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Through the looking glass: why the 'cosmic horizon' is not a horizon★

Pim van Oirschot,[1,2]† Juliana Kwan[1] and Geraint F. Lewis[1]

[1]*Sydney Institute for Astronomy, School of Physics, A29, University of Sydney, NSW 2006, Australia*
[2]*Department of Astrophysics, IMAPP, Radboud University Nijmegen, PO Box 9010, 6500 GL Nijmegen, the Netherlands*

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ABSTRACT

The present standard model of cosmology, Λ cold dark matter (ΛCDM), contains some intriguing coincidences. Not only are the dominant contributions to the energy density approximately of the same order at the present epoch, but we also note that contrary to the emergence of cosmic acceleration as a recent phenomenon, the time-averaged value of the deceleration parameter over the age of the Universe is nearly zero. Curious features like these in ΛCDM give rise to a number of alternate cosmologies being proposed to remove them, including models with an equation of state $w = -1/3$. In this paper, we examine the validity of some of these alternate models and we also address some persistent misconceptions about the Hubble sphere and the event horizon that lead to erroneous conclusions about cosmology.

Key words: cosmology: theory.

1 INTRODUCTION

There is growing observational evidence for the existence of a non-zero cosmological constant (Perlmutter et al. 1998; Riess et al. 1998; Spergel et al. 2003; Tegmark et al. 2004), yet there are many alternative theories for cosmic acceleration as a number of outstanding, fundamental questions concerning the Λ cold dark matter (ΛCDM) paradigm remain unsolved. A key problem with the cosmological constant is that its energy density derived from observations, Ω_Λ, is $\approx$120 orders of magnitude smaller than what we would expect from the predictions of quantum field theory (Weinberg 1989). Also, it is sometimes remarked that the near equality between the best-fitting values of Ω_Λ and $\Omega_{\rm m}$ obtained for ΛCDM presents a 'coincidence problem', since it implies that we are placed at a special time in cosmic history when the energy densities are approximately equal. There have been numerous attempts to remedy these problems, such as evolving dark energy (for a review, see Barnes et al. 2005), but none of these is particularly convincing or well supported by observations and ΛCDM remains the standard model of cosmology.

One recent alternative model was dependent upon the properties of the 'cosmic horizon', $R_{\rm h}$, defined by Melia (2007) as a Schwarzschild radius $R_{\rm h} = 2GM(R_{\rm h})$ (throughout this paper, the speed of light is set equal to unity). In a Friedmann–Lemaître–Robbertson–Walker (FLRW) universe, with flat spatial geometry, $R_{\rm h}$ is equal to $1/H$, where $H(t)$ is the Hubble parameter. Melia (2009) showed that the time derivative (denoted by an overdot) of the 'cosmic horizon'

$$\dot{R}_{\rm h} = \frac{3(1+w)}{2}, \tag{1}$$

for a single component universe in which the cosmic fluid has an equation of state w. Note that $\dot{R}_{\rm h} = 1$ only for the special case of $w = -1/3$; thus $R_{\rm h}$ is exactly equal to t at all times in such a universe.

From the present-day best-fitting value $\Omega_{\Lambda,0} = 0.726 \pm 0.015$ (Komatsu et al. 2009; the subscript zero denotes the value of a quantity at the present time) and assuming a spatially flat universe, it can be derived that our Universe is approximately 13.7 billion years old. Using the value $H_0 = 70.5 \pm 1.3\,{\rm km\,s^{-1}\,Mpc^{-1}}$ (Komatsu et al. 2009), this age can be written as 0.989 Hubble time ($1/H_0$); thus

$$t_0 \approx \frac{1}{H_0} = R_{\rm h}(t_0). \tag{2}$$

Melia (2009) and Melia & Abdelqader (2009, hereafter M09) argue that this equality (or near equality) should signify that the best cosmological model is one in which these quantities are equal for all cosmic times, i.e. the $w = -1/3$ model mentioned above, and not just for a brief crossing that happens to occur now. However, as we shall argue in Section 2, this model relies on the ability of 'anthropic' reasoning to discriminate between cosmologies. Furthermore, the model proposed by M09 requires $R_{\rm h}$ to act as a true horizon, such that the redshifting of photons emanating from this surface becomes infinite. We shall show in Sections 4 and 5 that this assertion is erroneous and that the conclusions presented in M09 rely on a misapplication of the Hubble sphere. The goal of this paper is to clarify some of the pernicious misconceptions surrounding the Hubble sphere and to address the validity of the 'cosmic horizon' as a test of cosmology.

