The Long-Term Future of Extragalactic Astronomy

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ABSTRACT

If the current energy density of the universe is indeed dominated by a cosmological constant, then high-redshift sources will remain visible to us only until they reach some finite age in their rest-frame. The radiation emitted beyond that age will never reach us due to the acceleration of the cosmic expansion rate, and so we will never know how these sources looked like as they became older. The higher the current redshift of a source is, the younger it would appear as it fades out of sight. For the popular set of cosmological parameters, I show that a source at a redshift $z \sim 5$–10 would only be visible up to an age of ~ 4–6 billion years. Hence, arguments relating the properties of high–redshift sources to present–day counterparts will remain indirect even if we continue to monitor these sources for an infinite amount of time. These sources will not be visible to us when they reach the current age of the universe.

Subject headings: Cosmology: theory — cosmic microwave background

1. Introduction

Current observations of the microwave background and Type Ia supernovae indicate that the universe is flat and its expansion is currently dominated by a cosmological constant (Garnavich et al. 1998; Perlmutter et al. 1998; de Bernardis et al. 2000; Hanany et al. 2000; Netterfield et al. 2001; Lee et al. 2001; Wang et al. 2001). The cosmological scale factor is just entering an exponential expansion phase (similar to inflation) during which all comoving observers will eventually lose causal contact with each other. In this *Letter* I show that as a result of the acceleration in the cosmic expansion, sources fade out of our sight at a finite age. This implies that we would never be able to see their image as they get older. In §2, I calculate the *maximum visible age* of a source as a function of its currently measured redshift. For concreteness, I adopt the popular set of current density parameters with $\Omega_M = 0.3$ for matter and $\Omega_\Lambda = 0.7$ for the cosmological constant.

2. Maximum Visible Age as a Function of Current Source Redshift

The line-element for a flat universe is given by $ds^2 = c^2dt^2 - a^2(t)(dr^2 + r^2d\Omega)$, where $a(t)$ is the scale factor. Photon trajectories satisfy $ds = 0$, and so the comoving distance of a source that emits radiation at a cosmic time $t_{\rm em}$ and is observed at the current age of the universe t_0 is given by,

$$r = \int_{t_{\rm em}}^{t_0} \frac{c\ dt}{a(t)} \tag{1}$$

If the source continues to emit at a later time $t'_{\rm em}$, then this radiation will be observed by us at a future time $t'_{\rm obs}$. Since the source maintains its comoving coordinate, $r = \int_{t_{\rm em}}^{t_0}[c\ dt/a(t)] = \int_{t'_{\rm em}}^{t'_0}[c\ dt/a(t)]$, or equivalently

$$\int_{t_0}^{t'_0} \frac{dt}{a(t)} = \int_{t_{\rm em}}^{t'_{\rm em}} \frac{dt}{a(t)}. \tag{2}$$

The question of whether this equality can be satisfied for an arbitrary value of the source age, t'_0, depends on the future evolution of the scale factor $a(t)$. It is easy to see that as long as $0 < d\ln a/dt < 1$, this equality can be satisfied for an arbitrary value of $t'_{\rm em}$. This is the case, for example, in a matter-dominated universe where $a \propto t^{2/3}$. However, in a de Sitter universe the scale factor grows exponentially and so the integrand on the left-hand-side of equation (2) saturates at a finite value even as $t'_0 \to \infty$. This implies that there is a maximum intrinsic age, $t'_{\rm em}$, over which the source is visible to us. Emission after the source reaches this age will never be observable by us[1] (unless the vacuum energy density that makes the cosmological constant will decay). The maximum visible age obviously depends on $t_{\rm em}$ or the currently measured source redshift, z, which is given by the relation $a(t_{\rm em}) = (1+z)^{-1}$.

