OLD GALAXIES AT HIGH REDSHIFT AND THE COSMOLOGICAL CONSTANT

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Received 1996 August 2; accepted 1996 November 26

ABSTRACT

In a recent striking discovery, Dunlop et al. (1996) observed a galaxy at redshift $z = 1.55$ with an estimated age of 3.5 Gyr. This is incompatible with age estimates for a flat matter-dominated universe unless the Hubble constant is less than 45 km s$^{-1}$ Mpc$^{-1}$. While both an open universe and a universe with a cosmological constant alleviate this problem, I argue here that this result favors a nonzero cosmological constant, especially when it is considered in light of other cosmological constraints: (1) for the favored range of matter densities, the constraint is more stringent than the globular cluster age constraint, which already favors a nonzero cosmological constant; (2) the age-redshift relation for redshifts of order unity implies that the ratio between the age associated with redshift 1.55 and the present age is also generally larger for a cosmological constant-dominated universe than for an open universe; (3) structure formation is generally suppressed in low-density cosmologies, arguing against early galaxy formation. The additional constraints imposed by the new observation on the parameter space of $h$ versus $\Omega_{\text{matter}}$ (where $H = 100 \, h$ km s$^{-1}$ Mpc$^{-1}$) are derived for both cosmologies.

Subject headings: cosmology: theory — dark matter — distance scale — galaxies: evolution — large-scale structure of universe

Whenever big bang cosmology has been challenged by an age problem, a cosmological constant has been invoked as a possible remedy (i.e., Krauss & Turner 1995). The reason is simple. As long as the universe is decelerating, the present Hubble expansion rate sets an upper limit on the age of the universe as follows. If there were no deceleration as the universe evolved, the distance galaxies would have traveled since $t = 0$ would be $d = vt$. Since the Hubble constant $H = v/d$, then $H^{-1} = t$. If the universe has been decelerating, then distant galaxies would have achieved their present distances in a shorter time. Thus, for any matter-dominated (or radiation-dominated) cosmology the age of the universe $\tau < H^{-1}$. If independent estimates of the ages of galaxies are larger than this value, there is an apparent paradox. However, the addition of a cosmological constant allows a period of cosmic acceleration rather than deceleration and, hence, allows the obviation of this bound and the paradox. Recently it has been recognized that a number of other cosmological observables, including the baryon density of the universe and the shape of the power spectrum of galaxy-galaxy correlations, also argue in favor of a cosmological constant, at least if one is to preserve a flat universe, renewing interest in the possibility that the cosmological constant is nonzero, in spite of the theoretical microphysical problems associated with this idea (e.g., see Krauss & Turner 1995; Kofman, Gnedin, & Bahcall 1993).

These latter cosmological constraints do not distinguish between an open universe and a flat universe dominated by a cosmological constant, however. Indeed, the age problem, most recently quantified by the discrepancy between the inferred ages of globular clusters (Chaboyer et al. 1996) and the Hubble age, has provided perhaps the strongest motivation for considering one cosmology over the other (although COBE-normalized density fluctuations also are significant, as I shall describe later). The recent discovery of a 3.5 Gyr–old galaxy at a redshift of 1.55 is therefore particularly interesting in this regard.

Of interest in this case is the effect of a cosmological constant, not on the present age, but rather on the age of the universe at redshifts of order unity. It is clear that a cosmological constant which is significant today will only affect the evolution of the universe for low redshifts. However, it is well known that a cosmological constant alters the distance-redshift relation for redshifts of order unity—associating longer distances with a given redshift—enough to dramatically affect such things as the optical depth for gravitational lensing of distant quasars (Fukujita & Turner 1991; Krauss & White 1992; Kochanek 1992). For the same reason, one might expect that for low $z$, the age of the universe may be lengthened significantly compared to a flat matter-dominated universe or an open universe.

The age of a flat matter-dominated universe with Hubble constant $H$ is given by $\tau = (\frac{1}{2}) H^{-1}$. Since $H$ varies as $R^{-1/2}$ during the matter-dominated era, the age-redshift relation is trivially given as $\tau \approx (1 + z)^{-3/2}$. The $z$-dependent age for a matter-dominated open universe and for a cosmological constant–dominated flat universe are somewhat more complicated but, nevertheless, can be straightforwardly derived and expressed in terms of the present Hubble constant $H_0$ as follows:

**Open:** $\tau(z) = H_0^{-1} \int_0^{(1 + z)^{-1}} (1 + \Omega_{0, \text{matter}} + \Omega_{0, \text{matter}} x^{-1})^{-1/2} dx$, \hspace{1cm} (1)

**Λ:** $\tau(z) = \left(\frac{2}{3}\right) H_0^{-1} \Omega_{0, \Lambda}^{1/2} \ln \left\{ \left( \frac{\rho(z)}{\rho_0} + \frac{\Omega_{0, \Lambda}}{\Omega_{0, \text{matter}}} \right)^{1/2} + (\frac{\Omega_{0, \Lambda}}{\Omega_{0, \text{matter}}})^{1/2} \left( \frac{\rho(z)}{\rho_0} \right)^{-1/2} \right\}$, \hspace{1cm} (2)

where $\Omega_{0, \Lambda}$ and $\Omega_{0, \text{matter}}$ are the fractional contribution of the cosmological constant today and the matter density today, compared to the closure density, respectively, and $\rho_0$ is the energy density of matter at the present time.