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†E-mail: pimvanoirschot@gmail.com

2 CURIOUSER AND CURIOUSER: ONE COINCIDENCE PROBLEM BECOMES TWO

M09 argues that since $R_{\rm h}$ would equal t just once in the entire history of the universe if $w \neq -1/3$, it is an unacceptably improbable coincidence that $R_{\rm h} \approx t_0$ at present. In this section, we shall discuss the near equality of $R_{\rm h}$ and t_0 and show that it indeed poses an additional coincidence problem for ΛCDM. However, we argue that equation (2) cannot be used as the basis for constructing a cosmological model that is competitive with ΛCDM. Furthermore, instead of expressing the coincidence in terms of $R_{\rm h}$, we shall express it in terms of the average value of the deceleration parameter $q(t)$ over the age of the universe, $\langle q(t_0)\rangle$.

The deceleration parameter is defined in terms of the scalefactor $a(t)$, which embodies the evolutionary path of the universe, and it can be shown that for a flat FLRW universe (see e.g. Barnes et al. 2005)

$$q \equiv -\frac{\ddot{a}a}{\dot{a}^2} = \frac{1+3w}{2}. \tag{3}$$

Comparing equations (1) and (3), we see that $\dot{R}_{\rm h} = q + 1$. This yields that the time-averaged deceleration parameter

$$\langle q(t)\rangle = \frac{1}{t}\int_0^t \left[\dot{R}_{\rm h}(t') - 1\right] {\rm d}t' = \frac{1}{tH} - 1. \tag{4}$$

Inserting the above-mentioned values for t_0 and H_0, this expression gives $\langle q(t_0)\rangle = 0.0113 \pm 0.0154$ and the present average deceleration of the universe is remarkably close to zero. We shall assign the fact that $\langle q(t_0)\rangle$ is consistent with zero as a coincidence, but we note that it is a separate coincidence from the well-known ‘coincidence problem’ and in fact the duration of this event in cosmic history is so brief that it is a ‘greater’ coincidence in this respect than the approximate equality of the dominant energy densities.

Fig. 1 shows both coincidences for a flat FLRW universe with matter and dark energy. We use the present-day value of $\Omega_{\rm X,0} = 0.726$ from Komatsu et al. (2009) for the density parameter of dark energy and assume that the universe is spatially flat. The evolution of $\langle q\rangle$, visualized by the solid lines, can be read on the left axis, while the change of $\Omega_{\rm m}$ over time, visualized by the dashed lines, can be read on the right axis. The colours represent different values of the equation of state of dark energy, w. Red corresponds to $w = -1$, which is true for the cosmological constant. While the red dashed line drops from 1 to 0 in about two Hubble times, the red solid line indicates that $\langle q\rangle \approx 0$ only for a fraction of a Hubble time. Thus, the fact that the average value of the deceleration parameter over the age of the universe is nearly zero for ΛCDM is really a ‘greater’ coincidence then the well-known ‘coincidence problem’.

