Visibility of Gravitational Lenses and the Cosmological Constant Problem

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Abstract

Recent observations suggest appreciable star formation activity in early-type galaxies down to redshift \(z \sim 0.5\). If so, there is likely to be dust in these galaxies. We consider the possibility that obscuration by dust can reconcile the observed frequency of gravitational lensing of quasar images with the considerably larger rate predicted in a low density cosmologically flat universe dominated by a cosmological constant.

I. Introduction

The analysis of the Hubble Space Telescope (HST) Snapshot Survey for the gravitational lensing of quasars by foreground galaxies (Bahcall et al., 1992a, b; Maoz et al. 1993; Maoz & Rix 1993, hereafter MR) confirms the indications from previous discussions that the frequency of gravitational lensing favours the Einstein-de Sitter universe (density parameter \(\Omega = 1\) and cosmological constant \(\Lambda = 0\)) rather than a flat universe dominated by the cosmological constant (Fukugita, Futamase & Kasai 1990; Turner 1990; Fukugita & Turner 1991, hereafter FT; Fukugita \textit{et al.} 1992, hereafter FFKT; and Kochanek 1992). If the universe were Einstein-de Sitter, the frequency of gravitational lensing at separations \(\theta \sim 1\) arcsec is about what would be expected from the known properties of massive early-type galaxies, while the lensing rate at \(\theta \sim 2\) arcsec is greater than would be predicted under the assumption that the mass in a typical bright elliptical galaxy is distributed like the starlight. The natural way to remove this discrepancy assumes bright ellipticals typically have massive dark halos with velocity dispersion significantly larger than that of the central stars.

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If the universe were cosmologically flat with mass density $\Omega = 0.1$ times the Einstein-de Sitter value, on the other hand, the predicted lensing frequency at $\theta \sim 2$ arcsec would agree with the observations, within the considerable uncertainty in the abundance of galaxies with the large velocity dispersions which produce well-separated images, but the predicted lensing rate at $\theta \sim 1$ arcsec certainly would be much too large. Ratra & Quillen (1992) have pointed out that, for fixed $\Omega$ in a cosmologically flat universe, the predicted lensing rate is reduced by allowing time evolution of an effective cosmological “constant” represented by the energy density of an evolving dissipationless cosmic field. In this paper we consider a possible astronomical explanation for the relatively low observed lensing rate, that dust in the young galaxies at redshifts $z \gtrsim 0.5$ obscured many lensing events.

The Einstein-de Sitter cosmology is of particular interest because it agrees with Dicke’s (1970) coincidence argument, that if the universe is not Einstein-de Sitter then it is curious that we have appeared just at the epoch of transition away from matter-dominated expansion. A universe in which space curvature and a cosmological constant both are important at the present epoch requires a double Dicke coincidence, which seems quite unlikely. Thus the interesting low density models have negligible space curvature or else negligible $\Lambda$. The former is preferred because (1) it agrees with the requirement of inflation as an explanation for the large-scale homogeneity of the observed universe (Guth 1981), (2) it allows the expansion time to exceed the Hubble time $H_o^{-1}$, and (3) in this model the growth of linear density perturbations is not much suppressed relative to the Einstein-de Sitter case (Peebles 1984). The second point would be of particular importance if Hubble’s constant proved to be close to the larger of the currently discussed values, $H_0 = 80 \text{ km s}^{-1} \text{ Mpc}^{-1}$ (Jacoby et al. 1992; Fukugita, Hogan & Peebles 1993). However, at the bound found by MR from the HST lensing survey, $\Omega = 0.3$, the cosmologically flat model gives $H_o t_o = 0.96$ (compared to $H_o t_o = 0.81$ at $\Lambda = 0$ and the same $\Omega$), which would be of little help for the cosmic age problem. Thus it would be of considerable interest to know whether the lensing rate can be reconciled with a cosmologically flat model, with a constant $\Lambda$ and $\Omega = 0.1$. 
In the next section we review the indications of significant star formation in galaxies at \( z \approx 0.5 \). If stars are forming, one suspects there is dust in the gas out of which the stars formed and in the gas expelled by massive stars. We discuss the possible effect of the dust on the observed lensing rate under two crude models. The first simply assumes dust made all galaxies opaque at \( z > 0.5 \). The second assumes that for \( z > 0.5 \) the gas-to-star ratio in young bright ellipticals is that characteristic of present-day spirals, and the dust-to-gas ratio is that of the Milky Way. In either of the two cases early-type galaxies at \( z < 0.5 \) are assumed to be transparent. Table 1 shows the effect of these dust models on the lensing rate in cosmologically flat cosmologies.