Many independent estimators, including virial estimates of cluster masses, X-ray estimates of the total mass in clusters of galaxies, and large-scale velocity field measures,
suggest that $\Omega_{0,\text{matter}} \geq 0.2$. The equations above then imply that $\tau_0 < (8.27/h) \text{ Gyr for an open universe}$ and $\tau_0 < (10.46/h) \text{ Gyr for a cosmological constant–dominated flat universe versus } \tau_0 < (6.52/h) \text{ Gyr for a flat matter-dominated universe}$. A comparison of these ages with a 95% confidence lower bound on the age of the oldest globular clusters in our Galaxy, $\tau_0 \geq 12.1 \text{ Gyr}$, from a recent comprehensive analysis of theoretical and observational uncertainties in globular cluster age estimates (Chaboyer et al. 1996) provides a quantitative measure of the current cosmological "age problem."

To what extent does the recent Dunlop et al. (1996) observation impact on this situation? Setting $z = 1.55$ in the above equations, one finds $\tau < 2.67/h \text{ Gyr and } \tau < 3.53/h \text{ Gyr}$ for an open and cosmological constant–dominated flat universe, respectively. These relations clearly indicate that values of $h$ which satisfy the current cosmological age problem can also result in cosmological ages at $z = 1.55$ greater than 3.5 Gyr for both cosmological models. However, they also provide greater insight into the relative viability of both models, especially when other cosmological constraints are taken into account, as is the full allowed range of $\Omega_{0,\text{matter}}$. In the first place, note that not only is the absolute age of the universe at this redshift larger in a cosmological constant–dominated model than in an open universe model for this lowest allowed value of the matter density but that the ratio of ages is larger at $z = 1.55$ than for $z = 0$. This situation persists as long as $\Omega_{0,\text{matter}} \leq 0.5$. Moreover, while for $\Omega_{0,\text{matter}} = 0.2$ the $z = 1.55$ observation provides a weaker constraint on $h$ than the current globular cluster age estimate does, this situation quickly changes for larger values of $\Omega_{0,\text{matter}}$.

To fully appreciate the significance of these issues, it is useful to plot the constraint on the full $h, \Omega_{0,\text{matter}}$ parameter space implied by $\tau(z = 1.55) \geq 3.5 \text{ Gyr}$, for both open and flat $\Lambda$-dominated cosmologies, along with constraints from other cosmological measurements, following the approach of an earlier analysis for the flat $\Lambda$ model (Krauss & Turner 1995). Such constraints are presented in Figures 1a and 1b. The line representing the Dunlop et al. limit is explicitly labeled, and the viable region is constrained to be below this line. The other constraints arise as follows: region c represents the globular cluster age constraint $12 \text{ Gyr} < \tau_0 < 18 \text{ Gyr}$ (Chaboyer et al. 1996); region a arises from considerations of the baryon content of the universe determined by reconciling estimates from big bang nucleosynthesis (Krauss & Kerman 1996; Copi, Schramm, & Turner 1995), which suggest that $0.009 \leq \Omega_b h^2 \leq 0.022$, with determinations based on X-ray measurements of rich clusters of galaxies (White et al. 1993; White & Fabian 1995), which suggest $\Omega_b/\Omega_{\text{cluster}} \approx 0.05–0.08 h^{-3/2}$. Combining the two together and assuming $\Omega_{\text{cluster}} \approx \Omega_{\text{matter}}$, one derives the constraint $0.11 < \Omega_{\text{matter}} h^{3/2} < 0.44$; region b corresponds to the constraint coming from observations of the shape of power spectrum of galaxy clustering, which yield (Kofman et al. 1993; Peacock & Dodds 1994; da Costa et al. 1994) $0.2 < \Omega_{\text{matter}} h < 0.3$; the dashed curves in Figure 1a give limits on the allowed parameter space derived from matching the COBE normalized fluctuations in the CBR to inferred density fluctuations on galaxy scales in a flat $\Lambda$-dominated universe in cold dark matter models (White & Bunn 1995). Finally, in Figure 1a a bound (d) is shown which corresponds to the assumption that $\Omega_{\text{matter}} \geq 0.3$ for a flat $\Lambda$-dominated universe. This bound arises in part from considerations of gravitational lensing probabilities (Fukujita & Turner 1991; Krauss & White 1992; Kochanek 1992). It is also consistent with the fact that dynamical estimates of the clustered mass on large scales actually generally favor $\Omega_{\text{matter}} > 0.3$, rather than the more conservative estimate of 0.2 mentioned earlier.