Of course, it can be argued that perhaps we do not reside in the concordance cosmology and that this actually signifies a failing of the standard model. In fact, this ‘new’ coincidence was previously noted by Lima (2007), who thereafter suggested that the universe evolves through a cascade of alternately accelerating and deceleration regimes. But the origin of the physical mechanism responsible for these oscillations remains unknown, such that this model raises more questions than it answers. Similarly, in response to the coincidence that $R_{\rm h} \approx t_0$, M09 proposes that a model containing only a single fluid with $w = -1/3$ is a better fit to the observational data, since this would give rise to a ‘cosmic horizon’ that is fixed for all time. But, as soon as we include matter in our cosmology, $R_{\rm h}$ approaches t_0 only in the infinite future, and the fact that we observe

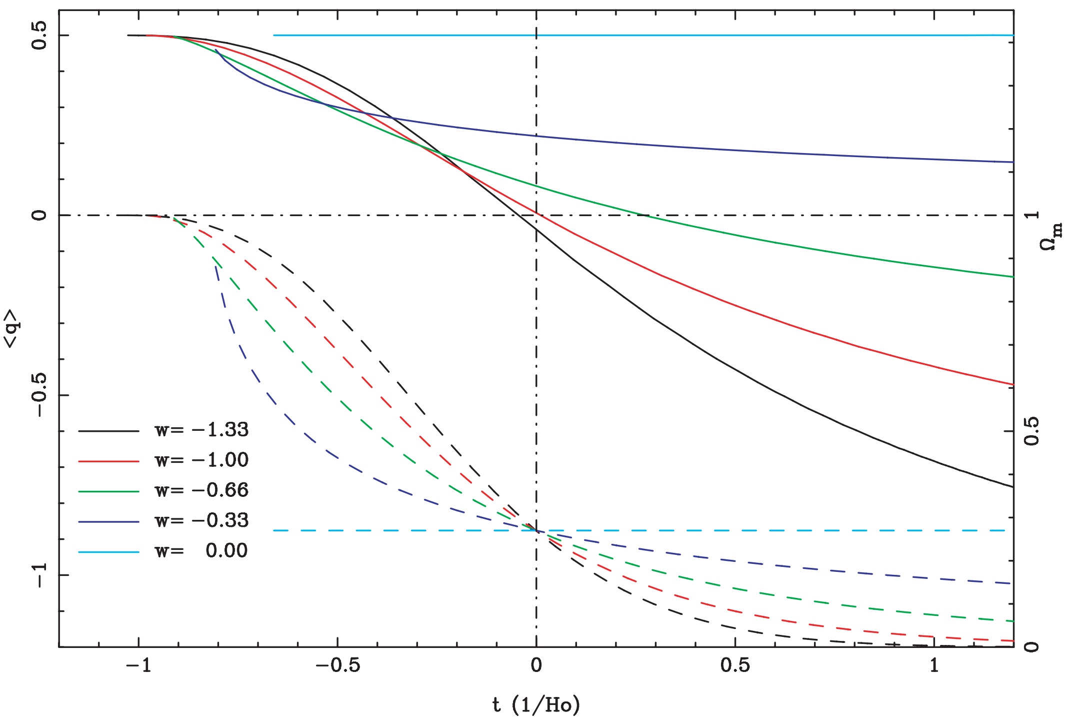

Figure 1. The solid lines represent the time-averaged value of the deceleration parameter $\langle q\rangle$ for flat cosmologies with a density parameter of dark energy, $\Omega_{\rm X,0} = 0.726$ and different equations of state, w, for the dark energy component. The dashed lines represent the evolution of the density parameter of matter, $\Omega_{\rm m}$, in the same models. The dot–dashed line at $t = 0$ corresponds to the present epoch, while the dot–dashed line at $\langle q\rangle = 0$ corresponds to a time-averaged deceleration of 0. Note that only the red solid line (corresponding to ΛCDM) goes through the intersection of these two lines.

the near equality of R_h and t_0 today suggests that the equation of state of dark energy is probably not $-1/3$ (the blue solid line in Fig. 1 clearly does not cross $\langle q \rangle = 0$).

With existing observational data, we can provide robust constraints on the equation of state parameter of dark energy, which currently imply a value of $w = -1.12 \pm 0.12$ (Riess et al. 2009). For a model to be competitive with the standard model, it is not only sufficient to remove a single outstanding problem with ΛCDM, but must also satisfy the areas where the ΛCDM model does well. Setting aside these objections, in the following sections, we investigate the cosmological model proposed by M09 to solve the coincidence problem by focusing on the conceptual arguments that underpin the model instead.

