THE OBSERVATORY

DOES VISCOSITY TURN INFLATION INTO THE CMB AND Λ?

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Consideration of the entropy production in the creation of the Cosmic Microwave Background leads to a simple model of the evolution of the Universe during this period which suggests a possible connection between the small observed acceleration term and the early inflation of a closed universe. From this we find an unexpected relationship between the Omegas of cosmology, and calculate the total volume of the Universe.

Introduction

While the uniformity of the large-scale structure of the Universe and the Gaussian structure of its fluctuations argue that some form of inflation occurred, as was early considered by Kasanas[1], there is as yet no agreed prediction for the amplitude of the fluctuations or for the entropy of the CMB. This entropy is by far the dominant contribution to the entropy of the Universe[2] unless the rather different gravitational entropy of giant black holes is considered. Such black holes are thought to be formed much later than the CMB, as observed by the *Planck* satellite. Here we shall follow Padmanabhan & Chitre[3] in using a purely phenomenological fluid-mechanical approach to the generation of the CMB's entropy which must have occurred close to the end of the inflationary era. At that time the major contributions to the density were the density of inflationary material ρ_i and the density of radiation ρ_r, so $\rho = \rho_i + \rho_r$. These are associated with pressures $p_i = -\rho_i c^2$ and $p_r = \frac{1}{3}\rho_r c^2$. In a homogeneous medium in uniform expansion, shear viscosity has no effect so the source of dissipative entropy creation is bulk viscosity which is zero for pure radiation by itself. We shall consider that the CMB has all the entropy, which increases as a result of the decay of the inflationary density. Let $a(t)$ be the scale factor and let $V = \frac{1}{3}4\pi a^3$. The expression for the bulk viscous stress tensor[4] is

$T^i_{j(visc)} = \zeta(\delta^i_j - u^i u_j)u^k_{;k}$ where ζ is our phenomenological coefficient of bulk viscosity which must vanish for pure radiation, $\rho_i = 0$. We shall also suppose that it vanishes when there is only inflationary material, $\rho_r = 0$. Without viscosity the radiation-and-Lambda universe can be integrated even with k the curvature term included[5]. Einstein's equations with the inclusion of the viscous term are

$$(\dot{a}^2 + kc^2)/a^2 = \tfrac{1}{3}\,8\pi G\rho, \qquad \dot{V}^2/V^2 \doteq 24\pi G\rho = \omega^2 X^2, \qquad (1)$$

(which is unaffected by viscosity) and which takes the second form when $k = 0$ or is inflated away. Here ω^2 is the constant $24\pi G\rho_0$ and $X^2 = \rho/\rho_0$, so the constant ρ_0 goes out. We choose it above equation (12). The other Einstein equation for homogeneous cosmology is

$$TdS/dt = d/dt(\rho c^2 V) + p\,dV/dt = \zeta\dot{V}^2/V. \qquad (2)$$

Here T is the temperature of the radiation and S is the entropy in volume V. We treat our system of inflationary density $\rho_i(t)$ and radiation $\rho_r(t)$ as analogous to a two-fluid system. Neither fluid treated in isolation has any bulk viscosity but we are going to argue that there is an effective bulk viscosity for the combined two-fluid system. We argue by analogy to a system of two perfect inviscid gases, one with an adiabatic index of, say, five thirds and the other of four thirds. If there were no interaction at all and both were initially at the same temperature, then after expansion the fluid with the higher index would have a lower temperature than the other. The resultant heat flow would cause an entropy increase unless the whole expansion were so slow that the temperature kept them in equilibrium at all times. In practice they would not quite equilibrate and the entropy creation *via* bulk viscosity depends on $\dot{V}^2$ so it only dissipates significantly when changes are quick enough.

We do not claim that the system of inflationary density and radiation is a direct analogue of the two-fluid system just discussed. We merely cite the latter as an example in which entropy is created *via* expansion and therefore *via* a bulk viscosity also, despite each fluid being inviscid in isolation. We emphasize that this form of bulk viscosity only occurs in a two-component system when those systems exchange energy because of the expansion. We shall therefore assume that our combined system has an effective coefficient of bulk viscosity ζ which must vanish when either ρ_i or ρ_r is zero. In the example just cited there was an exchange of internal energy between the two fluids that resulted from the expansion and led to the entropy increase. Thus we are led to the idea that the effective bulk viscosity is the vehicle through which the inflationary density decays to make the CMB. Thus we set

$$Vd(\rho_i c^2)/dt = -\zeta\dot{V}^2/V, \qquad (3)$$

where ζ must vanish when either ρ_r or ρ_i are zero. Since the velocity field on which the viscosity acts is only defined for the radiation field (inflationary material having no rest frame), it is natural to define a kinematic viscosity *via* the density ρ_r. For the dependence on ρ_i we take the ansatz,

$$\zeta = \nu_0\rho_r\sqrt{\rho_i/\rho}, \qquad (4)$$

where ν_0 is a kinematic bulk viscosity with dimensions $[L^2 T^{-1}]$. The square-root dependence leads to easier mathematics. In practice we shall work with a dimensionless kinematic viscosity $\nu = \tfrac{3}{4}\nu_0\omega/c^2$, so then $\zeta\dot{V}^2/V^2 = (4/3)\nu c^2\omega\rho_r\,XY$

where $Y = \sqrt{\rho_i/\rho_0}$,. Indeed with our final choice of ρ_0 as the density of the initial inflation, our dimensionless v will turn out to be 1, but for the present we retain it and leave ρ_0 to be decided later. We have now completed the physical input on which our model is based. Notice that we have only postulated something with the equation of state $p_i = -\rho_i c^2$. We have not postulated a scalar field with a specially chosen potential but we have assumed that inflation decays and we have postulated that it does so *via* the effective bulk viscosity that appears when two substances exchange energy *via* the expansion. Since the laws of thermodynamics are universal our only special assumption is the form assumed for the bulk viscosity. For different studies of inflation's end see ref. 6. To demonstrate that our equations do not violate causality by implying that sound waves move faster than light, we now show that our total stress-energy tensor including the viscous term obeys the strong energy condition which, for an isotropic system, reduces to a positive energy density which is not less than the modulus of the other diagonal components of the stress tensor. On putting $v = 1$ by choice of ρ_0 (see later), and dividing by $\rho_0 c^2$ these conditions are $X^2 \geq 0$ which is clearly satisfied, and $X^2 \geq |-Y^2 + (⅓)(X^2 - Y^2)(1 + 4Y/X)|$. Putting $z = Y/X$, this last condition is satisfied if $1 \geq |-z^2 + (⅓)(1 - z^2)(1 + 4z)|$ for all z in the range $0 \leq z \leq 1$ which is easy to demonstrate. Thus with this form of viscosity our actual solution obeys the conditions of causality and does not allow energy to move faster than light.

Mathematical solution and elucidation

Equation (3) divided by $\rho_0 c^2 V$ becomes

$$dY^2/dt = -[\zeta/(\rho_0 c^2)]\,\dot{V}^2/V^2, \qquad (5)$$

and equation (2) divided by $\rho_0 c^2 V$ becomes

$$dX^2/dt = -⅘(\rho_r/\rho_0)\,\dot{V}/V + [\zeta/(\rho_0 c^2)]\,\dot{V}^2/V^2. \qquad (6)$$

On division and simplification $Y = 0$ or

$$\frac{X\,dX}{Y\,dY} = \frac{\omega X}{v Y}\frac{V}{\dot{V}} - 1, \qquad \left(\frac{1}{v} - Y\right)\frac{dY}{dX} = X, \qquad (7)$$

where we used the approximate form of equation (1) only to get the final equation. On integration we find the circles seen in Fig. 1.

$$X^2 + (Y^2 - 1/v)^2 = R^2, \qquad (8)$$

where R^2 is the constant of integration. The region above the diagonal is unphysical. We require a solution with no initial entropy and therefore no CMB, so initially $X = Y$. Solutions starting above the horizontal line BS, such as ASEO, have a strange initial increase in density, caused by decay of ρ_i, despite the universal expansion as they traverse AS. All the inflationary density has disappeared when E is reached. Thereafter the final trajectory EO is a pure radiation universe. The solution that starts at B has no initial change in density and has eliminated all inflationary density when it reaches O where the total density vanishes too. In solutions such as CD a variable inflation never ceases and all the CMB has disappeared when D is reached. We shall concentrate on the circle solution BO which has $R = 1/v = 1$. To find how this solution behaves
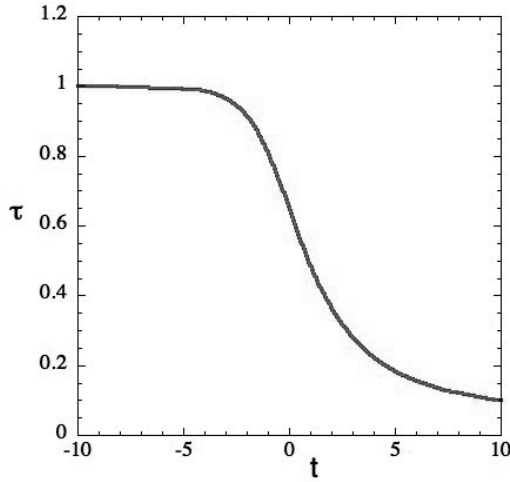
The inflationary density Y^2 and the total density X^2 plotted in square-root form as $Y(X)$ with $v = 1$. Different solutions lie on different circles.

in time we turn to equation (5) and use (1), (4), and (8), with $R = 1/v$, to recast it in the form

$$\tilde{t} = (4/3)\omega t/v = \int - \frac{v^{-2}dY}{[Y(v^{-1}-Y)]\sqrt{2v^{-1}Y - Y^2}}. \tag{9}$$

With the substitution

$$Y = \frac{2(\tau^2/v)}{1 + \tau^2}, \tag{10}$$

the integral is evaluated to give

$$\tilde{t}(\tau) = \frac{4\omega t}{3v} = \frac{1}{\tau} + \ln\left(\frac{1-\tau}{1+\tau}\right), \ X = \frac{2(\tau/v)}{1+\tau^2}, \ \frac{\rho_r}{\rho_0} = X^2 - Y^2 = \frac{4\tau^2(1-\tau^2)}{v^2(1+\tau^2)^2}. \tag{11}$$

From these formulae we get the density X^2, the inflationary density Y^2, and the radiation density as functions of time. The graph of $\tau(\tilde{t})$ is shown in Fig. 2.

As τ tends to unity from below, t tends to negative infinity, X and Y become $1/v$, the radiation density vanishes; thus at negative infinite time we start in a pure inflationary state with a density $\rho_I = \rho_0/v^2$. We now choose our as-yet-arbitrary ρ_0 to be the density ρ_I of this initial inflationary state. This implies that our dimensionless $v = 1$ and $\omega^2 = 24\pi G\rho_I$, $v_0 = \frac{1}{34}c^2/\omega$. The vs in the denominators of $X, Y, X^2 – Y^2$, *etc.* all disappear.

From nearly infinite negative time to a finite but negative time, τ decreases very gradually from 1, and when the logarithmic term becomes -2, $\tau = (e^2 - 1)/(e^2 + 1) = 0·76$ and $\tilde{t} = -0·689$. Later, when the logarithm is -1, $\tau = 0·462$ and $\tilde{t} = 1·164$. Soon thereafter the logarithmic term has little influence and the standard solution for the radiation-filled Universe takes over with $\tilde{t} = 1/\tau$ and $\frac{1}{3}8\pi G\rho = 1/(2t)^2$, $\rho_r = \rho$.

FIG. 2

$\tau(\tilde{t})$ as a function of dimensionless time, $\tilde{t}$. For a long time from $-\infty$, τ remains very close to one as the Universe inflates. Then viscous dissipation turns inflationary energy into the CMB. Thereafter $\tau \propto 1/\tilde{t}$ which is the era of the radiation Universe.