The evolution of the scale factor is dictated by the Friedman equation,

$$\frac{1}{a}\frac{da}{dt} = H_0\left[\frac{\Omega_M}{a^3} + \Omega_\Lambda\right]^{1/2}, \tag{3}$$

where $\Omega_M + \Omega_\Lambda = 1$. Equations (1) and (3) admit an analytic solution (Edwards 1972, 1973; Dabrowski & Stelmach 1986, 1987; Weinberg 1972, 1989; Eisenstein 1997) for $r(t_{\rm em}, t_0)$ in terms of an incomplete elliptic integral, and

$$a(t) = \left(\frac{1-\Omega_M}{\Omega_M}\right)^{1/3}\left[\sinh\left(\frac{3}{2}\sqrt{1-\Omega_M}H_0 t\right)\right]^{2/3}. \tag{4}$$

Pen (1999) provides a simple fitting formula for $r(a)$.

Figure 1 shows the source age, $t'_{\rm em}$, as a function of the future observing time, t'_0. All time scales are normalized by the inverse of the current Hubble expansion rate, $H_0 = (\dot{a}/a)|_{t_0}$. Clearly, as the source redshift increases, its maximum visible age (i.e. the asymptotic value of $t'_{\rm em}$ for $t'_0 \to \infty$) decreases. Typically, the maximum emission time $t'_{\rm em}$ is much longer than the current

[1]The observed redshift of the source diverges exponentially as $t'_0 \to \infty$ and so does the luminosity distance. Hence the flux received from the source declines exponentially with observing time, t'_0 , as $t'_0 \to \infty$. As the image of the source fades, it stays frozen at a fixed age along its evolution. This situation is qualitatively analogous to the observed properties of a source falling through the event horizon of a Schwarzschild black hole (Shapiro & Teukolsky 1983).

emission time t_{em}, and so only sources which are steady over many Hubble times at their current redshift will be suitable for this discussion. Unfortunately, the microwave background anisotropies generated at $z \sim 1000$ vary on the Hubble time at that redshift, and will therefore not maintain a fixed comoving distance from us on longer times.

Figure 2 plots the maximum visible age as a function of the currently measured redshift for the source.

3. Discussion

Figure 2 implies that a source at a redshift $z = 5$ ($z = 10$) will only be visible to us up to an age of $\sim$ 6 Gyr (4 Gyr). Thus, we will never be able to identify the counterpart to this source in a current map of the universe at redshifts $z \lesssim 1$ even if we continue to monitor this source indefinitely. This is because the age of the currently observed universe at $z \lesssim 1$ exceeds 6 Gyr. In other words, arguments relating the properties of high-redshift sources to counterparts in the present–day universe will forever remain indirect (unless the cosmological constant will decay).

The *visible age* limit become stricter for flux–limited observations where the maximum value of t_0' is constrained by the requirement that the luminosity distance will not exceed some value. While the flux limit may depend on technological advances in instrumentation, the visible age limit derived in this *Letter* for $t_0' \to \infty$ is absolute.

The prospects for extragalactic astronomy in the long–term future appear grim. In contrast to a matter-dominated universe, the statistics of visible sources in a Λ-dominated universe is getting worse with the advance of cosmic time. Within $\lesssim 10^{11}$ years, we will be able to see only those galaxies that are gravitationally bound to local group of galaxies, including the Virgo cluster and possibly some parts of the local supercluster (where the global overdensity in a sphere around Virgo is larger than a few). All other sources of light will fade away beyond detection and their fading image will be frozen at a fixed age.