3 THE COSMOLOGICAL FRAMEWORK

The application of the cosmological principle of perfect homogeneity and isotropy uniquely determines the space–time geometry of the standard cosmological model, which is most simply encapsulated by the FLRW metric as follows:

$$ds^2 = dt^2 - a^2(t)\left[\frac{dr^2}{1-kr^2} + r^2(d\theta^2 + \sin^2\theta d\phi^2)\right], \tag{5}$$

where t represents the cosmic time (the time measured by an observer that is spatially stationary in the above coordinates) and (r, θ, ϕ) are spherical comoving coordinates. The curvature parameter k is $+1$ for a closed universe, 0 for a flat universe or -1 for an open universe.

This metric may be written in a number of different, but equivalent forms via a coordinate transformation for convenience. In our discussion, it is most expedient to use conformal and the observer-dependent coordinates of M09, while restricting our attention to a flat universe with two dimensions (t, r). Note that the discussion could be trivially extended to include all four dimensions, but this does not affect the main thrust of our arguments.

After applying the transformation $d\,\eta = dt/a(t)$ to equation (5), the conformal form of the FLRW metric reads as

$$ds^2 = a^2(\eta)(d\eta^2 - dr^2). \tag{6}$$

The time coordinate is now given by η, but it does not correspond to any observer.[1] Since photons travel along null geodesics ($ds = 0$) in the radial direction, we find from equation (6) that light cones in conformal coordinates are determined by

$$dr = \pm d\eta; \tag{7}$$

thus light rays follow straight lines at $\pm 45°$ angles when the metric is conformal, which makes them useful for making causal comparisons, such as those implied by cosmic horizons.

The observer-dependent form of equation (5), as derived by M09, is given by

$$ds^2 = \Phi\left[dt + \left(\frac{R}{R_h}\right)\Phi^{-1}dR\right]^2 - \Phi^{-1}dR^2, \tag{8}$$

where $\Phi \equiv 1 - (R/R_h)^2$ and the radial coordinate $R(t)$ is related to the comoving distance r via

$$R \equiv a(t)r, \tag{9}$$

[1] Often, the conformal radial coordinate is denoted by χ, but since we consider a flat universe, we can keep the symbol r.

that is, R is equivalent to the proper distance and a comoving observer does not remain stationary with respect to the spatial coordinates of this metric. The significance of the term R_h will be addressed in the following sections, but for now it is sufficient to note that a singularity occurs in the metric when $R \to R_h$.

4 HORIZONS IN COSMOLOGY

There are three main features when considering cosmological space–time diagrams in general: the event horizon, the particle horizon and the Hubble sphere. The event horizon is defined by the surface in space–time that encloses all events that can ever be detected for a comoving observer at $t \to \infty$, that is, it consists of a light cone projected backwards at the end of conformal time (see the thin solid line in Fig. 2). The existence of an event horizon is determined by the convergence of the integral

$$\eta_{max} \equiv \int_{t_0}^{\infty} \frac{dt}{a(t)}, \tag{10}$$

which also implies that the conformal time is bounded in the future; indeed, the two conditions are equivalent. Just as we have defined the conformal time remaining in equation (10), we are equally at liberty to determine if the universe had a finite conformal past. The limits on equation (10) would then be changed to integrate from $t = 0$ to $t = t_0$. Finite values of either integral correspond to the beginning, η_{min}, and end, η_{max}, of the universe in conformal coordinates.