A nice feature of this model is that we can integrate to find the scale factor. From equations (1) and (9) we deduce that

$$\frac{\dot{a}}{a\dot{Y}} = \frac{da}{a\,dY} = \frac{\omega X}{3\dot{Y}} = -\frac{1}{2(X^2 - Y^2)}, \tag{12}$$

which, thanks to equation (8), integrates to give

$$(a/a_h)^4 = [(Y)^{-1} - 1] = (1 - \tau^2)/(2\tau^2), \tag{13}$$

where a_h is the value of a when $Y = \frac{1}{2}$ and the radiation density reaches its maximum of $\rho_I/2$. At large times $1/\tau = \tilde{t}$, $a \propto \tilde{t}^{1/2}$ and we have the radiation Universe. From equations (13) and (11)

$$\rho_r a^4 = 2\rho_I a_h^4 \left[\frac{1 - \tau^2}{1 + \tau^2}\right]^2 \to 2\rho_I a_h^4 \tag{14}$$

which becomes constant as $\tau \to 0$. This gives the energy in the black-body radiation at late times such as the present. Using σ for Stefan's constant, standard statistical mechanics of black-body radiation gives an entropy density $s = (4/3)(4\sigma/c)T^3$, corresponding to an energy density $\rho_r c^2 = (4\sigma/c)T^4$, thus $s = (4/3)(4\sigma/c)^{1/4}(\rho_r c^2)^{3/4}$. The entropy per unit co-moving volume merely accumulates as the inflationary matter decays. The expansion does not affect it. The total entropy generated in the closed Universe at the end of the inflationary era is the entropy density times the volume of the closed Universe today. This is evaluated at $\tau = 0$.

$$S = 2\pi^2 a^3 s = (8/3)(4\sigma/c)^{1/4}\pi^2[a^3(\rho_r c^2)^{3/4}]_0; \qquad k = +1; \tag{15}$$
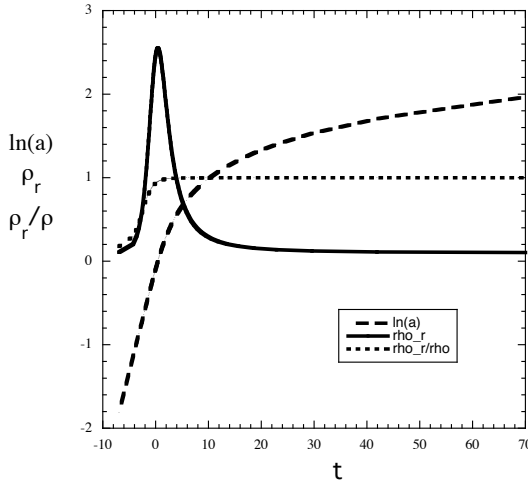
we know all the terms in this expression except a.

The radiation density both linearly and as a fraction of the total density is plotted together with $\ln(a)$ as functions of time $\tilde{t}$. As inflationary density generates the CMB *via* viscosity there is a strong peak in the radiation density whose maximum reaches a half of the initial inflationary density ρ_i; thereafter the coupling dies out as the CMB's intensity diminishes.

Late re-inflation in a closed universe

In the considerations above we neglected the curvature term k/a^2 in equation (1). It is indeed small near the end of the inflationary era and in the radiation era, but both the inflationary density and the radiation density eventually become small. Could it be that this small term eventually outlasts the others? We shall evaluate this small term using perturbation theory. The second equation (1) becomes

$$\dot{V}^2/V^2 = \omega^2 X^2[1 - 9kc^2/(\omega^2 X^2 a^2)]. \tag{16}$$

Then the first of equation (7) becomes

$$\frac{XdX}{YdY} = \frac{1}{Y}[1 + 9kc^2/(2\omega^2 X^2 a^2)] - 1. \tag{17}$$

We now multiply by $2Y$ and integrate under the initial condition that $X = Y = 1 = \tau$ to find

$$X^2 = 2Y - \frac{9kc^2}{\omega^2 a_h^2}\int_Y^1 \frac{a_h^2 dY}{a^2 X^2} - Y^2. \tag{18}$$

We evaluate the integral using the unperturbed functions a/a_h given in (13) and X given in (8), remembering that ν is now 1. The integral becomes $I = \int (Y - Y^2)^{-1/2}(2 - Y)^{-1} dY$. We put $Y = \tilde{\tau}^2/(1 + \tilde{\tau}^2)$ and find

$I = 2^{-1/2}[\pi/2 - \tan^{-1}(\tilde{\tau}/\sqrt{2}\,)]$. Note that $\tilde{\tau} = \sqrt{2}\,\tau/\sqrt{1 - \tau^2}$. Thus

$$X^2 = 2Y - Y^2 - 2\delta(\tau), \quad \delta(\tau) = \frac{9kc^2}{\sqrt{2}\,\omega^2 a_h^2}\left[\frac{\pi}{2} - \tan^{-1}\frac{\tau}{\sqrt{1 - \tau^2}}\right]. \qquad (19)$$

Inflation ensures that $3c/(\omega a_h) \ll 1$; much is beyond the current horizon at the end of inflation so this δ is indeed small. We notice that $\delta(\tau)$ does not vanish at late times when $\tau \to 0$. Indeed the big bracket becomes $\pi/2$. The destruction of inflationary density ceases because there is too little radiation left, so the viscosity becomes too weak. We look to times when $\rho_r/\rho_I = X^2 - Y^2 = 0$. From (19) this occurs when $\frac{1}{2} - Y = \frac{1}{2}\Delta$, $\Delta^2 = 1 - 4\delta$ or approximately when $Y = \delta$. Thus in such a model the inflationary density never quite disappears but survives the radiation era to emerge as a Lambda-like term when the radiation dies out. δ has a very minor effect on the transition from the inflationary era to the radiation era but, as the radiation density finally decreases, it becomes constant and then represents the survival of a remnant of the inflationary density. Although δ is a function of τ it only becomes important when it is constant. For this reason we shall treat it as though it were constant in our mathematics but we shall remember that it is near zero during the inflationary era but almost constant during the radiation era. The radiation density $X^2 - Y^2 = 0$ when $-\delta + X - Y^2 = 0$, $Y = 2\delta/(1 \pm \sqrt{1 - 4\delta}) \doteq 2\delta/[1 \pm (1 - 2\delta)]$. The upper sign gives a root close to δ in place of zero while the lower sign gives a root 1. Any solution for Y that starts between these roots is limited to lie between them at all times so the lower root gives a lower bound to the inflationary density. If we have a very small δ we may identify the small root with the current Lambda term by putting $\delta = (\sqrt{\rho_\Lambda/\rho_I} - \rho_\Lambda/\rho_I)$, where the final term is negligible. The use of (19) along with (14) and (15) gives us an important relationship between the current Λ term, the initial inflation in a closed $k = 1$ universe, and the total entropy in its CMB, currently ($\tau \to \delta$).

$$\sqrt{\Lambda c^2} = \sqrt{8\pi G\rho_\Lambda} = \frac{(3\pi/2)kc^2}{\sqrt{16\pi G\,\rho_I a_h^2}} = \frac{(3\pi/2)kc^2}{(\sqrt{8\pi G\rho_r a^2})_0} = C_1/S^{2/3}; \qquad (20)$$

$$\sqrt{\Omega_\Lambda \Omega_r} = -(\pi/2)\Omega_k \qquad (21)$$

where C_1 is a known constant and (21) follows from the definitions of the Ωs with $\Omega_k = -kc^2/(a^2 H_0^2)$. Notice that a negative k is inconsistent with (21) so with these parameters renewed inflation is evidence for a closed universe. For $\Omega_\Lambda = 0.7$ and $\Omega_r = 8.8 \times 10^{-5}$ equation (21) gives $\Omega_k = -0.0050$. This is fully consistent with the *Planck* data on its own[7] which gives -0.005 ± 0.017 and is also consistent with that data supplemented with data from Baryon Acoustic Oscillations which give 0.00 ± 0.005. From equation (20) we may determine the total entropy from the measured Λ term, and dividing the total entropy by the measured entropy density we find the volume of the whole Universe. We can actually do this more directly by solving equation (20) for a^2 and using the expression $V_T = 2\pi^2 a^3 = 55777\,(c/H_0)^3$ for the total volume of the closed Universe and $a = 14.1c/H_0$.

For small delta the expression for $\tilde{t}(\tau)$ is only slightly modified to

$$\tilde{t}(\tau) = \frac{1}{q^3\tau} + \ln\left(\frac{1 - \tau}{1 + \tau}\right) + O(\delta^2) = \frac{16c^2 t}{9\nu_0} = \frac{4\omega t}{3}, \quad q^2 = 1 - 2\delta, \qquad (22)$$

When we do not neglect δ^2, the expression for $\tilde{t}$ is more complicated, but putting $\delta = 0$ for the terms that dominate during inflation and leaving it for the terms that matter later we find

$$\tilde{t}(\tau) = \ln\frac{1-\tau}{1+\tau} + \ln\left[\frac{\tau+\beta}{\tau-\beta}\right]^{\mu}, \quad \mu = \frac{1-\Delta+2q}{\Delta\sqrt{(q+q^2+\delta)(q^2-\delta-q\Delta)_0}} \doteq 2/\delta,$$

$$\beta^2 = \frac{\delta^2}{2(q+1-\delta)} \doteq \left[\frac{\delta}{2}\right]^2, \qquad \Delta^2 = 1-4\delta, \quad q^2 = 1-2\delta. \tag{23}$$

τ now lies in the range $\beta \leq \tau \leq 1$ and at both ends $X = Y$. Notice that $\beta = O(\delta)$. When $\tau \gg \beta$ and $\delta \ll 1$ (22) agrees with (23). The expressions for X and Y, remembering that $q = 1$ when $\tau = 1$, are

$$X = 2q\tau/(1+\tau^2) \quad \text{and} \quad Y = \left[1 - q\frac{1-\tau^2}{1+\tau^2}\right] = \frac{[(2-\delta)\tau^2+\delta]}{(1+\tau^2)}. \tag{24}$$

The initial inflation occurs as τ approaches one from below. In the end as $\tau \to \beta$, $\tilde{t} \to \infty$, $Y \to 1 - q(1-\beta^2)/(1+\beta^2) \doteq \delta$ so a small part of inflationary material now survives. Nevertheless there is still a long period in which radiation dominates

$$\rho_r = \rho_I(Y - Y^2 - \delta); \qquad \rho_r/\rho = (X^2 - Y^2)/X^2 = \frac{Y - Y^2 - \delta}{Y - \frac{1}{2}Y^2 - \delta}. \tag{25}$$

Whenever Y is small but greater than the small $\delta + 10\delta^2$, we see that the radiation is the dominant contribution to the density, and from (22) this occurs when τ is small and $\tilde{t}$ large but not so large that the residual ρ_Λ takes over. We can again integrate equation (12) with the new formula for $X^2 - Y^2$. Without assuming δ small this gives

$$(a/a_1)^4 = \left[\frac{\Delta}{Y - (1-\Delta)/2} - 1\right]^{1/\Delta}; \qquad \Delta^2 = 1-4\delta. \tag{26}$$

The final exponential growth of a cannot be recovered from this general formula and equation (22) because the exponent involves $t\delta$ and we have neglected δ^2 in deriving (22); however, once we realize that the density becomes ρ_Λ we can then integrate $\dot{a}/a = \sqrt{\frac{1}{3}8\pi G\rho_\Lambda}$ to give the correct late-time behaviour, as may be checked more laboriously using (23). It is no longer true that the total density and the inflationary density vanish together as in equation (8). This is because with the renewed inflation neither ever vanish. Indeed, initially we tried an integration constant in (8), found it had to be small to renew inflation, and then discovered that a small final constant could be generated by the k term starting from nothing.

How is it that such a small term can have such a big effect? In choosing $R = 1/v$ in equation (8) we chose the smallest bulk viscosity that would just eliminate all the inflationary material. A larger value would have eliminated it all earlier leaving the $Y = 0$ pure-radiation solution; a smaller value would have led to continued inflation unless the value gave D so close to 0 that the radiation density dominated for a time. By choosing initially that value of the viscosity

that could only just eliminate the inflationary material we left the way open for the small effect of the closed Universe to cause the re-inflation. In this sense our viscous model suggests rather than predicts the interesting cosmological conclusions (20) and (21). To make this toy model more realistic, dark matter and baryons must be added as an initially small extra decay product. Whether they are a product of the CMB or of inflationary density is not currently known, but when the entropy of the CMB was created they would have made a very small contribution to the density. When relativistic, those will have a gamma of 4/3 so they will only change the model later as they become non-relativistic, but the final re-inflation will be unaffected unless the bulk viscosity of the small surviving inflationary density with them is far larger than that which generated the CMB.

Conclusions

The exchange of energy between fluids in expansion is accomplished by an effective bulk viscosity which generates an entropy increase. The incorporation of these ideas into cosmology leads to a simple and calculable model of the inflationary and the radiation eras which, by keeping the small curvature term for a closed universe, is readily extended to give an eventual re-inflation. The value of Lambda is related to properties of the Universe in the much earlier inflationary era by $\rho_\Lambda = [(\pi/2)(3c^2)/(8\pi G)]^2/(\rho_I a_h^4)]$, where a_h is the scale factor when half the inflationary density remains. This is re-expressed, *cf* equation (20), to give the value of the current Lambda term in terms of the present total entropy in the Universe's CMB. This has allowed us to calculate the total volume of the closed Universe to be about 55777 $(c/H_0)^3$, far larger than the currently observable volume within the horizon. It has also given the relationship $\sqrt{\Omega_\Lambda \Omega_r} = -(\pi/2)\,\Omega_k$ which can be checked observationally. In the model given, the density and temperature of the CMB tend to zero as time $t \to -\infty$. However, Padmanabhan[8] has claimed that the temperature should never be less than the horizon temperature so our model should perhaps start when that equality holds.