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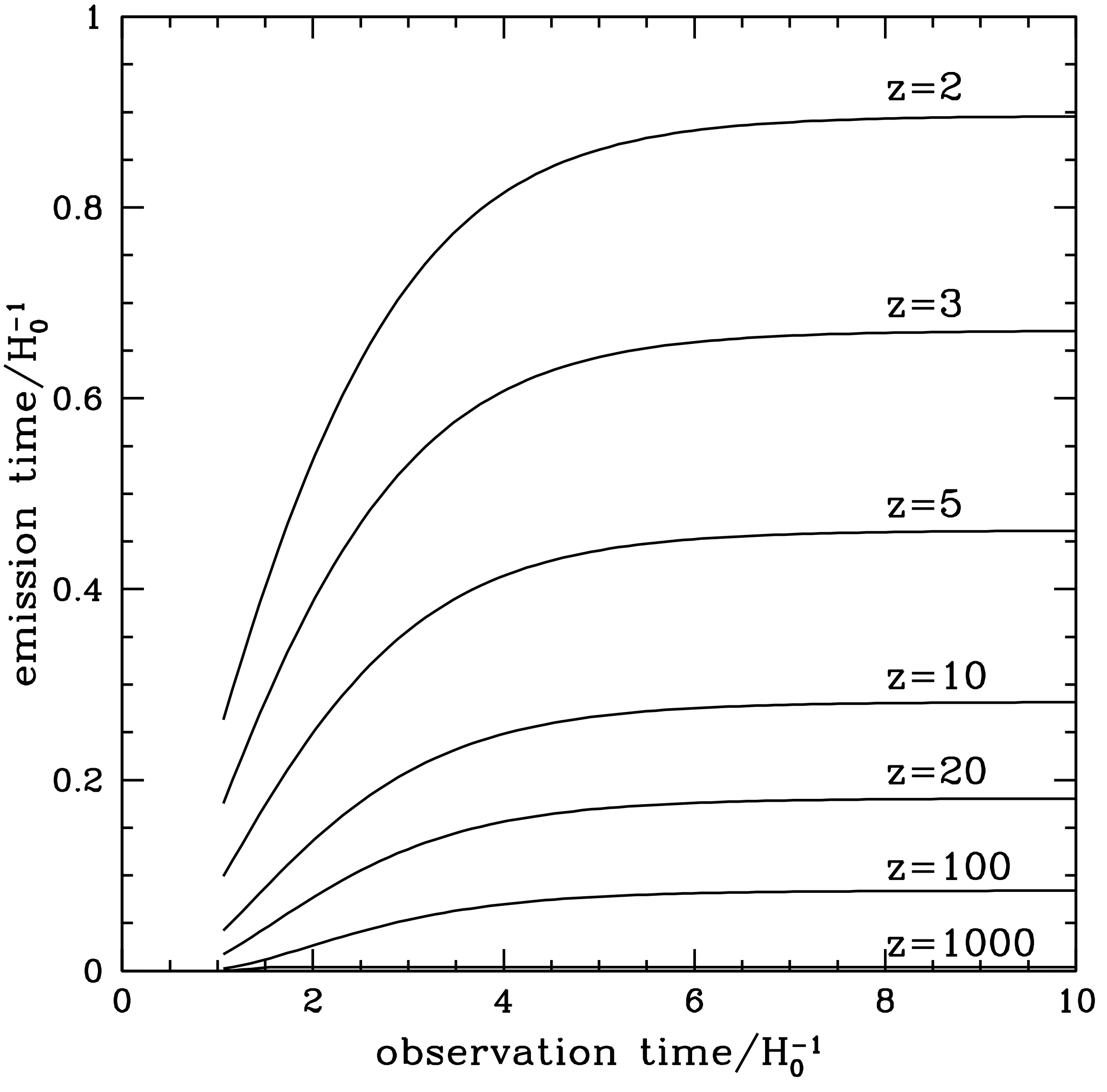

Fig. 1.— Emission time as a function of observation time for an $\Omega_M = 0.3$, $\Omega_\Lambda = 0.7$ universe. Time is measured in units of $H_0^{-1} = 14h_{0.7}^{-1}$ Gyr, where $h_{0.7} \equiv (H_0/70\ \mathrm{km\ s^{-1}\ Mpc^{-1}})$. For any currently measured source redshift, z, there is a maximum age up to which we can see that source even if we continue to monitor it indefinitely.