While the latter bound is not included explicitly in Figure 1b, corresponding to an open universe, it is clear that the age constraint coming from globular clusters, combined with the power spectrum constraint, together imply a joint allowed region in which $\Omega_{\text{matter}} > 0.3$ in any case. Note that it is precisely in this allowed region that the new Dunlop et al. observation provides a tighter parameter space constraint than the globular cluster age limit. Thus, for all effective purposes, in an open universe this new constraint is actually stronger than the previous well-known globular age constraint. Note also that a noticeable fraction of the previously allowed range of parameter space in the case of an open universe is now excluded. By comparison, the Dunlop et al. constraint is only marginally stronger than the globular cluster age constraint for a flat $\Lambda$-dominated universe, and essentially all of the parameter space which was previously allowed is still allowed.

Also note that the constraint from COBE which appears in Figure 1a is not included on Figure 1b. This is because the COBE normalized density fluctuations generally are more difficult to fit to observed density fluctuations on galactic scales in low-density open universe models (Kofman et al. 1993; da Costa 1994). This is because the growth of density fluctuations since recombination is suppressed in low-density models compared to $\Lambda$-dominated models because the former become curvature-dominated at earlier redshifts than the latter become $\Lambda$-dominated (Kofman et al. 1993; White & Bunn 1995). Moreover, and perhaps more important in the context of this discussion, because the growth of fluctuations is suppressed, galaxy formation will tend to occur later in a low-density universe, at least one with an initial relativity flat spectrum of density fluctuations. This in itself tends to argue against the formation of galaxies as old as 3.5 Gyr at a redshift of 1.55 in such models.

In conclusion, the new Dunlop et al. observation provides a more severe constraint on open universe models than it does on cosmological constant–dominated flat models. It is completely consistent with previous cosmological constraints on $\Lambda$-dominated models, while it noticeably reduces the allowed $h – \Omega_{\text{matter}}$ parameter space for open models. In particular, for the range of parameter space which was favored by other cosmological constraints, the $z = 1.55$ age limit is more powerful than existing globular cluster age constraints. In other words, it provides an even more severe "age problem" for such cosmologies. Arguments based on structure formation in light of the COBE results reinforce this favoring of $\Lambda$-dominated models in the context of this new result because they generally allow earlier galaxy formation in these models.

It is very important to note, however, that the constraints here, being cosmological, may best be considered as suggestive. It is possible that any one of them could be subject to large, as of yet unanticipated systematic shifts. However, at present the data seem to point in at least one consistent direction. And, on the face of it, the observation for a 3.5 Gyr old galaxy at a redshift of 1.55 seems to provide additional evidence favoring a cosmological constant--
FIG. 1a

FIG. 1b

FIG. 1.—(a) Constraints on the parameter space of $h = H_0/100 \text{ km s}^{-1} \text{ Mpc}^{-1})$ vs. $\Omega_{\text{matter}}$ for a flat $\Lambda$-dominated universe coming from diverse cosmological observations. The heavy line represents the limit of the region excluded by the recent observation of a 3.5 Gyr old galaxy at a redshift of 1.55. Region a represents a bound coming from a comparison of big bang nucleosynthesis predictions with X-ray observations of rich clusters. Region b represents the constraint imposed by the shape of the power spectrum of matter density perturbations on galaxy scales. Region c comes from constraints on the age of globular clusters. The bound (d) arises both from observations of gravitational lensing and dynamical estimates of the clustered mass in the universe. The dashed lines represent the limits of the regions allowed by a comparison of COBE CBR fluctuations with matter density fluctuations for CDM models. (b) Same as (a), except for the case of an open universe. Regions a–c are based on the same constraints as displayed in Fig. 1a.
dominated universe. In particular, if $h > 0.65$ it will be very difficult for any other cosmology to satisfy both age constraints. Also, if other old galaxies are discovered at similar, or higher redshifts, the only model with a nonzero range of allowed parameter space for any value of the Hubble constant may be that in which the cosmological constant is nonzero. For this reason, independent probes of the cosmological constant, including direct measures of $q_0$ from Type Ia supernovae (Perlmutter et al. 1995), and full sky measurements of CBR anisotropies on small angular scales take on even greater interest.

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