The event horizon is distinct from the particle horizon, which is a surface that divides all fundamental particles into two classes: those that have already been observable at the present, t_0, and those that have not. [See Rindler (1956) for further details.] In other words, the particle horizon is equal to the path of a photon originated from the big bang (see the dot–dashed curve in Fig. 2). We already noted that an event horizon only exists in a universe with a finite conformal

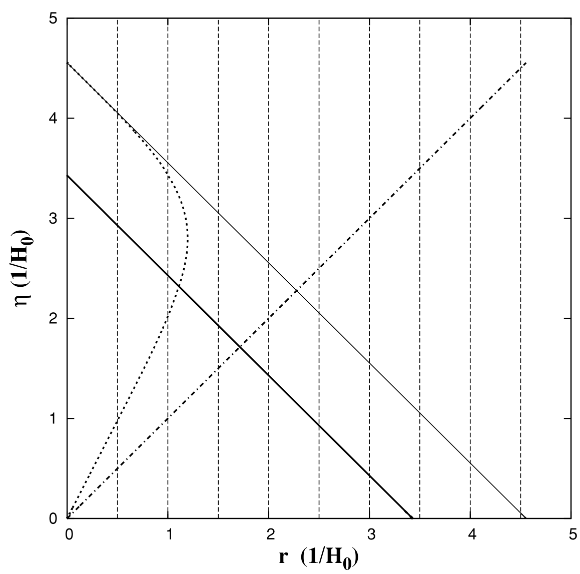

Figure 2. Space–time diagram in conformal coordinates to illustrate the event horizon (thin solid line), particle horizon (dot–dashed line), Hubble surface (dotted line) and the past light cone (thick solid line). The dashed lines illustrate the paths of comoving observers. The cosmological parameters used were $\Omega_{\Lambda,0} = 0.726$ and $\Omega_{m,0} = 0.274$. Clearly, the Hubble sphere never coincides with the event horizon, rather it asymptotically approaches it as $\eta \to \eta_{max}$. [See also fig. 2 in Gudmundsson & Björnsson (2002), fig. 1 in Davis & Lineweaver (2004) or fig. 12.2 in Longair (2008).]

future, likewise a particle horizon only exists in a universe that have a finite conformal past.

If the universe has a flat spatial geometry and if it contains only a single cosmic fluid with an equation of state $w \neq -1$, then $a(t) \propto t^n$, with $n = 2/[3\,(1 + w)]$. For a de Sitter universe ($\Omega_{\Lambda,0} = 1$, $\Omega_{\mathrm{m},0} = 0$), $w = -1$, and we have the special case that $a(t) = \mathrm{e}^{H_0 t}$. From these expressions for the scalefactor, we can see that the integral in equation (10) remains finite if and only if $w < -1/3$. If we change the limits to integrate from $t = 0$ to $t = t_0$, the integral would remain finite if and only if $w > -1/3$. Thus, a single component flat universe with $w < -1/3$ has an event horizon only, while it has a particle horizon only if $w > -1/3$. If $w = -1/3$, then such a universe neither has an event horizon nor a particle horizon. Because our universe was previously dominated by radiation ($w_\mathrm{r} = +1/3$) and matter ($w_\mathrm{m} = 0$), it has a particle horizon, and it also has an event horizon because it is currently dominated by dark energy, which must have an equation of state $w < -1/3$ for cosmic acceleration.

4.1 The Hubble sphere

The Hubble sphere marks the surface at which comoving systems are receding from an observer at the speed of light according to Hubble's law:

$$v_{\mathrm{rec}} \equiv HR, \tag{11}$$

that is, an object sitting on the Hubble sphere would have a recessional velocity, $v_{\mathrm{rec}} = c$ (Harrison 1991; Davis & Lineweaver 2004). Any object more distant than the Hubble sphere is receding from us at a speed greater than the speed of light. An object at a distance R away has two components to its velocity, which may be written as in terms of a recessional and peculiar velocity as follows:

$$\dot{R} = \dot{a}r + a\dot{r} = v_{\mathrm{rec}} + v_{\mathrm{pec}}. \tag{12}$$

It is important to distinguish between these velocities; although the recessional velocity may be greater than c, locally the peculiar velocity is always subluminal. In fact, a greater than light speed velocity is only inferred from non-local comparisons; if the velocity vectors were parallely propagated along a null geodesic and then a measurement of the redshift was taken, the resultant velocity would be less than the speed of light (Bunn & Hogg 2009). Thus, the definition of the Hubble sphere alone is sufficient to conclude that we must be careful when drawing conclusions with regards to its physical meaning.