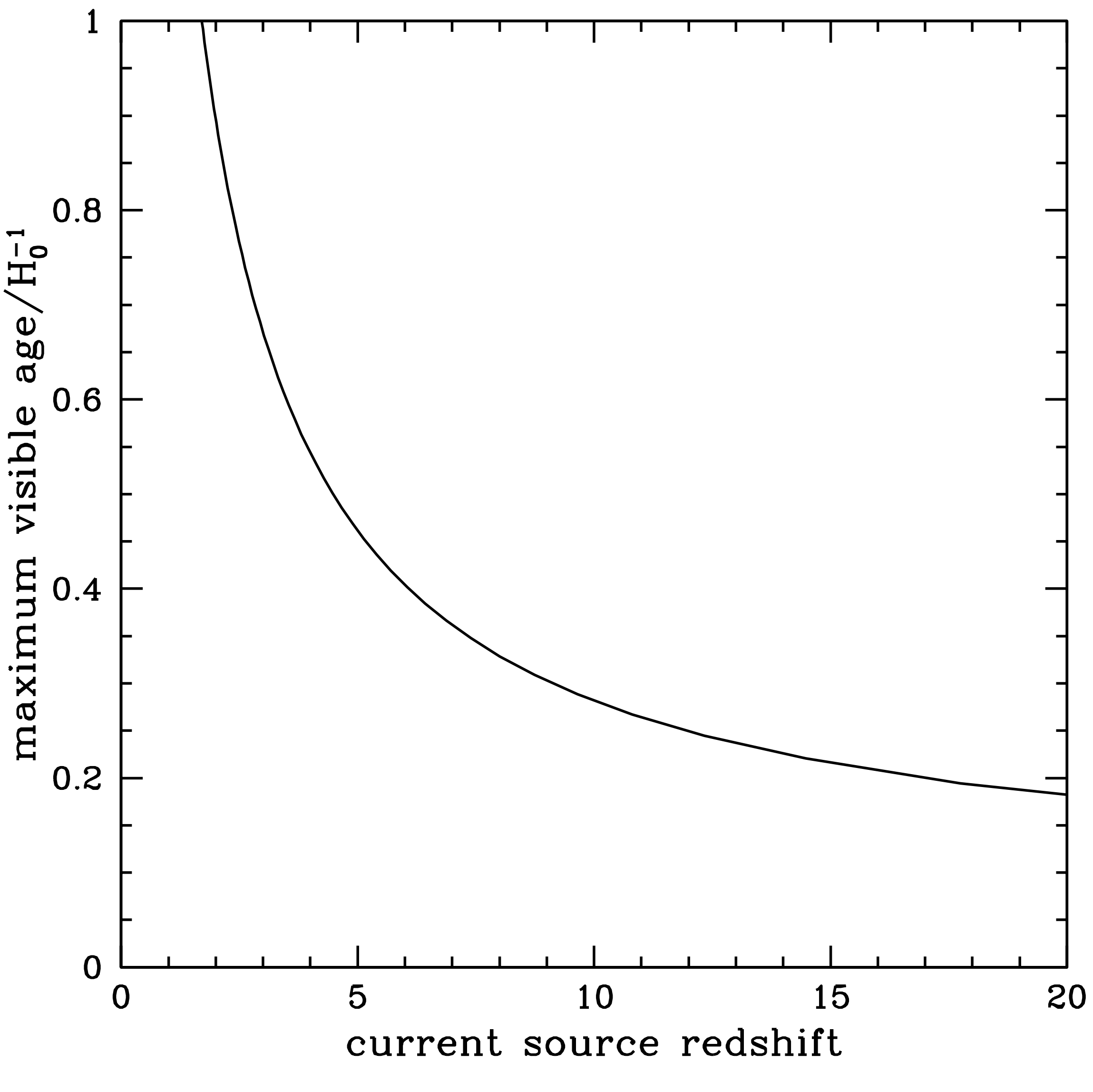

Fig. 2.— Maximum *visible age* of a source (in units of $H_0^{-1} = 14h_{0.7}^{-1}$ Gyr) as a function of its currently measured redshift, z.