II. Dust in Young Galaxies?

We are not aware of any previous discussion of the possible effect of dust on the observed rate of gravitational lensing. The lack of serious consideration of this issue is quite reasonable, because arcsecond gravitational lensing of quasar images is thought to be dominated by massive early-type galaxies, and few such nearby galaxies show evidence of dust (Centaurus A being the prominent exception). Furthermore, we do not even have a clear picture of the typical obscuration in present-day spiral galaxies (Burstein, Haynes & Faber 1991). Pei, Fall & Bechtold (1991) find evidence of obscuration by dust in damped Lyman-\( \alpha \) clouds, but the redshifts are well above those of observed gravitational lenses, and the nature of these young galaxies, whether protospirals or protoellipticals or dwarfs, is not clear. Thus we have little empirical evidence on which to base a model for the dust in young ellipticals. As emphasized by Heisler & Ostriker (1988) and in earlier references therein, however, there are good astronomical reasons to think young galaxies are dusty.

The most familiar observation suggesting there is gas in galaxies at redshifts \( z \sim 0.5 \) is the Butcher-Oemler effect (Butcher & Oemler 1978, 1984), that the fraction of cluster members with the colors of spiral galaxies is considerably larger at \( z \sim 0.35 \) to 0.5 than at the present epoch. A similar trend is observed in the field (Koo & Kron 1992). The idea that the colors are due to increased star formation activity is corroborated by the observation that at \( z \approx 0.3 - 0.4 \) an appreciable fraction of cluster galaxies exhibit the
Balmer absorption lines characteristic of A stars which would have formed at redshifts not much earlier than the epoch of observation (Gunn & Dressler 1988; Dressler & Gunn 1992). The HST observations by Dressler, Oemler, Gunn and Butcher (Dressler 1993) of a cluster at \( z \sim 0.4 \) suggest the Butcher-Oemler effect in this system arises from an unusually large abundance of spiral cluster members. The spirals may since have faded, or possibly this is an unusual cluster. Since the galaxy images in this cluster tend to be irregular, however, suggesting the merging rate is large, one might expect there is a large rate of occurrence of the Centaurus A phenomenon resulting from mergers of spirals in the bright ellipticals.

Perhaps more direct evidence of gas in young giant ellipticals is the alignment of the radio and optical images. This effect appears at redshift \( z \sim 0.7 \), and most interpretations involve gas either in star formation or in scattering of starlight along the radio jet (Daly 1992; McCarthy 1993).

We shall estimate the possible effect of dust on the observed lensing rate under the following assumptions. (a) We follow Silk (1993), who notes that the star formation accommodated by a gas component which is about 2 percent of the stellar mass would account for the general evolution of galaxy colors, and the incidence of A-star spectra, at \( z \gtrsim 0.5 \). (b) We assume the conversion from gas to dust to extinction is the same as in the Milky Way. (c) We approximate the space distribution of the gas by a truncated King model.

### III. Gravitational Lensing Frequencies

For the analysis of gravitational lensing, galaxies are usefully approximated by singular isothermal spheres. In this model the lensing frequency, neglecting obscuration, is (Turner, Ostriker & Gott 1984; FT)

\[
\tau = \int_0^{z_s} F(1 + z_L)^3 \left( \frac{D_{OL} D_{LS}}{R_0 D_{OS}} \right)^2 \left( \frac{1}{R_0} \frac{dt}{dz_L} \right) dz_L ,
\]

where \( D_{OL}, D_{OS}, D_{LS} \) are the angular size distances among the observer \( O \), lens \( L \) and source \( S \), \( R_0 = 1/H_0 \) is the Hubble distance, the quasar and lens are at redshifts \( z_S \) and \( z_L \), and the parameter \( F = 16\pi^3 n_0 \sigma^4 R_0^3 \) depends on the comoving number density \( n_0 \) of galaxies and the line of sight velocity dispersion \( \sigma \) in the isothermal gas sphere model for
the mass distribution. FT find $F_E = 0.019 \pm 0.008$ for ellipticals, $F_{S0} = 0.021 \pm 0.009$ for S0s and $F_S = 0.007 \pm 0.002$ for spirals, where dark halos are assumed to give velocity dispersion $(3/2)^{1/2}$ that of stars. With these numbers in equation (1), the lensing probability for the 502 quasars in the HST sample (Maoz et al. 1993) is $\tau = 1.06 \times 10^{-3}$ per quasar for the Einstein-de Sitter model and $7.04 \times 10^{-3}$ for a $\Lambda$-dominated flat universe with $\Omega_0 = 0.1$. The dominant contributions come from E+S0 galaxies, in particular those with redshifts $\sim (1/3)z_S$ for the Einstein-de Sitter model and $\sim (1/2)z_S$ for the low density case. The relatively large predicted frequencies are due to a large average redshift of the HST quasar sample, $\langle z_S \rangle = 2.2$.