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SPECTROSCOPIC BINARY ORBITS
FROM PHOTOELECTRIC RADIAL VELOCITIES

PAPER 258: HD 5142, HD 5855, HD 34654, AND HD 80959

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Cambridge Observatories

Orbits are presented for the four stars whose identities appear in the title of this paper. Their periods are about 5, 11½, and 2⅔ years, and 119 days, respectively. Their orbits are all of moderate eccentricity; they have quite small mass functions, and all the systems are observationally single-lined.

Introduction

Like several recent papers in this series, this one provides orbits for four late-type stars. Three of them are stars of *HD* type K0 and apparent magnitudes near 9, which were first observed in the Cambridge 'Clube Selected Areas' programme; the odd one is HD 34654, which is brighter, at magnitude 7·3, and has an *HD* type of F8.

HD 5142

HD 5142 is a star a little brighter than the eighth magnitude, to be found in the constellation Pisces, just over 15′ south-preceding 66 Psc. It is listed in the *Henry Draper Catalogue* as being of magnitude 8·6 and spectral type K0; the *HD* magnitude is very pessimistic, because the *V* magnitude found by *Hipparcos* is 7·87, with a $(B − V)$ of $1^{m}·15$ which would suggest a type slightly later than K0. The (revised[1]) *Hipparcos* parallax is 4·09 ± 1·01 milliseconds of arc, so HD 5142 is about 250 pc away, with a distance modulus of about 7 magnitudes and thus an absolute magnitude of about +1 that shows it to be a giant.

The reason that HD 5142 came to the writer's attention is that it is within one of the 'Clube Selected Areas'[2] (Area 11), and its *HD* type of K0 qualified it to be an actual 'Clube' star. On that account it was first observed for radial velocity by the writer during the interval in the 1990s when he had no operational spectrometer at his home site at Cambridge, but depended on the kindness of other observatories (Haute-Provence, Palomar, and the DAO, Victoria) which offered him observing time on appropriate instrumentation. In the case of HD 5142, the first three observations were made at the DAO in the 1990s and appear at the head of Table I here. The binary nature of the object became apparent already at the second observation. When the Cambridge *Coravel* became operational, HD 5142 was observed reasonably regularly with it, and 67 measurements that are featured in Table I were made with it in the years 2002–2016. In the solution of the orbit, the two data sources have been given equal weight, but the zero-point of the DAO observations has been adjusted by +1·2 km s^{-1}. A discrepancy in the 'raw' velocities of such a nature and magnitude (the latter quantity related to the colour of the star) is quite normally to be found in a comparison of the results from the two spectrometers, and although it may seem a bit unsatisfactory it is routinely dealt with by making an empirical adjustment to the DAO data; the adjustment has already been made to the relevant velocities in Table I. In the solution of the orbit, the DAO and Cambridge velocities have been accorded equal weights.

Table I

Radial-velocity observations of HD 5142

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

Date (UT)		MJD	Velocity km s^{-1}	Phase	(O−C) km s^{-1}
1992 Sept.	7·03*	48872·03	+2·4	0·329	+0·3
1995 Sept.	27·06*	49987·06	−7·0	0·969	−0·1
1998 July	23·13*	51017·13	−0·6	1·561	−0·4
2002 Dec.	18·84	52626·84	+0·8	2·486	0·0
2003 Oct.	27·93	52939·93	−1·5	2·666	+0·4
Nov.	26·93	969·93	−1·9	·683	+0·3
Dec.	17·89	990·89	−2·2	·696	+0·2
2004 Jan.	24·84	53028·84	−3·2	2·717	−0·3
Feb.	25·78	060·78	−3·7	·736	−0·5
Aug.	7·13	224·13	−5·5	·830	0·0
Sept.	5·08	253·08	−6·0	·846	−0·1
Oct.	7·07	285·07	−6·2	·865	+0·1
Nov.	14·00	323·00	−6·6	·886	+0·2
Dec.	17·84	356·84	−6·8	·906	+0·4
2005 Jan.	8·80	53378·80	−7·2	2·918	+0·1
Feb.	8·75	409·75	−7·9	·936	−0·5
Aug.	7·14	589·14	−3·2	3·039	+0·1
Sept.	7·10	620·10	−2·1	·057	+0·2
	28·10	641·10	−1·5	·069	+0·1
Oct.	26·01	669·01	−1·0	·085	−0·2
Nov.	18·94	692·94	+0·1	·099	+0·3
Dec.	8·91	712·91	+0·2	·110	−0·1
2006 Jan.	4·75	53739·75	+0·8	3·126	0·0
Feb.	8·77	774·77	+0·9	·146	−0·4
July	4·12	940·12	+2·4	·241	+0·1
Aug.	30·12	977·12	+2·2	·262	−0·1
Sept.	23·05	54001·05	+2·4	·276	+0·1
Oct.	26·99	034·99	+2·5	·296	+0·2
Nov.	24·03	063·03	+1·9	·312	−0·3
Dec.	2·87	071·87	+2·4	·317	+0·2
2007 Jan.	10·85	54110·85	+2·3	3·339	+0·2
Feb.	7·76	138·76	+1·9	·355	−0·1
Aug.	6·14	318·14	+1·5	·458	+0·4
Oct.	31·97	404·97	+0·6	·508	+0·1
Dec.	16·80	450·80	+0·4	·534	+0·2
2008 Jan.	24·78	54489·78	−0·3	3·557	−0·2
Feb.	26·78	522·78	−0·5	·576	−0·1
July	25·12	672·12	−2·2	·662	−0·4
Sept.	19·04	728·04	−2·3	·694	+0·1
Oct.	18·98	757·98	−2·7	·711	0·0
Nov.	21·94	791·94	−3·0	·730	+0·1
Dec.	30·79	830·79	−3·4	·753	+0·2
2009 Jan.	24·79	54855·79	−3·9	3·767	+0·1
Dec.	6·85	55171·85	−7·3	·949	0·0
2010 Feb.	20·77	55247·77	−6·2	3·992	−0·2
Aug.	11·13	419·13	−0·4	4·091	+0·1

TABLE I (*concluded*)

Date (UT)		MJD	Velocity km s⁻¹	Phase	(O−C) km s⁻¹
2011 Jan.	9·85	55570·85	+1·9	4·178	+0·1
Dec.	28·85	923·85	+1·8	·381	0·0
2012 Jan.	28·76	55954·76	+1·7	4·399	0·0
Mar.	1·77	987·77	+1·4	·418	−0·1
Aug.	9·14	56148·14	+0·6	·510	+0·1
Nov.	3·05	234·05	−0·2	·559	−0·1
2013 Jan.	9·80	56301·80	−0·7	4·598	0·0
Feb.	2·81	325·81	−0·8	·612	+0·1
Mar.	2·77	353·77	−1·7	·628	−0·5
Sept.	8·14	543·14	−3·3	·737	0·0
Nov.	19·90	615·90	−4·1	·779	+0·1
Dec.	9·88	635·88	−4·5	·790	0·0
2014 Jan.	9·85	56666·85	−5·1	4·808	−0·2
Nov.	2·97	963·97	−6·6	·979	0·0
Dec.	5·86	996·86	−5·5	·998	+0·3
	28·80	57019·80	−5·0	5·011	+0·1
2015 Jan.	16·78	57038·78	−4·3	5·022	+0·1
	28·81	050·81	−4·2	·029	−0·2
Feb.	3·75	056·75	−3·8	·032	0·0
	18·77	071·77	−3·2	·041	+0·1
	21·79	074·79	−3·4	·042	−0·2
Sept.	7·13	272·13	+1·3	·156	−0·2
Dec.	7·90	363·90	+1·9	·208	−0·3
2016 Jan.	15·77	57402·77	+2·3	5·231	0·0

*Observed with DAO 48-inch telescope.
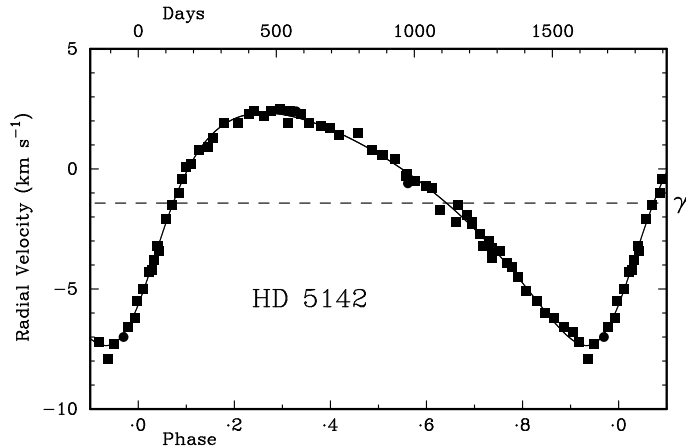
FIG. 1

The observed radial velocities of HD 5142 plotted as a function of phase, with the velocity curve corresponding to the adopted orbital elements drawn through them. As in the cases of all the stars discussed in this paper, the great majority of the observations were made with the Cambridge *Coravel* and are plotted as filled squares; there are, however, three measurements that were obtained with the DAO 48-inch telescope; they were given the same weight as the Cambridge observations, and are plotted as filled circles.

The Cambridge data alone span about 2½ cycles of the orbit, whose period of nearly 5 years is determined with a standard error less than two days. The orbit is depicted in Fig. 1, and its elements are as follows:

$$P \;=\; 1740 \cdot 2 \pm 1 \cdot 7 \text{ days} \qquad (T)_1 \;=\; \text{MJD } 55261 \pm 6$$

$$\gamma \;=\; -1 \cdot 42 \pm 0 \cdot 03 \text{ km s}^{-1} \qquad a_1 \sin i \;=\; 108 \cdot 7 \pm 1 \cdot 1 \text{ Gm}$$

$$K \;=\; 4 \cdot 84 \pm 0 \cdot 05 \text{ km s}^{-1} \qquad f(m) \;=\; 0 \cdot 0169 \pm 0 \cdot 0005 \; M_\odot$$

$$e \;=\; 0 \cdot 348 \pm 0 \cdot 007$$

$$\omega \;=\; 229 \cdot 7 \pm 1 \cdot 1 \text{ degrees} \qquad \text{R.m.s residual (wt.1)} \;=\; 0 \cdot 21 \text{ km s}^{-1}$$

HD 5855

HD 5855, like HD 5142 discussed above, is a 'Clube' star, with an *HD* type of K0 (one of the defining characteristics of Clube stars), and like HD 5142 it is in Area 11; whereas the nearest 'bright star' to HD 5142 is 66 Psc, the nearest one to HD 5855 is 67 Psc. In fact a small linear chain of stars leads in the south-following direction from 67 Psc (HD 5382) *via* HD 5514 and HD 5650 to HD 5855, a total distance of about a degree and a quarter. The *Hipparcos* V and B magnitudes for HD 5855 are $8^m \cdot 86$ and $9^m \cdot 77$, respectively. There does not appear to be any modern spectral classification, but the very small proper motion of the star suggests that it is a giant, in which case the colour index would suggest a type of about G6. Remarkably little interest has been exhibited up till now in HD 5855: the *only* paper retrieved for it by *Simbad* is the present writer's own[2], entitled 'Photoelectric radial velocities, Paper XIII. 406 ninth-magnitude K0 stars in the Clube Selected Areas'. It gives two velocities, mutually accordant, obtained for the star in the early 1970s with the original radial-velocity spectrometer at Cambridge.

There was an interval of 25 years before the object was observed again, in 1998; the writer was then on one of the observing runs, noted in the section above, at the DAO 48-inch reflector. The velocity was in appreciable disagreement with that found in the 1970s; just to make sure, it was observed again in the same observing run, and the new result was confirmed.

Quite soon afterwards, in 1999, the new '*Coravel*' spectrometer was inaugurated at Cambridge, and HD 5855 was naturally one of the objects on its observing programme. The variability of the star's velocity was soon confirmed. For a few years observations were made monthly during the season when the star was accessible in the night-time sky, but later, when the nature of the orbit was known, the star was observed somewhat less assiduously. Now there is a total of 60 radial velocities obtained with the Cambridge *Coravel*, set out in Table II, as well as the two early ones from the original spectrometer and the two obtained with the DAO spectrometer. The latter have been accorded a zero-point adjustment of $+1 \cdot 2$ km s^{-1}, while the two early Cambridge velocities have been attributed a weight of ¼. The orbital elements are found to be:

$$P \;=\; 4209 \pm 7 \text{ days} \qquad (T)_1 \;=\; \text{MJD } 51972 \pm 9$$

$$\gamma \;=\; -24 \cdot 59 \pm 0 \cdot 05 \text{ km s}^{-1} \qquad a_1 \sin i \;=\; 274 \cdot 7 \pm 3 \cdot 5 \text{ Gm}$$

$$K \;=\; 5 \cdot 78 \pm 0 \cdot 06 \text{ km s}^{-1} \qquad f(m) \;=\; 0 \cdot 0467 \pm 0 \cdot 0018 \; M_\odot$$

$$e \;=\; 0 \cdot 571 \pm 0 \cdot 007$$

$$\omega \;=\; 217 \cdot 8 \pm 1 \cdot 3 \text{ degrees} \qquad \text{R.m.s residual (wt.1)} \;=\; 0 \cdot 30 \text{ km s}^{-1}$$

The orbit is illustrated in Fig. 2.