The 'cosmic horizon', or characteristic radius at which $R_\mathrm{h} = 1/H$ in Melia (2007, 2009) and M09, is nothing more than the boundary of the Hubble sphere, the Hubble surface. Remembering that we had set $c = 1$ earlier in this paper, the equality between the 'cosmic horizon' and the Hubble sphere becomes clear. It is well documented in the literature that the Hubble sphere does not constitute a true horizon nor are events outside the Hubble sphere permanently hidden from the observer's view (Harrison 1981; Davis & Lineweaver 2004). Although photons emitted towards the observer by objects inside the Hubble sphere approach the observer, those emitted by galaxies outside the Hubble sphere recede, if the Hubble parameter H decreases with time and R_h increases and overtakes light rays which were initially beyond the 'cosmic horizon'. It is the particle horizon rather than the Hubble sphere that defines the farthest distance from which we can receive a signal at the present time. In fact, for the concordance cosmology, the Hubble surface currently lies at $z \approx 1.5$ (Davis & Lineweaver 2004) and, as any extragalactic astronomer will attest, is certainly not a limit to how far we can observe.

There are two exceptions, however, for which the Hubble sphere does constitute a horizon that cannot be traversed. In these cases, it is degenerate with the particle horizon or with the event horizon for every cosmic instant. In other words, the slope of the Hubble surface in a conformal diagram (the dotted line in Fig. 2) is always ± 1, because the slope of the particle horizon in a conformal diagram is $+1$ and the slope of the event horizon is -1. To express the 'cosmic horizon' in terms of the comoving coordinate r, we use equation (9). This gives $r_\mathrm{h} = R_\mathrm{h}/a$. The slope of the Hubble surface in a conformal diagram is therefore equal to

$$\frac{\mathrm{d}r_\mathrm{h}}{\mathrm{d}\eta} = a\dot{r}_\mathrm{h} = -\frac{\ddot{a}a}{\dot{a}^2}, \tag{13}$$

and we arrive at the definition of q given earlier in equation (3). Note that q is only constant in a single component universe; thus the Hubble surface is not a cosmological horizon at all, except when it becomes degenerate with the particle horizon in universe with radiation only ($q = 1$) and with the event horizon in a de Sitter universe ($q = -1$). [See also Harrison (1991).]

5 REDSHIFTING IN THE OBSERVER-DEPENDENT FORM OF THE METRIC

M09 originally showed that for $\mathrm{d}R = \mathrm{d}\theta = \mathrm{d}\phi = 0$, the time interval $\mathrm{d}t$ in the observer-dependent form of the metric (equation 8) must go to infinity as $R \to R_\mathrm{h}$, leading them to conclude that the 'cosmic horizon' is like the event horizon of a black hole, infinitely redshifting any emission coinciding with it. This in contrast to Davis & Lineweaver (2004), who pointed out that redshift does not go to infinity for objects on our Hubble sphere (in general) and for many cosmological models we can see beyond it. Here, we examine observed redshift of a photon exchanged between two observers in the observer-dependent coordinates. As is apparent in Fig. 2, this redshift should not go to infinity.

It is straightforward to demonstrate that the 4-velocity of any comoving observer (which has fixed spatial coordinates in the FLRW metric) is given by

$$u^\alpha = (1, \dot{a}r, 0, 0). \tag{14}$$

Furthermore, from Killing's equation, it can be demonstrated that this space–time admits a Killing vector of the form

$$\xi^\alpha = [0, ak(\theta,\phi), l(\theta,\phi), m(\theta,\phi)], \tag{15}$$

where k, l and m represent three currently undetermined functions, respectively; as we will be considering photon paths in the (t, R) plane, their exact form is unnecessary. The existence of the Killing vector allows us to define a quantity, e, which is conserved along the geodesic path of the photon, namely

$$e = \boldsymbol{\xi} \cdot \boldsymbol{p} = \left(\frac{R}{R_\mathrm{h}}\right) ap^t - ap^R, \tag{16}$$

where p^t and p^R are the components of the photon 4-momentum and the function k is subsumed into the constant e.

