merrily for several years on a number of investigations, CQ Cep and other WR binaries among them. Perhaps equally enjoyable was my introduction to the hot-star conference circuit, with symposia in Bali, Elba, and Porto Heli in Greece among many. Allan played a major role in these festivities, often on the scientific organizing committee, and regularly giving a keynote lecture.

On my return to the UK, Allan remained a regular visitor, first to our house in Sussex, where he frequently tormented me over a pint or three by foretelling the demise of the Royal Greenwich Observatory (or 'sleepy hollow' as he described it). But we remained pals and he began to involve me in his ornithological passion, with visits to bird reserves near his home in Kent, and latterly to Otmoor in Oxfordshire, near our home, after I was — very reluctantly, but, as it turned out, fortunately — transferred from RGO to Rutherford Appleton Laboratory. (His prophesy over the RGO was correct!)

Just a couple of years ago, Allan was diagnosed with kidney cancer but apparently made good progress with a changing menu of therapies. But earlier this year, that good progress was cast aside by a collapsed lung, the perhaps-slow treatment of which resulted in a substantial loss of weight (not that Allan ever had much to spare). He was, characteristically, vexed to miss out on our cruise on the Douro in July. Clearly the situation was serious but still I was shocked and deeply saddened to learn that Allan had passed away on the morning of September 3.

Allan had a distinguished career in astronomy, and although an international player he remained a UCL man through and through: awarded his PhD in 1976, he went on to hold posts as an SERC Postdoctoral Research Assistant (1976–79), SERC Advanced Research Fellow (1979–84), and Royal Society University Research Fellow (1984–92). He was promoted to Reader in 1990, Professor in 1995, and Emeritus Professor on his retirement in 2006. As well as supervising a series of PhD students, many of whom have themselves gone on to successful academic careers, he was active in 'astropolitics' at national and international level. (I'm grateful to Professor Ian Howarth for some details of Allan's early career at UCL.)

Allan will be greatly missed by his many friends and colleagues; I have certainly lost a wonderful companion. — DAVID STICKLAND.

Here and There

BREXIT SOLVED: LONDON RE-LOCATED TO NORTHERN ITALY

Tiangong-1, or "The Heavenly Palace" is expected to re-enter Earth's atmosphere somewhere between the 43rd north and south parallels, roughly between the latitudes of London in Britain and Wellington in New Zealand, according to the European Space Agency (ESA). — *The Daily Telegraph*, 2018 March 28, p. 17.

HE'D BE SUPERMAN

If Gill could achieve a diurnal baseline of about 24,000 km, … — *J. Hist. Astron.*, **49**, 16, 2018.