<p style="text-align:center">TABLE II</p>

<p style="text-align:center">*Radial-velocity observations of HD 5855*</p>

<p style="text-align:center">*Except as noted, the observations were made with the Cambridge Coravel*</p>

Date (UT)		MJD	Velocity km s^{-1}	Phase	(O−C) km s^{-1}
1971 Nov.	29·85*	41284·85	−22·9	$\overline{2}$·461	−0·5
1973 Sept.	15·01*	41940·01	−22·6	$\overline{2}$·617	+1·1
1998 July	24·12†	51018·12	−26·1	0·773	−0·2
	31·11†	025·11	−25·8	·775	+0·1
1999 Dec.	19·86	51531·86	−29·3	0·895	+0·2
2000 Jan.	9·81	51552·81	−29·7	0·900	0·0
Aug.	9·13	765·13	−32·4	·951	−0·1
Oct.	9·09	826·09	−32·7	·965	+0·1
Nov.	4·04	852·04	−32·9	·972	+0·1
Dec.	27·90	905·90	−33·6	·984	−0·8
2001 Jan.	15·78	51924·78	−32·0	0·989	+0·6
Feb.	9·75	949·75	−32·0	·995	+0·2
July	31·12	52121·12	−27·3	1·035	0·0
Aug.	21·10	142·10	−26·4	·040	+0·3
Sept.	30·06	182·06	−26·3	·050	−0·6
Oct.	18·99	200·99	−25·1	·054	+0·2
Nov.	10·00	223·00	−25·2	·060	−0·3
Dec.	29·77	272·77	−23·8	·071	+0·3
2002 Jan.	24·82	52298·82	−23·3	1·078	+0·4
Feb.	23·78	328·78	−23·9	·085	−0·5
July	27·10	482·10	−21·8	·121	+0·4
Aug.	29·11	515·11	−22·1	·129	0·0
Sept.	27·09	544·09	−22·5	·136	−0·5
Oct.	19·05	566·05	−21·7	·141	+0·2
Nov.	21·92	599·92	−21·9	·149	−0·1
Dec.	17·89	625·89	−21·7	·155	0·0
2003 Jan.	11·84	52650·84	−21·6	1·161	+0·1
Feb.	14·80	684·80	−22·0	·169	−0·4
Aug.	15·11	866·11	−21·1	·212	+0·3
Sept.	14·09	896·09	−21·4	·220	0·0
Oct.	12·07	924·07	−21·3	·226	+0·1
2004 Feb.	25·79	53060·79	−22·1	1·259	−0·7
Aug.	20·12	237·12	−21·7	·301	−0·2
Oct.	22·05	300·05	−21·7	·316	−0·1
Dec.	17·85	356·85	−21·6	·329	0·0
2005 Feb.	15·77	53416·77	−22·0	1·343	−0·3
Sept.	8·11	621·11	−22·0	·392	−0·1
2006 Mar.	2·78	53796·78	−21·9	1·434	+0·3
Oct.	27·01	54035·01	−22·2	·490	+0·4
2007 Feb.	2·78	54133·78	−22·8	1·514	−0·1
Sept.	30·06	373·06	−23·4	·570	−0·2
2008 Feb.	16·76	54512·76	−23·6	1·604	−0·1
Aug.	15·14	693·14	−23·7	·646	+0·3

TABLE II (*concluded*)

Date (UT)		MJD	Velocity km s⁻¹	Phase	(O−C) km s⁻¹
2009 Mar.	5·78	54895·78	−24·5	1·695	+0·1
Sept.	4·11	55078·11	−25·4	·738	−0·2
Dec.	6·85	171·85	−25·3	·760	+0·3
2010 Feb.	21·77	55248·77	−26·0	1·778	0·0
Sept.	15·09	454·09	−27·2	·827	−0·1
Nov.	10·94	510·94	−27·3	·841	+0·2
2011 Jan.	9·85	55570·85	−28·5	1·855	−0·6
Sept.	13·09	817·09	−30·0	·914	+0·3
Oct.	20·01	854·01	−31·0	·922	−0·2
Dec.	28·86	923·86	−31·8	·939	−0·1
2012 Aug.	10·14	56149·14	−32·4	1·992	0·0
Sept.	4·12	174·12	−32·0	·998	−0·1
Nov.	3·06	234·06	−30·3	2·013	0·0
Dec.	1·93	262·93	−29·6	·019	−0·2
2013 Jan.	9·84	56301·84	−28·3	2·029	−0·2
Feb.	27·77	350·77	−26·5	·040	+0·2
Oct.	24·00	589·00	−22·4	·097	+0·5
2014 Aug.	29·12	56898·12	−21·7	2·170	−0·1
Nov.	24·88	985·88	−21·0	·191	+0·5
2015 Sept.	7·14	57272·14	−21·5	2·259	−0·1
Dec.	7·93	363·93	−21·5	·281	0·0

★ Observed with original Cambridge spectrometer.
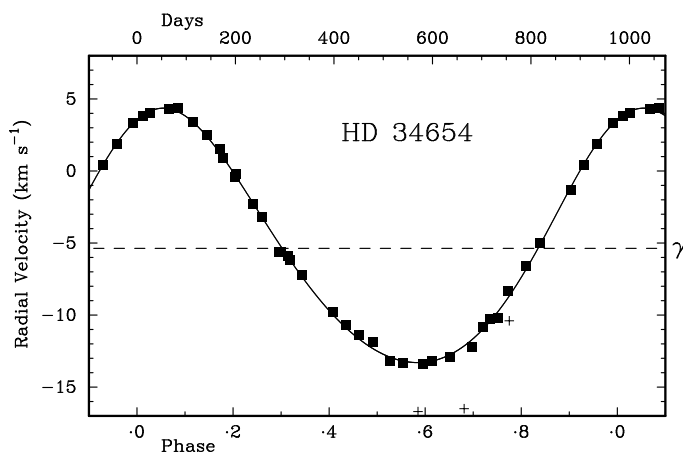† Observed with DAO 48-inch telescope.
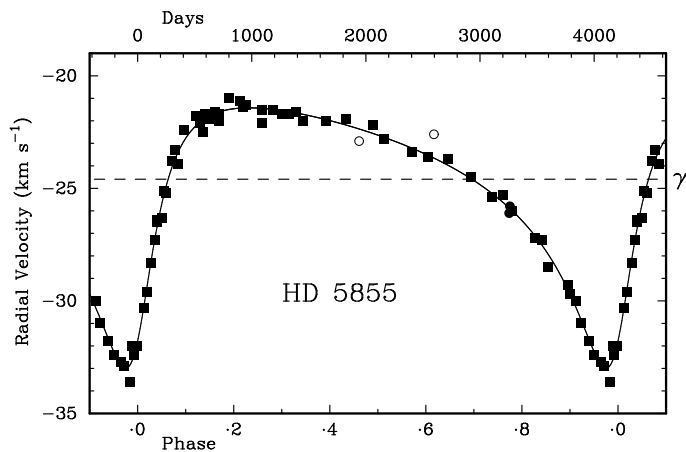
FIG. 2

The observed radial velocities of HD 5855 plotted as a function of phase, with the velocity curve corresponding to the adopted orbital elements drawn through them. Two early velocities obtained with the original radial-velocity spectrometer at Cambridge and plotted as open circles were given weight ¼ in the solution of the orbit.

HD 34654

HD 34654 is a seventh-magnitude star at a high declination (64°) in Camelopardus; it is to be found about 4° south-following α Cam, about three-quarters of the way to the fifth-magnitude object 17 Cam. Its entry in the *Henry Draper Catalogue*[3] shows it as magnitude 8·0, with spectral type F8. As far as its magnitude is concerned, the *HD* is unusually pessimistic, because the presently received V magnitude (for which we are indebted to *Hipparcos*, or more specifically to its *Tycho* star mapper according to the *Tycho 2* reduction[4]) is $7^m{\cdot}30$, with $(B - V) = 0^m{\cdot}54$. The only MK classification of which the present writer is aware is the F8·5 V, with the rider "Sr II strong", put forward by Gray *et al.*[5]. The 'Geneva–Copenhagen survey'[6] gave an M_V of $+4^m{\cdot}07$ for HD 34654, in exact agreement with expectation[7] for a type of F8·5; Gray *et al.*[5], however, appearing to rely on the (revised[1]) *Hipparcos* parallax, listed the absolute magnitude as $+3^m{\cdot}39 \pm 0^m{\cdot}25$.

The star's considerable proper motion (which independently indicated the likelihood of its main-sequence luminosity) was already known a hundred years ago when it was published[8] in Part I of *Cincinnati Publications*, Volume 18, as $\mu_\alpha = +0^s{\cdot}0270$, $\mu_\delta = -0''{\cdot}133$. Part IV of the same Cincinnati volume forms a sort of synopsis of the preceding three parts and assigns a running number (in this case[9] 681) to the star of present interest. In addition to repeating the proper-motion components in α and δ, Part IV presents them in polar coördinates as $\mu = 0''{\cdot}222$, p.a. $= 126°{\cdot}8$. The same proper-motion components are repeated in the ensuing Volume 19 of the *Cincinnati Publications*, which is augmented by additional stars — the one of interest here is demoted to no. 973. The identification used for our star in those publications is "A Oe 5726", after the identification in the earliest catalogue utilized at Cincinnati for the star, 5726 being the running number in Oeltzen's reduction[10] of the *BD*[11] position to epoch 1842.

Long afterwards, Luyten[12], who used the blink method to compare directly two plates taken with the Palomar 48-inch Schmidt camera (an unspecified number of) years apart, or in other cases by comparison of positions derived from automated measurements of two such plates, obtained a very similar result, $0''{\cdot}219$ in p.a. 127°. Although quite analogous values were obtained both by *Hipparcos* and by *Tycho 2*, the high precision of those values brought to light a significant discrepancy between them that could well be understood as manifesting a non-linearity of motion attributable to movement in an orbit. A discrepancy of that nature could arise because, whereas the *Hipparcos* mission itself lasted only three years, the proper motions in *Tycho 2* take account of previous positional measurements dating back many years. Such discrepancies were discussed by Makarov & Kaplan[13] and by Frankowski *et al.*[14], who found the case of HD 34654 to be significant at the very high level of $\chi^2 = 44{\cdot}80$, yielding a probability listed as 1·00000 that it was not due to chance.

The apparent certainty that HD 34654 is a spectroscopic binary led to the addition of that star to the Cambridge radial-velocity observing programme in 2009. Only two observations were made in the spring of that year, at the end of the season of accessibility of the object to the 36-inch telescope, but when it was next observed, the best part of a year later, a major change had occurred in its radial velocity. Since then the star has been watched systematically, and a total of 37 measurements has been made of it. They are set out in Table III, at the head of which are three velocities obtained photographically with the Mount Wilson

Table III

Radial-velocity observations of HD 34654

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

Date (UT)		MJD	Velocity km s⁻¹	Phase	(O − C) km s⁻¹
1944 Nov.	26·40*	31420·40	−16·7	0·585	−3·4
1947 Oct.	31·46*	32489·46	−16·5	1·681	−4·4
1948 Jan.	31·22*	32581·22	−10·4	1·775	−1·7
2009 Mar.	4·98	54894·98	−12·9	24·651	−0·1
Apr.	19·86	940·86	−12·2	·698	−0·5
2010 Jan.	31·01	55227·01	+3·3	24·991	0·0
Feb.	20·83	247·83	+3·8	25·013	−0·1
Apr.	14·83	300·83	+4·3	·067	0·0
Oct.	20·16	489·16	−3·2	·260	0·0
Nov.	24·19	524·19	−5·6	·296	−0·5
Dec.	12·19	542·19	−5·9	·315	+0·1
	17·06	547·06	−6·2	·320	0·0
2011 Jan.	9·92	55570·92	−7·2	25·344	+0·2
Apr.	7·91	658·91	−10·7	·434	+0·2
Oct.	1·18	835·18	−13·2	·615	0·0
2012 Jan.	10·96	55936·96	−10·8	25·719	+0·2
	27·02	953·02	−10·3	·736	+0·1
Feb.	11·85	968·85	−10·2	·752	−0·5
Mar.	1·84	987·84	−8·3	·771	+0·5
Apr.	7·82	56024·82	−6·6	·809	+0·3
Aug.	31·16	170·16	+1·9	·958	0·0
Nov.	6·17	237·17	+4·0	26·027	−0·2
2013 Jan.	3·08	56295·08	+4·4	26·086	+0·3
	31·87	323·87	+3·4	·116	0·0
Mar.	2·82	353·82	+2·5	·147	+0·1
Apr.	2·85	384·85	+0·9	·178	−0·1
	26·85	408·85	−0·4	·203	−0·2
Nov.	13·15	609·15	−9·8	·408	+0·2
2014 Jan.	3·95	56660·95	−11·4	26·461	+0·2
Feb.	2·92	690·92	−11·9	·492	+0·5
Mar.	7·85	723·85	−13·2	·526	−0·3
Apr.	4·87	751·87	−13·3	·555	−0·1
2015 Jan.	6·95	57028·95	−5·0	26·839	+0·1
Mar.	10·87	091·87	−1·3	·903	−0·2
Apr.	5·87	117·87	+0·4	·930	−0·1
Nov.	28·08	354·08	+1·5	27·172	+0·2
2016 Jan.	1·03	57388·03	−0·2	27·207	+0·2
Feb.	2·96	420·96	−2·3	·241	−0·1
Mar.	31·83	478·83	−5·6	·300	−0·3
2017 Jan.	13·99	57766·99	−13·4	27·595	−0·1

*Mt. Wilson photographic observation; wt. 0.