If two observers exchange a photon, the energy of the photon as seen by the receiver, E_r, compared to the energy as measured by the emitter, E_e, is simply given by

$$\frac{E_\mathrm{r}}{E_\mathrm{e}} = \frac{-\boldsymbol{u}_r \cdot \boldsymbol{p}(\mathrm{r})}{-\boldsymbol{u}_e \cdot \boldsymbol{p}(\mathrm{e})}, \tag{17}$$

where the $\boldsymbol{u}$ are the 4-velocities of the receiver and the emitter, while $\boldsymbol{p}$ is the 4-momentum of the photon. In general, we would have to propagate the photon between the emitter and the receiver, although the presence of the Killing vector allows us to simplify this procedure by noting that

$$E = -\boldsymbol{u} \cdot \boldsymbol{p} = -\left\{ \Phi p^t + \left(\frac{R}{R_{\rm h}}\right) p^R + \left[\left(\frac{R}{R_{\rm h}}\right) p^t - p^R \right] \dot{a} r \right\}; \tag{18}$$

then

$$E = -\frac{e}{a}\left(\frac{R}{R_{\rm h}} - \frac{p^R}{p^t}\right). \tag{19}$$

The ratios of the components of the photon 4-momentum can be determined from the metric (equation 8), remembering that photons follow null paths ($\mathrm{d}s = 0$) and so

$$\frac{\mathrm{d}R}{\mathrm{d}t} = \frac{p^R}{p^t} = \frac{-\Phi}{\left(\frac{R}{R_{\rm h}}\right) \pm 1}. \tag{20}$$

Following a photon from a positive R to the origin selects the solution that

$$\frac{p^R}{p^t} = -\left(1 - \frac{R}{R_{\rm h}}\right) \tag{21}$$

and clearly

$$E = -\frac{e}{a}. \tag{22}$$

Given this, a photon exchanged between two observers on the observer-dependent form of the FLRW metric (equation 8) will be seen to have an energy dependent upon the scalefactor, a, at the time of emission and receipt, such that

$$\frac{E_{\rm r}}{E_{\rm e}} = \frac{a_{\rm e}}{a_{\rm r}} = \frac{1}{1+z}, \tag{23}$$

precisely the form seen in comoving coordinates (as expected).

Fig. 3 shows a space–time diagram in the observer-dependent coordinates used by M09 for a universe containing a single component with $w = 0$. The solid line is a past light cone at the moment the universe is about 4.5 Hubble times old. The dotted line is the ‘cosmic horizon’ and the dashed lines are worldlines from comoving observers. As is seen in this figure, photon paths (a past light cone) can extend through the ‘cosmic horizon’ and hence objects even on the ‘cosmic horizon’ are seen with a finite redshift z. The shape of the light cone would be exactly the same at any other moment of time as would be the behaviour of the $R_{\rm h}$ for other values of $w > -1$.

It is interesting to note that in examining the past light cone in Fig. 3, the ‘cosmic horizon’ marks the turnaround point for a photon path, a transition between the photon moving away and then moving towards us, and hence our past light cone only encompasses events with $R \le R_{\rm h}$, although the emission from an object on the horizon is not infinitely redshifted. We return to this point in the next section.