FIG. 3

The observed radial velocities of HD 34654 plotted as a function of phase, with the velocity curve corresponding to the adopted orbital elements drawn through them. The first three velocities were obtained photographically with the Mt. Wilson 60-inch telescope in the 1940s; they are plotted as plusses and have not been included in the solution of the orbit.

60-inch reflector in the 1940s. The orbit has been derived from the Cambridge observations alone; its elements are given in the informal table below, and the orbit is illustrated in Fig. 3. The mass function requires the unseen secondary component in HD 34654 to have a mass of at least 0·6 $M_\odot$; the white dwarf that is proposed by Gray *et al.*[5] would be consonant with that minimum value.

$$P = 975·4 \pm 1·6 \text{ days} \qquad (T)_1 = \text{MJD } 56211 \pm 11$$
$$\gamma = -5·37 \pm 0·04 \text{ km s}^{-1} \qquad a_1 \sin i = 117·7 \pm 0·9 \text{ Gm}$$
$$K = 8·83 \pm 0·06 \text{ km s}^{-1} \qquad f(m) = 0·0684 \pm 0·0015 \ M_\odot$$
$$e = 0·112 \pm 0·007$$
$$\omega = 335 \pm 4 \text{ degrees} \qquad \text{R.m.s residual (wt.1)} = 0·24 \text{ km s}^{-1}$$

HD 80959

HD 80959 is a late-type star near the southern margin of Clube Area 5. It has not been very popular with the writer of these papers, because it is almost at the pessima, in both magnitude and declination, among the 'Clube' stars that are nominally accessible to observation from Cambridge. Its *V* and *B* magnitudes, as determined by *Tycho 2*, are 9^m·66 and 10^m·81, so it is nearly three-quarters of a magnitude (a factor of two) fainter than the nominal ninth-magnitude brightness of the Clube stars. Area 5 is centred in the south-following corner of the constellation Cancer, but with a radius of some 13° it extends well into the mainly-southern constellations Hydra and Sextans. HD 80959 is near the eastern margin of Hydra, in a region that would appear barren to the naked eye (even one whose owner was at a favourable latitude); it is about 5° north of, and slightly preceding, α Hya. The spectral type given by the *Henry Draper Catalogue* for HD 80959 (as for all Clube stars, as it is one of their defining characteristics) is K0; the Michigan re-classification[15] listed it as G8/K0(V). The only publication retrieved for the star by *Simbad* is the relevant volume of the Michigan catalogue to which reference has just been made.

The Cambridge observing effort referred to as the 'Clube' programme proceeded in a number of stages that were not pre-planned from the outset. Initially a set of centres for the Areas was adopted: they were all at Galactic latitudes ±35° and were at 45° intervals of Galactic longitude — so the number of designated 'Areas' was 16. Only 12 of them, however, were actually accessible in the sky with the telescope in Cambridge, so the initial publication of the results of the programme[2] was restricted to that sub-set of the Areas. The radial velocities were mostly obtained with the original radial-velocity spectrometer, upon which the photoelectric method of velocity determination was developed by the present writer[16] in the 1960s. The writer viewed with somewhat mixed feelings such approval as was forthcoming from certain quarters with regard to the publication of the 12 Areas, because the approval was very properly tempered by the obvious advice that the value of the results would have been considerably increased if *all* of the Areas had been observed instead of only those observable from the author's home site. Taking on board that criticism, the writer then asked for, and was granted, observing time on the *Coravel* spectrometer that was sometimes mounted on the 60-inch reflector at the ESO site in Chile.

With the bigger telescope, and the interest being nominally confined to six Areas that passed reasonably near to the ESO zenith, the southern observations proceeded very quickly. There was, however, still a need to observe all the objects at least twice, in different seasons, to try to identify spectroscopic binaries among the programme stars. (Binaries with large amplitudes could considerably falsify estimates of the velocity dispersion of the objects, which was one of the quantities that the programme aimed to determine.) Owing to the need to observe all the stars at least twice, and the fact that they were scattered at all right ascensions and could not all be observed in any one observing run, it was necessary in principle to make four visits to ESO; and when one of the four visits proved to be almost entirely lost to cloud, a fifth visit became necessary. Needless to say, the writer is very grateful to the authorities at ESO for granting him the use of their excellent equipment so willingly. The ESO velocities were presented in a second paper[17] on the Clube stars, in 2006; they were so numerous and so good that the situation that the ESO effort had been intended to remedy recurred! — but in reverse: there were more and better velocities available for the far-southern stars than for the rest of the programme objects.

At the risk, then, of being seen to do something whose logicality might be called into question, some ten years ago the writer deemed some of the northern Clube Areas to be arbitrarily enlarged to bring appropriately more stars of the specified magnitude range and spectral type into the programme in each Area. The main results of that extension of the original tranche of the work have not been made public, but stars that were newly discovered to have variable velocities were nevertheless regarded as being worthy of regular observation.

Arriving, finally, at the *dénouement* of this possibly discursive introduction, we declare that HD 80959 is one of the many stars that were belatedly added to the Clube programme to bring the numbers of stars in the various Areas more nearly into equality than they were on the initial basis of equality of sky areas. The need to do that arose because the southern Areas were much richer in terms of *HD* stars per unit area of sky, simply as a result of an idiosyncrasy of the manner in which stars were assigned to the *Henry Draper Catalogue*. Actually HD 80959 is itself a southern star, in the sense that it is in the southern hemisphere, at a declination near −4°; but it is in Area 5, the coördinates of whose centre definitely mark it out as a northern Area. In fact, even after the

efforts that were made to bring the numbers of stars per Area into near-equality, the total number of stars observed in Area 5, at 52, is the smallest for any of the 16 Areas. In the writer's original publication[2] of radial velocities in the (Cambridge-accessible) Clube Areas, Area 5 had the smallest number of stars observed (30) and the smallest total number of observations (72).

Radial velocities and orbit of HD 80959

The first measurement of HD 80959 was made with the Cambridge *Coravel* in 2013 April. In comparison with the velocities of most Galactic stars, it was unusually high — above +80 km s^{-1} — but the high velocity has proved to be a permanent characteristic of HD 80959; indeed, at the maxima of velocity the observed values have touched +100 km s^{-1}. The writer's second measurement

TABLE IV

Radial-velocity observations of HD 80959

Date (UT)		MJD	Velocity km s^{-1}	Phase	(O−C) km s^{-1}
2013 Apr.	2·93	56384·93	+81·8	0·990	+0·6
2014 Jan.	13·17	56670·17	98·4	3·384	+0·1
	27·11	684·11	99·6	·501	−0·2
Feb.	6·05	694·05	99·9	·584	+0·6
	16·07	704·07	97·6	·668	+0·1
	26·95	714·95	93·4	·759	−0·3
Mar.	1·98	717·98	91·9	·785	−0·4
	4·96	720·96	91·5	·810	+0·7
	7·98	723·98	89·6	·835	+0·4
	12·02	728·02	86·7	·869	−0·3
	15·99	731·99	83·9	·902	−0·9
	19·88	735·88	83·0	·935	0·0
	25·93	741·93	81·6	·986	+0·3
Apr.	14·90	761·90	86·8	4·153	−0·8
	16·87	763·87	88·8	·170	+0·2
	19·91	766·91	90·1	·195	−0·1
	28·88	775·88	94·7	·271	+0·3
May	2·86	779·86	95·3	·304	−0·5
Nov.	6·26	967·26	86·8	5·877	+0·4
	24·26	985·26	80·7	6·028	−0·6
Dec.	6·28	997·28	86·4	·129	+0·4
2015 Jan.	17·11	57039·11	99·5	6·480	−0·2
	23·09	045·09	100·1	·530	+0·3
	27·12	049·12	99·3	·564	−0·3
Feb.	2·05	055·05	98·7	·614	−0·1
Mar.	26·94	107·94	82·1	7·058	−0·1
	31·95	112·95	84·8	·100	+0·6
Apr.	6·90	118·90	87·4	·150	+0·1
	14·90	126·90	92·2	·217	+0·7
	18·89	130·89	93·8	·250	+0·5
	30·87	142·87	97·7	·351	+0·2
Dec.	21·21	377·21	96·1	9·318	−0·2
2016 Jan.	1·14	57388·14	98·9	9·409	0·0
Feb.	3·12	421·12	96·8	·686	−0·1
Mar.	31·91	478·91	88·2	10·171	−0·5
Apr.	5·90	483·90	91·1	·213	−0·2
	30·86	508·86	99·0	·422	−0·1
2017 Jan.	21·15	57774·15	+98·0	12·649	0·0

was not made until the beginning of 2014, and showed a substantial disagreement with the first one, so the star was transferred to the binary programme and observed reasonably systematically. There are sometimes complaints in the observing records about the star being faint, being low down where the seeing was bad, being troubled by moonlight (which, however, could not vitiate the measured velocity, since that is always far beyond where the 'moonlight dip' could blend with it); and on one occasion the observation being terminated when the telescope tracked into the floor of the dome!* The total number of radial velocities available now for the determination of the orbit is 38. They are set out in Table IV, which also lists the phases and residuals that correspond to the derived orbit, whose elements are presented below. A diagram of the orbit appears here as Fig. 4. The mass function is slightly less than a hundredth of a solar mass, so one must suppose that the orbital inclination is far from 90° and/or the (unseen) secondary star is of much lower mass than the primary.

$$P = 119 \cdot 15 \pm 0 \cdot 09 \text{ days} \qquad (T)_1 = \text{MJD } 56981 \cdot 9 \pm 1 \cdot 2$$
$$\gamma = +92 \cdot 19 \pm 0 \cdot 08 \text{ km s}^{-1} \qquad a_1 \sin i = 15 \cdot 05 \pm 0 \cdot 18 \text{ Gm}$$
$$K = 9 \cdot 34 \pm 0 \cdot 11 \text{ km s}^{-1} \qquad f(m) = 0 \cdot 00958 \pm 0 \cdot 00035 \, M_\odot$$
$$e = 0 \cdot 183 \pm 0 \cdot 011$$
$$\omega = 177 \pm 4 \text{ degrees} \qquad \text{R.m.s residual (wt.1)} = 0 \cdot 39 \text{ km s}^{-1}$$
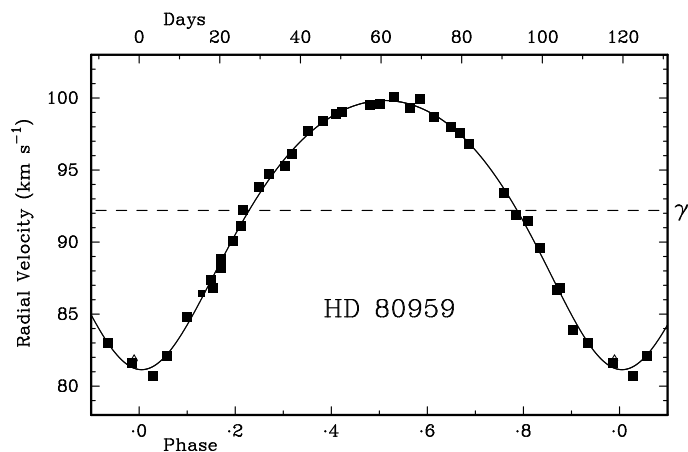
FIG. 4

The observed radial velocities of HD 80959 plotted as a function of phase, with the velocity curve corresponding to the adopted orbital elements drawn through them. All the observations of this star were obtained at Cambridge with the *Coravel*, but the first observation is plotted as an open triangle, largely hidden near the bottom of the curve.

*It should be mentioned that that happens at positive angular altitudes, even for southern-hemisphere declinations, that are accessible only near the meridian. The 'observing floor', illustrated in the cross-section in Fig. 1 in ref. 16, is not intended to be load-bearing but exists only for convenience of access to the telescope; it has a degree of compliance, so the force that it applies if the telescope tracks into it does not immediately become large, but it pushes the star image off the slit, and that alerts the observer to stop the integration and rescue the telescope.

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CORRESPONDENCE

To the Editors of 'The Observatory'

A Formula for Confusion

That Virginia Trimble found a mistake in a book[1] which she reviewed[2] for this *Magazine* is not surprising, and in itself not disturbing: mistakes are made, and it is difficult to avoid them completely. In this particular case, however, four things make it worth writing about: it is a common mistake, made by a well-known astronomer (though, fortunately, not by someone who works in cosmology), in a book from a major scientific publisher, and has been pointed out in the literature decades ago. To recap: the book contains a formula for cosmological "redshifts larger than one", namely the relativistic Doppler formula★. It should be obvious that that formula cannot be correct, because it gives the velocity as a function of just the redshift; there are no cosmological parameters! Even the Hubble constant is absent. This implies that, even at arbitrarily high redshift, the velocity is independent of the cosmological model, and does not depend on even the Hubble constant (despite the fact that the latter is the proportionality constant in the velocity–distance relation!), while at the same time it is common knowledge that, except in the limit of small redshifts, the relation between

★Presumably this is supposed to be the formula correct for all redshifts, but giving significantly different results from $v = cz$ only at redshifts larger than 1; but even this is wrong: it is never the correct formula, and significant deviations exist for $z < 1$ as well.

observed and 'absolute' or 'physical' quantities depends on the cosmological model. Indeed, the inverse process — fitting for the cosmological parameters by comparing observations to theoretical predictions for various cosmological models — is the basis of classical observational cosmology.

We shouldn't blame the author too much, though; no-one can be an expert in all areas covered by a wide-ranging book such as the one reviewed. Such authors usually can't rely on the primary literature, but must turn to secondary (or farther-removed) sources. The bigger problem is thus that the mistake is common in the secondary — and not unheard of even in the primary — literature, and as the current example indicates, is propagated *via* the tried-and-tested practice of copying mistakes, coupled with insufficient diligence on the part of those involved.

This entire issue should have disappeared after Harrison's article[3], which specifically addresses not just this confusion, but also the fact that even by the time it was written there was a history of misconceptions. He also devotes much space to this in his classic textbook[4]; both the book and the article are essential reading for anyone even remotely interested in cosmology. In particular, this is not a case of genuine confusion, or an undecided issue: Harrison got it right, and many others got it wrong. The facts that he explicitly pointed out that others got it wrong and that no-one has rebutted him should make it clear that he is right. Probably the only way to eradicate the misconception is to point it out — as Trimble did in her review — whenever and wherever it occurs, regardless of who makes the mistake. (Even a third of my previous correspondence in this *Magazine*[5,6] has touched on that misconception.)

In addition to the luminosity and angular-diameter distances mentioned by Trimble (certainly the two most important in observational cosmology), there is also the proper distance or metric distance, which is the basic distance in General Relativity and is the easiest to visualize: it is what one would measure with a rigid ruler (done during so short a time that the expansion of the Universe can be neglected). It is that distance and its derivative with respect to cosmic time which appear in the velocity–distance relation $v = HD$ (v is the velocity, H the Hubble constant, and D the proper distance), which (in a Friedmann–Lemaître cosmological model (a homogeneous and isotropic model based on General Relativity)) is always exactly linear (otherwise a homogeneous and isotropic universe would not remain so as it expands) and valid for arbitrarily large distances and velocities. However, neither of those is 'directly' observable, even by the roundabout definition of 'directly' in observational cosmology. (One can determine H from observations in the limit of small redshift z by using z as a proxy for velocity, and luminosity distance or angular-size distance as an approximation (exactly valid in the limit of zero redshift) for proper distance. Unlike the velocity–distance relation, however, in general the redshift–distance (or redshift–apparent-magnitude) relation is valid only in the limit of small redshifts. Thus, the non-relativistic Doppler formula $v = cz$ is valid at low redshifts (whether or not one thinks of the cosmological redshift as some sort of Doppler shift[7]) essentially because many things are linear to first order; this does not imply that the relativistic Doppler formula is correct for large cosmological redshifts.)

Why does that misconception still persist? One reason might be that in practice cosmological velocities play no role in observational cosmology. Given a redshift and cosmological model, the velocity and distance in the velocity–distance relation can be calculated, but that is of little practical use. (In particular, in general the Hubble sphere — defined as c/H, the distance at which

the recession velocity is equal to the speed of light — does not correspond to any sort of horizon.[8]) At the same time, despite its simple and useful true meaning — that $1 + z$ is the ratio of the scale factor of the Universe now to that at the time the radiation received now was emitted — popular-science writers like to introduce it *via* the Doppler effect, which is not really useful because if one has to explain the acoustic Doppler effect to get the analogy to work, one might as well cut to the chase and say that the wavelength is stretched *via* the expansion of the Universe. (Whether that is completely correct in some sense is another question, but that point of view doesn't lead to misconceptions or wrong numerical results.)

Observational cosmology is based on the way distances as a function of redshift depend on the cosmological parameters. Not only are there several types of distances (not all of which have practical uses in cosmology), but the general solution involves elliptic integrals in the idealized Friedmann–Lemaître case (and is even more complicated if one takes into account the fact that small-scale inhomogeneities can appreciably affect observable distances, even if they do not appreciably affect the large-scale kinematics or dynamics of the Universe[9]). Although the relationships between the various distances are relatively simple (though their values can be very different at high redshift), the topic is perhaps too advanced for many popular-science works, so it is glossed over. Also, since light-years are deemed to be easier to understand than parsecs, that unit of distance is often used. While a simple factor converts one to the other, 'light-year' evokes the idea of distance measured *via* light-travel time, which is the one distance which is *not* simply related to the others. Compared to that, the velocity–distance relation might seem easier to tackle, so readers are presented with something which is neither useful in practical observational cosmology (because neither the distance nor the velocity involved is observable) nor understandable without having first to understand why Special Relativity is not applicable in that case.

In summary, popular-science writers have ignored Einstein's advice to make things as simple as possible — but not simpler. That is probably due to the fact that the details of distance calculation are too complicated for such books, leading to an over-emphasis on the velocity–distance relation and the Doppler effect (which are not actually needed at all in classical cosmology), which are then presented wrongly, probably because of confusion between the redshift–distance and velocity–distance laws[3]. Non-cosmologists (and, sadly, even some cosmologists) then uncritically repeat that mistake. Some blame must also go to publishers, since obviously not enough fact-checking is done (there are numerous examples of that), perhaps because of the apparently wrong assumption that the author has had that done before submitting the manuscript. Since even well-known authors have made that mistake, other authors and/or publishers might be sceptical of claims that so much of the popular literature is wrong in that respect. Lack of basic fact-checking is also supported by Trimble's examples of misspelled names and 'fake facts' presented as truth. (To some extent, buggy and/or wrongly-used software, perhaps in conjunction with an editor whose first language is not English, might be responsible: maybe the manuscript was correct, but errors were introduced later. I know of no other way to explain how 'one' (the indefinite pronoun, and certainly written that way by the author) became '1' in the finished product in another book I reviewed in these pages.[10])

As a side-note, to some extent I can understand the frustration of non-experts trying to make sense of the primary literature on cosmological distances. Different symbols are used by different authors for the same distance and, more confusingly, the same symbol is used for different distances. (In extreme cases, a distance — unambiguously identified by a formula — is given a wrong name.) For example, just last week I was re-reading (an English translation of) a classic paper by Zel'dovich[11], where he discusses the calculation of distances in various cosmological models, but instead of the redshift z as the independent variable, he uses Δ, which one can show (this is not even mentioned in the text) to be equal to $1 - 1/(1 + z)$. This has the nice property that it ranges from 0 to 1 instead of from 1 to ∞. In the Einstein–de Sitter universe, the angular-size distance (called f by Zeldovich — more confusion), in units of the Hubble length c/H, is given by $2(1 - \Delta)(1 - \sqrt{1 - \Delta})$, while in (the relativistic equivalent of) the Milne model it is $\Delta(1 - \Delta/2)$. The equivalents are $2((1 + z)^{-1} - (1 + z)^{-3/2})$ and $0{\cdot}5(1 - (1 + z)^{-2})$, respectively. As help for those interested in these matters, we collected various formulae into appendices in a paper[9] concerned with distance calculation, using modern and consistent notation in the formulae and in the definitions of all distances. (However, at the time, *A&A* insisted on some material being published only electronically, and separately from the main paper. Both are available, together as intended, at arXiv.[12])

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REVIEWS

Optical, Infrared and Radio Astronomy: From Techniques to Observation, by R. Poggiani (Springer), 2017. Pp. 179, 24 × 16 cm. Price £57·99/$89·99 (hardbound; ISBN 978 3 319 44731 5).

This slim volume addresses the essentials of ground-based observational astronomy, at a level appropriate to introductory first-year undergraduate courses in the UK (although it's apparently based on a lecture course delivered at the University of Pisa to graduate students specializing in astrophysics, who I can only suppose have no prior astronomy background).

The book starts with basic material covering the electromagnetic spectrum, atmospheric windows, time, and co-ordinate systems. It then deals with ground-based observations in the optical (telescopes, detectors, photometry, spectroscopy), followed by succinct overviews of infrared and radio/sub-mm astronomies. Finally, twenty-odd pages summarize observing practicalities (including target selection and proposal preparation), and data analysis. Although the material is entirely standard, the presentation is distinguished by its pragmatic approach, including pointers on the use of internet resources such as CDS, NED, arXiv, *etc*. This sometimes degenerates into little more than seemingly arbitrary lists, however (as in a rather tedious 4-page section on "Large [optical] Telescopes"; one might argue that instruments such as the 25-cm *ASAS* telescope scarcely qualify for inclusion here).

Each chapter has a brief list of references (of ~100 in total, many are duplicated from chapter to chapter, few are to primary sources, and almost half are to Springer books), and many also have one or two 'Problems', which are often no more than review questions (*e.g.*, "Compare equatorial and alt-azimuth mounts"). It's evident that the book hasn't been copy-edited by a native English speaker, although only occasionally do the infelicities introduce potential misunderstanding (*e.g.*, "Due to the Earth *revolution* [*sic*; and my emphasis]… stars will make about 366 diurnal cycles, while the Sun will make only about 365 cycles"; and, supposedly, "The reflecting telescope is made up of conical surfaces"). Other questionable statements are less easily explained ("The first star catalog, realized by Bessel during the nineteenth century, included a few tens of stars").

While the coverage throughout is sufficient to make the apprentice observer aware of many of the important factors, it's hardly up to the job of a reference handbook (*e.g.*, the section on 'Reduction of photometric observations' consists of five sentences, and 'Reduction of interferometric data' of four!). I suppose that as a cheap paperback this book may have just about passed muster as a text for astronomy undergraduates, but as a pricey hardback I find it hard to see who would need, or want, to buy it. — IAN D. HOWARTH.

The Sun, by L. Golub & J. M. Pasachoff (Reaktion Books), 2017. Pp. 222, 23 × 18 cm. Price £25 (hardbound; ISBN 978 1 78023 759 2).

Leon Golub & Jay Pasachoff's new book, *The Sun*, offers an impressively accessible and comprehensive introduction to the complex coupled system that is our nearest star. The reader is guided naturally from our very first observations of sunspots through to understanding the importance of the underlying magnetic fields (of which sunspots are the most obvious manifestation) and how that drives all of solar activity and leads to the creation of the heliosphere.

The authors continually highlight the importance of bringing together ideas both from other branches of science and from philosophy in order to make progress, and through their meticulous attention to historical detail, including the personal contributions of individuals, they very clearly demonstrate the importance (and the ups and downs) of the scientific process, including its politics! This I found to be really unique and appealing compared to other books on the Sun.

In several appendices they also outline the safest ways to observe the Sun, including providing details of how to take the best eclipse photographs, and demonstrating that even the youngest of keen amateurs can get involved. Given the huge public interest in the Eclipse MegaMovie project (in which Pasachoff was involved) this should serve as a fantastic guide for the next generation of solar observers. Highly recommended. — SARAH MATTHEWS.

Worlds Fantastic, Worlds Familiar, by B. J. Buratti (Cambridge University Press), 2017. Pp. 239, 23·5 × 16 cm. Price £19·99/$29·99 (hardbound; ISBN 978 1 107 15274 8).

So many factual tomes have been written about our Solar System over the past six decades that a new approach is to be welcomed. Here, planetary scientist Bonnie Buratti provides an insider's view of the solid objects that orbit the Sun, concentrating on the planets and moons that she has studied over the years, as well as some others that she finds most interesting. Buratti's account of the great age of discovery in the planetary sciences necessarily includes the key facts about the distant worlds that have come into focus over the decades. However, the book is also illuminated by personal anecdotes, such as her involvement in debates over the possible discoveries of plumes erupting from Europa and tiny Enceladus.

As befits a scientist who grew up under the tutelage of Carl Sagan, the author's devotion to educational outreach is made clear throughout, as she endeavours to communicate to the next generation of students the wonder and joy of science and the enterprise of discovery. Buratti also puts the story of scientific discovery in context by making frequent references to science-fiction stories and speculative theories that abounded before the space age. These include popular accounts of a tropical swamp on Venus and the infamous canals on Mars. The book concludes with a chapter on the latest scientific challenge: the discovery and characterization of the myriad of exoplanets that populate our Galaxy.