5.1 Metric divergence

As was shown in the previous section, $R_{\rm h}$ corresponds to a stationary point in the past light cone, where the trajectory changes from moving away from the big bang to moving towards us. The analysis of M09 considers the path of objects with fixed R, such that $u^R = 0$; what do these correspond to? By examining the light cone structure as we approach the ‘cosmic horizon’, it is apparent that

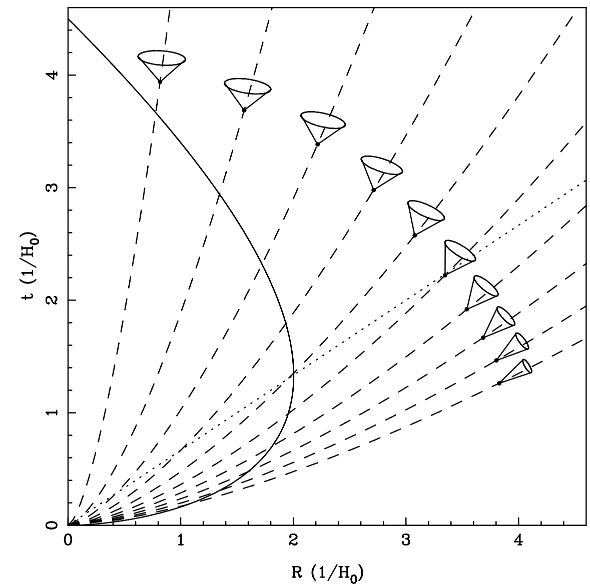

Figure 3. Space–time diagram in observer-dependent coordinates (t, R) for an Einstein–de Sitter ($w = 0$) universe, using the metric in equation (8). The Hubble sphere or cosmic horizon is given by the dotted curve, while the solid line represents a light cone. Dashed lines represent the paths of comoving observers with their light cones; although stationary in r, their proper distance R increases.

such a trajectory is approaching the left-hand side of the light cone, implying that compared to a comoving observer at that point they are moving closer and closer to the speed of light. Remembering that for our comoving observer, $u^t = \mathrm{d}t/\mathrm{d}\tau = 1$ (where τ is the proper time registered by the comoving observer) and for the fixed observer of M09 $u^t = \Phi^{-1/2}$, it is apparent that the divergence is time dilation between the comoving and the fixed observer, going to infinity at $R_{\rm h,}$ where the fixed observer is forced to travel at the speed of light. In summary, the divergence noted by M09 is due to forcing unphysical properties on the emitter by requiring $\mathrm{d}R = 0$. If these unphysical properties were not demanded, the observer-dependent coordinates could be used to describe the space–time geometry, as long as one neglects the singularity in the metric as $R \to R_{\rm h}$.

6 CONCLUSION

The inferred cosmic acceleration presents a conceptual dilemma; there is abundant observational evidence that favours the existence of a cosmological constant, yet some predictions and consequences of ΛCDM remain so puzzling that modern cosmology is littered with alternate mechanisms for reproducing the observational signatures of accelerated expansion. The similarity between the $1/H_0$ and the current age of the universe as pointed out by M09 and Lima (2007), as well as the original coincidence that $\Omega_{\Lambda,0} \sim \Omega_{\rm m,0}$, is genuinely problematic. While it is surprising that the average deceleration parameter should be close to zero at this particular instant in cosmic time, and may signify that aspects of the standard model are contrived, arguments of this nature cannot be prioritized over constraints from observations. The near equality of the Hubble surface $R_{\rm h}$ and the age of the universe t_0 requires a cautious interpretation and does not immediately exclude a cosmological model with a non-zero cosmological constant. Furthermore, it is worth emphasizing that a single space–time geometry may be expressed in several different coordinate systems and not all features of the metric necessarily contain a physical meaning; a poignant example is provided by the divergence at the event horizon in the Schwarzschild metric, which may be shown to be a coordinate singularity when written in Eddington–Finkelstein coordinates. M09 used observer-dependent coordinates to argue that R_h is a true horizon, while the theoretical framework to infer any conclusions about cosmic horizons was already there. Since R_h is the Hubble surface, it is not a physical horizon at which an infinite redshift is measured (except in a de Sitter universe), despite the divergence in the observer-dependent form of the FLRW metric.

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