The text is clearly written and accessible to anyone with a modicum of scientific education. There are numerous black-and-white illustrations, some of which are also reproduced in a separate colour section. This enjoyable account achieves its objective of informing the lay reader about 'the final frontier', and it may well encourage some up-and-coming scientists to delve deeper into the secrets of distant worlds. — PETER BOND.

Next Stop Mars: The Why, How, and When of Human Missions, by G. Genta (Springer), 2017. Pp. 415, 24 × 17 cm. Price £35·99/$44·99 (paperback; ISBN 978 3 319 44310 2).

Giancarlo Genta is Professor of Machine Construction at Torino and leads a Mars-study group of the International Academy of Astronautics. Reaching Mars as the next stopping point in our 'spacefaring phase' is analysed in 14 chapters

and several technical appendices. *Next Stop Mars* is one of the best books of its type I have seen, in discussing problems, opportunities, and alternatives for the first human Mars mission. It is assumed that there would be at least three coordinated missions, including two landings, with humans spending a year or more upon the surface. The 2035 perihelic opposition offers the next best chance, and the saving of two months' travel time over a Hohmann transfer for a small additional energy expenditure *via* a Type I fast trajectory.

We begin with half a century of Mars projects with comprehensive listings of past and present design and feasibility studies, including more recent private initiatives. The three-page historical sketch (Section 1.1) overrates the importance of Schiaparelli's mapping, but Chapter 3 gives an excellent summary of the planet and its satellites, including a useful table of surface compositions at different locations. The space environment and its attendant hazards are well covered, as are the human aspects and the dynamics of interplanetary flight and mission design. Chapter 8 examines the future Martian base and the use of 3-D printers combined with the sintering of regolith fines for constructional purposes. We are told that a six-person, two-year mission would consume 135 tonnes of water and 7·2 tonnes of food.

Further chapters consider mobility upon Mars, communications issues, as well as some more ambitious future schemes (such as terraforming and using the improbable space elevator). Genta concludes that even the first mission must go beyond 'flags and footprints' to make us into true space-farers. The opportunity for sending a crewed mission during the next perihelic opposition has already been lost. So let us pin our hopes upon 2035. — RICHARD MCKIM.

The Great Canoes in the Sky, by S. R. Chadwick & M. Paviour-Smith (Springer), 2017. Pp. 233, 28·5 × 21·5 cm. Price £19·99/$34·99 (hardbound; ISBN 978 3 319 22622 4).

This book presents an unusual juxtaposition of modern science-based astronomy and the star lore passed on orally through multiple generations of South Pacific and Australian indigenous peoples.

There are nine chapters in all, each of which has an appropriate astronomical introduction. The main contents of the first eight chapters are then of an anthropological nature with information gathered from many of the Pacific Island nations and, stretching the definition of Pacific Islands somewhat, Australia! The final chapter deals with the development of astronomy since the invention of the telescope and photography. There are in all over 100 pictures of astronomical objects produced mainly by additional computer processing of images obtained with instruments such as the *Hubble Space Telescope*. The star lore and associated stories are very readable and often quite surprising: who would have thought that the bright stars in the Southern Cross plus the pointers (α and β Centauri) could be used by the Australian Aborigines as an *aide memoire* for permitted degrees of relationships allowable in marriage? Other practical uses to which the stars are put are described, including navigation (an excellent section on a star compass used by the navigators of the Caroline Islands) and calendrical markers (the heliacal rising of the Pleiades — *Matariki* in the Maori language — used to signify the beginning of the Maori New Year in New Zealand). There is a bibliography of seven pages containing mainly anthropological references, an index, and a very poor map section consisting of three maps without informative legends, each of which uses less than half the available page leaving the rest blank, plus an additional 13 blank pages to complete the volume.

The proof reading was not of the highest quality with spelling mistakes (page 173, Pleiades, *not* Pleaides) and misidentifications of stars on some charts (figures 7.1 and 7.12 identify Aldebaran as Antares) and an important place name Whanganui a Tara (Wellington) missing from a map (figure 5.18). A further criticism is the use of single-column printing in a volume 215-mm wide which makes the book somewhat difficult to read. Despite those negative comments, the unusual and original combination of astronomy and anthropology makes for interesting, informative, and entertaining reading. — RICHARD DODD.

A Walk through the Heavens, 4th Edition, by M. D. Heifetz & W. Tirion (Cambridge University Press), 2017. Pp. 97, 24·5 × 19 cm. Price £14·99/$19·99 (paperback; ISBN 978 1 316 64551 2).

Constellations and their names are useful tools for astronomers, and the modern IAU-approved list of 88 was drawn up to avoid ambiguities. But constellation patterns are also a product of the human imagination, with many of them stretching back for millennia and based on myths and legends. Different civilizations have had different patterns and different stories about them, but all major peoples seem to have wondered at the stars and woven stories around them, although the current IAU constellations are largely based on Greek and other Mediterranean-area traditions.

How should one introduce the constellation patterns to someone who wants to learn about the stars? This book approaches the complete beginner by taking them on a journey round the sky (hence the title), starting with a brief introduction to how distances are measured on the sky, even briefer but useful instructions for using the various illustrations, and a set of sky maps for the four seasons (for the northern hemisphere — a companion book treats the southern stars). Then the authors begin from Ursa Major, or the Big Dipper (this is an American book), and describe it with the help of two diagrams. Some two dozen further diagrams follow, each starting from a constellation previously described and explaining on the facing page how to find bright stars in one or more other constellations (and hence locate the constellation) by moving in various directions across the sky. Occasionally the instructions for the move will invoke a constellation not previously described (*e.g.*, Scorpius on pp. 40–41, Fig. 24), but not very often; presumably the reader is supposed to have started by making a careful study of the overall seasonal sky maps. There is also a helpful alphabetical index of the constellations, listing the figures in which each appears. That deals with the other slight problem that the ordering of the illustrations doesn't seem to form a completely coherent pattern; to my surprise, Orion appears very late in the sequence, despite being (to my mind) the most recognizable constellation after Ursa Major. This section ends with two plots of the Milky Way and its surrounding constellations (with some overlap in galactic longitude between the two), unfortunately without any commentary — it would have been useful to have pointed out which parts of the Milky Way can be seen from which hemisphere.

The third part of the book moves from the practical to the narrative, retelling legends surrounding about three dozen constellations, from Andromeda to Virgo, with the Pleiades and the Milky Way thrown in for good measure. Many of the legends are of Greek origin, but there are also a sizeable number of others: Australian Aboriginals, American Indian, Norse, and African, for example. The authors have deliberately omitted the more violent stories, and the Milky Way merits ten stories (although not the one often quoted for the origin of the name). These give a nice cross-section of the multitude of tales about our

constellations; for more detail the reader will need to look elsewhere⋆, but the detail I know about seems generally accurate, although there is a curious confusion in the story about Sagittarius and Scorpius, where Hercules is said to need guarding from the scorpion, a need that I have not found mentioned elsewhere, and then it is Orion that is mentioned as appearing to be the target of the sting.

Finally, a fourth part covers a range of other topics: circumpolar stars, tests of vision (with samples of stars to look for), star colours, the Zodiac and planets, where there is a useful table of the constellations in which the four brightest planets are to be found for every month from 2017 January to 2024 December. The book concludes with an annotated map of the Moon, some possible binocular objects, the principal meteor showers, and various tables. There is no general index, but the detailed list of contents at the beginning makes up for that.

Overall, this is a very suitable and attractive book for the complete newcomer to astronomy, which gives just enough information to whet the appetite for more. The text is clearly written, and Wil Tirion's sky maps are well up to his usual high standard. — Robert Connon Smith.

Out of the Shadow of a Giant, by John Gribbin & Mary Gribbin (William Collins), 2017. Pp. 302, 24 × 16 cm. Price £25 (hardbound; ISBN 978 0 00 822059 4).

This excellent historical investigation by John and Mary Gribbin, Visiting Fellows at the University of Sussex, examines the different roles played by Isaac Newton, Robert Hooke, and Edmond Halley in the British scientific revolution of the late 17th Century. The idea for the project arose from a conversation at the Royal Society between John Gribbin and Lisa Jardine, who pondered how science might have developed had Newton never lived. They concluded that Hooke and Halley would have led science down a similar path, but perhaps at a slower pace. Newton's giant status in science, and the impact of *Principia Mathematica* with its three laws of motion and the law of universal gravitation, have overshadowed major advances made by the two men. Ironically, but for Halley's enthusiasm and hard cash, *Principia* would probably never have been published.

The Gribbins shine a bright light on both Hooke (of the stretched spring 'law') and Halley (of comet fame). Their elegant and meticulously researched narrative succeeds admirably in bringing those two out of the shadow. Hooke gets about twice as many pages as Halley. There are several places where their interests overlapped: the inverse-square law of gravity, navigation, the longitude problem and the mariner's compass, and time-keeping. Good coverage is given here of Halley's sea voyages to survey the southern skies and to map magnetic variation. The first two chapters of this book cover Hooke's achievements as a gifted instrument maker, an experimentalist, an imaginative demonstrator, and the author of *Micrographia*, the first scientific best-seller. Hooke daringly wrote in English, and in the first person. Young Samuel Pepys FRS, rated it "the most ingenious book that I ever read in my life". Chapter 3 showcases Hooke's monumental achievements as a Surveyor for the City of London after the Great Fire of 1666. The authors pick four of his projects as examples of his collaborations with Christopher Wren, the Savilian Professor of Astronomy: restoring the Fleet Stream to a navigable river; the design and rebuilding of 55

⋆For example, *Patterns in the Sky*, by Julius D. W. Staal (Hodder and Stoughton, 1961).

churches in the City; the Monument built to celebrate the recovery of the City from the Fire; and the structural design of the dome of St Paul's. This is a most enjoyable book about the ingenious trinity who set natural philosophy on a new course after England's Civil War. — SIMON MITTON.

Bayesian Models for Astrophysical Data, by J. M. Hilbe, R. S. de Souza & E. E. O. Ishide (Cambridge University Press), 2017. Pp. 393, 25 × 19 cm. Price £60/$75 (hardbound; ISBN 978 1 107 13308 2).

Joe Hilbe was the founding president of the International Astrostatistics Association (IAA), and was one of the leading promoters of the field of astrostatistics. Very sadly he passed away shortly after this book was published, and he will be very much missed. For this book, he teamed up with two younger members of the astrostatistics field to produce a software-orientated resource for those who are interested in applying statistical modelling techniques to data. The emphasis of the book is very much on providing fully working example codes to treat a wide variety of problems, and it includes many programs in R, JAGS, PYTHON, and STAN, which will be very valuable for the increasing numbers of astronomers who are using those languages and packages. The codes are also freely available on-line. The pedagogical element is reinforced by this very extensive provision of codes, and the repetition of similar codes allows the reader to compare, see what is common, and what varies, and this will help in adapting them to new situations. Many different distributions are discussed, and in some cases there are hints at how they might arise from a principled statistical analysis, whereas in others they appear to be parametrizations that could be useful descriptive models for data for which the underlying physical causes may be unknown. Both types will find application in astrophysics in different settings. There is extensive discussion of generalized linear models, some simple forays into Bayesian hierarchical models, and a number of case studies from astronomy. The book also discusses briefly some aspects of model comparison, but not from a particularly Bayesian perspective. As mentioned earlier, the focus of the book is not on providing a full understanding of how the distributions arise, but to give guidelines on how to write code for applications, including building multi-level models, and here it succeeds well, and is an excellent resource in conjunction with powerful packages such as STAN and JAGS. — ALAN HEAVENS.

Atmospheric Evolution on Inhabited and Lifeless Worlds, by D. C. Catling & J. F. Kasting (Cambridge University Press), 2017. Pp. 579, 25 × 19·5 cm. Price £54·99/$89·99 (hardbound; ISBN 978 0 512 84412 3).

New books on the atmospheric sciences keep coming, driven on one hand by widespread and growing interest in climate-change mechanisms and forecasts, and on the other by the on-going discovery of exoplanets with a zoo of probable atmospheres, scattered throughout the observable Universe. The latest addition to the canon by David Catling and James Kasting is particularly noteworthy for its very comprehensive coverage of the subject, in nearly six hundred large pages, and for the eminence of its authors, both well-known and respected in the field. Much of the material covered is standard stuff — radiative transfer, photochemistry, thermodynamics, and so forth — but with a refreshingly clear treatment that will be of value to students, particularly those at the graduate level. The real strength, however, is in the coverage of evolutionary aspects: given the known physics, and the geological record, *etc.*, what can we say about

the Earth's atmosphere in the past, its origins, and how it evolved to what we see today? Closely coupled with this new account, and a major theme of the book, is the habitability (not just for humans, but for all life forms, including those we may not know about yet) of our planet at the various stages of its development, and that of other worlds in the Solar System and far beyond.

It is hard to find fault with such an excellent book, but making an effort I found the pioneering infrared experimentalist Rudy Hanel referred to as Robert, and the colour figures grouped in a central 'insert', when many publishers have thankfully found a way to move on from that particular parsimony. Such trivia do nothing to detract from a quite riveting read, something which cannot often be said about a text-book and reference work, which this is too. The saga of how the climate may have evolved on the Earth and other planets is something about which we in fact know quite little for sure. However, it has been extensively researched, using fragments of evidence, theories, inferences, and most commonly of all an array of assumption-ridden models. Climate modelling is a hot topic, and 'hindcasting' to try to learn about past behaviour is as fraught an exercise as predicting future change on present-day Earth, but important, of course, and fascinating. This is an excellent account of the current state of the art. — F. W. Taylor.

The Pillars of Creation, by M. Beech (Springer), 2017. Pp. 269, 24 × 17 cm. Price £26·99/$34·99 (paperback; ISBN 978 3 319 48774 8).

I was sorely disappointed by this book. Described as written for "science enthusiasts ... and presenting an accessible explanation of how stars are born from the interstellar medium and giant molecular clouds", *The Pillars of Creation* should have offered a comprehensive survey of the progenitorial stuff that comprises the stars, the interstellar medium, and even we ourselves. Rather, it meanders only loosely towards that goal, not even introducing the topic of GMCs until mid-book, and irritatingly postponing repeatedly the other topics until "later chapters". Considerable space is given over in the text to basic descriptions — distance, luminosity, spectral classification, and the like, and how to determine them. It is certainly sensible to include those sections *briefly*, but the style is the converse of succinct, partly because of chatty background histories that do not add much to the necessary information, and serve to delay the principal theme of the book further still. Only the topic of magnitude plus extinction is placed appropriately in an Annexe. However, once the main topics are eventually reached, a somewhat improved focus is achieved

Beech has a passion for his topic, and writes persuasively. However, it is not obvious for whom the book is intended. Most professionals do not need to be taught about measuring distance, spectral classification, or energy units, but there are enough equations to deter a "science enthusiast". References to published papers are curious: Beech spells out the title of each referenced journal in full (and not always correctly; *Journal of the Royal Astronomical Society* is not helpful), and gives the month of the issue but no page number. He also refers to authors by their full names, which conveys a somewhat superior familiarity but falls down when he selects the wrong first name (did we know Andrew Thackrey [*sic*] of Radcliffe Observatory?). On the other hand, the descriptions and discussions of the principal themes are appropriate for those of the specialist.

Unfortunately, the book has rather many mistakes, and not only mere grammar and punctuation. In the context of spectral classification, for instance, we are told that the Fraunhofer A line at λ 0·759 μm is in the *blue*, that "a set [*sic*]

of closely spaced strong lines is called H & K", and that sub-class divisions are labelled 0 to 9, with 0 being the coolest within a class and 9 the hottest. Typos and mis-spellings are not infrequent, some (such as expressing 1 eV as 19^{-19} instead of 10^{-19}) more serious than others (though whether Yerkes Observatory is really "in Chicago", or that the year 1900 is the turn of the 19th Century, is probably of little consequence). Incorrect or incomplete figure captions are more upsetting. Recommending his own publications as sources of "further information" is probably not wise.

One gains the distinct impression that the author set out to express his passion for this particular area of astrophysics, but with rather little plan in mind for creating a readable book at the same time. The main topics are covered well enough and contain plenty both to inform and challenge, though many of the assertions (such as ages and distances) seem to have little or no foundation. The enthusiasm is plentiful — in places the writing waxes lyrical and melodramatic, but too often it wanders off into pages of speculation that dilute rather than enhance the actual scientific content. The over-use of words like "Indeed", "accordingly", or "essentially", which pepper most pages, strengthens that impression. An unsolicited criticism of the concern aroused by the award of the 1974 Nobel Prize for Physics to Ryle and Hewish and not to the student also involved is both entirely uncalled for and incorrect. When the first 20 pages of my copy of the book parted from their binding it was as if Springer was commiserating with me.

The Pillars of Creation is like a draft, rather than a finished product. The material that has been assembled needs better organization and filtering for presentation in a way that satisfies rather than irritates. Keeping the sub-topics better in perspective, retaining a clear theme-line throughout, and (please!) efficient proof-reading would have made an appreciable difference. What a pity. One really cannot recommend a book in this state. — Elizabeth Griffin.

Supernova Explosions, by David Branch & J. Craig Wheeler (Springer), 2017. Pp. 721, 23 × 15 cm. Price £87·50/$139 (hardbound; ISBN 978 3 662 55052 6).

According to a reliable source (your reviewer's previous publications), authors David Branch and Craig Wheeler together have a record of 84 years of publications about supernovae. That expertise has been directed toward producing a volume with an enormous richness of both broad principles and detail. The intended readership is "advanced undergraduate and graduate students of astronomy and physics and astronomers and physicists contemplating research on supernovae or related fields", not "pundits like ourselves" (add in the reviewer's record to get 134 years of publication).

They have focussed on SN explosions themselves, with less attention to prior stellar evolution, remnants, and by-products like cosmic rays and gamma-ray bursts. Very little is said, deliberately, about how one turns photons received into usable observational data. And 'history' is almost confined to a footnote in the Preface, depriving the historian of two citations to bolster her h-index, though in fact Baade, Bethe, Zwicky, and a few other notables of the past have crept into the main text.

The index is extensive, but slightly odd. Sixteen types of neutrino reactions are indexed (all but one on pp. 181–182), but not the Crab Nebula. The Crab does appear in Section 7.4 as one of nine historic supernovae with associated remnants. The reader is told that the mass of the remnant has been estimated as less than 54 $M_\odot$ but greater than 7 $M_\odot$. And the associated kinetic energy is of order or less than 0·1 B. Flip madly to the list of abbreviations at the back

to find out how many flying elephants have a kinetic energy of 1 B. Not there. Not indexed. Think, think, think. Hans Bethe used to write and speak of energy in units of FOE, fifty-one-ergs. Check index for Bethe. Yes! There it is! A 'B' is 10^{51} ergs!

Some 250 individual events in addition to SN 1054 appear, ranging from early Zwicky discoveries to products of the Palomar Transient Factory, and an accidental find from the OGLE microlensing survey — SN 1987A gets Chapter 11 to itself. Not surprisingly, both the number of types and the classification schemes have multiplied with the numbers of recognized events, though the eternal verity "mostly nuclear energy *versus* mostly gravitational energy" persists. Subtypes can be defined by light-curve shape (P for plateau *versus* L for linear) and line widths (n for narrow, particularly the hydrogen lines) as well as the obvious "superluminous supernovae", which occur both with (Type II) and without (Type I) hydrogen lines. Different degrees of interaction with circumstellar and interstellar material, strengths of magnetic fields, and the presence or absence of binary companions are also important and addressed.

Perfection would, of course, tempt the ghost of Fritz Zwicky, and the book is not at risk of that. The image of Cas A is colour-coded for data from *HST*, *SST*, and *Chandra*, but we are not told which colour is which. But my favourite is Fig. 1.2, whose two pieces are labelled "Thermonuclear Supernovae" and "Care Collapse Supernovae". The models of pre-explosive evolution, ejection of matter in the core-collapse events (this is still a bit of a problem), and interactions with surroundings are, of course, the products of numerous elaborate computer codes, many of which are indexed. The prize for 'most biological looking' goes to Fig. 19.5, "Evolution of a flame bubble after ignition in a carbon white dwarf of M_{ch}. C. M. Malone *et al.* (2004)". Was the progenitor of that explosive feature a single accreting degenerate star or a merged double degenerate? Yes, say the authors, still a bit puzzled that a large fraction of SNe Ia have very similar properties but don't seem to be traceable to one sort of origin or the other.

Branch and Wheeler express hope that the book will be of use to those who consult it (yes, definitely) — for a while (so there is always hope for answers to the oldest questions from the next round of data, modelling, and reviewing).

Conflict-of-interest statement: A heavy box containing *Supernova Explosions* arrived in my mailbox recently. The packing slip did not ask for any money in return. Perhaps this is because I am listed in the front matter as a member of the editorial board for the series. If so, then our 12 complimentary copies have added about $8 each to the price you paid for your one of 200. — VIRGINIA TRIMBLE.

Before Time Began: The Big Bang & the Emerging Universe, by H. Satz (Oxford University Press), 2017. Pp. 170, 22·2 × 14·5 cm. Price £19·99 (hardbound; ISBN 978 0 19 879242 0).

This book, according to the preface an updated version of a book in German[1], is in the tradition of small cosmology books which don't attempt to be comprehensive, but rather cover a few aspects in somewhat more detail than more-general popular accounts. Some of them have become classics, such as Heckmann's book[2] (still in print!) on relativistic cosmology which introduced many to the Newtonian cosmology of Milne and McCrea (almost always referred to in that order, opposite to that on their paper[3]), Bondi's text-book[4] (though at the times those two books were written not that much was known

about cosmology, so they are rather thorough for their times despite being thin), and Berry's, which[5] emphasizes the connection between cosmology and GR. This book, written by an emeritus professor of theoretical physics at the University of Bielefeld, Germany, focusses on phase transitions, the multiverse, and the connection between entropy and gravitation. Though the details of all of those are quite technical, the book provides a good popular account. All three are topics of current research but usually not covered in books at this level. Although he points out that not everyone shares his views, the author presents the multiverse as fact, likening it to a second Copernican Revolution. While there is not (yet) complete consensus on that, I think that his point of view is fine for a popular-science book.

The eight chapters cover inflation and what preceded it, particle physics in the early Universe, phase transitions, the CMB and cosmological parameters, structure formation, dark matter and the cosmological constant, and the ultimate fate of the Universe. Three appendices explore topics in somewhat more (mathematical) detail. There are several figures, some in colour, throughout the text, which is followed by a brief list of eight books and three papers for further reading, an index for persons, and one for topics. There are neither footnotes nor endnotes (but none are needed).

Unfortunately, the author repeats a claim I have seen elsewhere that the cosmological constant (or 'dark energy') causes the *expansion* of the Universe. While it does cause the *acceleration*, it does not cause the expansion. That should be obvious from the fact that there are cosmological models without a cosmological constant which expand. Moreover, with a non-zero cosmological constant of either sign, the Universe can expand or contract; this is determined by initial conditions.* It is a shame that that mistake mars an otherwise good and well-written book. An informed editor could have corrected it, the few minor mistakes, and the few errors in style. (I noticed only one Germanism, and there are practically no typographical errors; in that respect this book is better than most books I have reviewed in these pages.) My only other gripes are that the author rules out (primordial) black holes as dark-matter candidates (some parameter space is still allowed[7]) and the roles of the density parameter and the cosmological constant in determining the spatial curvature are described somewhat confusingly.

With the caveats above, I recommend the book since it fills an otherwise rather vacant niche, and the few faults do not detract seriously from the narrative. I do wonder, though, if the publishers of this and similar books don't have them read by someone knowledgeable in the field. That could significantly improve such books at almost negligible cost. — PHILLIP HELBIG.

References

(1) H. Satz, *Kosmische Dämmerung* (C. H. Beck, Munich), 2016.
(2) O. Heckmann, *Theorien der Kosmologie* (Springer, Berlin), 1968.
(3) W. H. McCrea & E. A. Milne, *Quart. J. Math.*, **5**, 73, 1934.
(4) H. Bondi, *Cosmology* (Cambridge University Press), 1961.
(5) M. V. Berry, *Cosmology and Gravitation* (Adam Hilger, Bristol), 1986.
(6) T. Padmanabhan, *Gen. Rel. Grav.*, **42**, 2743, 2010.
(7) B. Carr, F. Kühnel & M. Sandstad, *Phys. Rev. D*, **94**, 3504, 2016.

*Of course, many things can be explained by an appeal to initial conditions. With regard to the flatness and horizon problems, for example, that is rightly seen as unsatisfactory. One can ask what causes the initial conditions, in other words, what causes the expansion of the Universe[6]. However, that is not the context in which the author makes his claim.

CORRIGENDUM

On page 306 of the 2017 December issue, the ISBN of the paperback issue of *Astrochemistry* was given incorrectly; it should be 978 1 78634 038 2. In fact, the number that was given (978 1 78634 037 5) is the ISBN for the *hardbound* copy which is available at a price of £81. And on page 313 of that same issue, the editor of *Universe* was given as Rosie Pickles, whereas the publisher's preferred attribution is to 'Phaidon Editors'. We apologise for these errors.

Here and There

SURELY A ROSE-TINTED FILTER?

This image of Abell 39 was taken with the WIYN Observatory's 35-meter telescope at Kitt Peak National Observatory through a blue-green filter... — *S&T*, 2017 July, p. 34.

MOVE OVER, MT. EVEREST

The TMT's planned location on Mauna Kea, the summit of which is over 10000m above sea level … — *Physics World*, 2017 July, p. 7.

NOT A GOOD DIAGNOSTIC TOOL

In the NIR the contrast between stellar spots or plagues and the rest of the stellar disk is reduced. — *Exp. Astron.*, **41**, 351, 2016.