The value of $\tau$ from equation (1) must be corrected for (i) finite core size ($\sim 0.63 \times$), (ii) angular selection effect ($\sim 0.95 \times$) for E and S0, and (iii) the magnification bias ($\sim 9.1 \times$). With these corrections, and neglecting obscuration, the predicted lensing rate for the 502 quasars is shown in the second row of Table 1, and can be compared to the observed rate in the first line. We list separately the lensing events at angular separation $\theta < 1$ arcsec, which are insensitive to the presence or absence of a dark halo, and the events at $\theta > 2$ arcsec which dominantly arise from a dark halo with a large $\sigma$.

The predictions in the second row of the table, which are based on the procedures detailed in FFKT, are generally similar to those of MR, except that the MR prediction for the lensing rate at $\theta > 2$ arcsec is a factor of two lower. This arises from the differences in the models for the dark halo, and the spread may be a useful measure of the uncertainty in the predictions at large $\theta$. We conclude that, within this uncertainty, the lensing rate at $\theta > 2$ arcsec is not inconsistent with the low density model. The issue to be considered next is the possible effect of obscuration at the smaller impact parameters for lensing events at $\theta \sim 1$ arcsec, where the observed lensing rate definitely is lower than would be expected in the low density model.

IV. Models for Obscuration

The third line in the table shows the effect of obscuration in an extreme case, in which galaxies are transparent at $z < 0.5$ while at larger redshifts dust completely obscures all
events by blocking at least one of the lines of sight. We represent this by placing a cutoff in the integral in equation (1) at $z = 0.5$. The reduction factor for the low density case is relatively large because the distribution of lens redshifts peaks around $(1/2)z_S$, substantially deeper than in the Einstein-de Sitter model. Also, the redshift cutoff doubles the mean ratio $\langle D_{LS}/D_{OS} \rangle$, and correspondingly increases the typical image separation. Thus in the low density model the peak of the probability distribution $dP/d\theta$ is $\theta \sim 2''$ with the cutoff, compared to $\theta \sim 0.9''$ in the completely unobscured case.

A possibly more realistic approach uses the ratio of dust to starlight observed in nearby objects. We again assume the galaxies responsible for lensing are transparent at $z < 0.5$, and at larger redshifts we assign each young early-type galaxy a fixed gas mass with density as a function of radius

$$\rho(r) = \rho_o [1 + (r/r_c)^2]^{-3/2}, \quad (2)$$

at $r < 10$ kpc, and $\rho(r) = 0$ at larger radii. To normalize this expression we assume the HI gas mass is 2% of the total stellar mass based on the nominal mass-to-light ratio $M_{\text{stellar}}/L = 5$ and the galaxy luminosity calibrated to $M_B^* = -20.4$ at $H_0 = 80$ km s$^{-1}$ Mpc$^{-1}$. We use the linear relation between the HI column density and obscuration in the B-band in the Milky Way (Burstein & Heiles 1978),

$$A_B = 4E_B = 0.79N_{21} - 0.22, \quad N_{\text{HI}} = 10^{21}N_{21} \text{ cm}^{-2}. \quad (3)$$

The computed effect on the observed lensing probability depends only weakly on the choice of the core radius in equation (2) in the range $r_c = 0.5$ to 5 kpc.

We consider two aspects of the effect of obscuration. Let us confine ourselves to the case of a low density universe. First, in lensing events with large magnification the impact parameters are at $r_p \sim 4$ kpc for $\theta = 1''$ and $z_L = 0.5$, and the quantity of interest is the typical value of the extinction $A$ at this distance from the center of a young bright elliptical galaxy. Second, if the impact parameters of the two images are substantially different the image with the smaller impact parameter is less strongly magnified and would be expected
to be more strongly obscured. Obscuration thus tends to push the magnitude difference of the images beyond the threshold for detection.

The effect of the mean obscuration $\langle A \rangle$ can be included in the expression for the factor $B(m)$ by which the probability for observing lensing of a faint background quasar event is enhanced by its magnification:

$$B(m) = \frac{\int_{\Delta_0}^{\infty} N_Q(m + \Delta - \langle A \rangle) P(\Delta) d\Delta}{N_Q(m)}.$$  \hfill (4)

Here $N_Q(m)$ is the differential quasar number-apparent magnitude luminosity function, and $P(\Delta) = 7.37 \times 10^{-0.8\Delta}$ (for $\Delta \geq \Delta_0 = 2.5 \log 2$) (FT).

With the above model and numbers we find that the mean extinction is $A = 0.8$, and that this reduces the effective magnification enhancement factor $B(m)$ in the HST sample by 60%.

Next, let us consider the magnitude difference of the images. In the singular isothermal sphere model the two images of a quasar at true angular distance $\theta_S$ from the centre of a galaxy appear at angles $\theta_1 = \beta + \theta_S$, $\theta_2 = -\beta + \theta_S$ where $\beta = 4\pi \sigma^2 D_{LS}/D_{OS} > \theta_s$ for two images. The magnitude difference resulting from the difference in magnification of the two images is $\Delta m = 2.5 \log[(\beta + \theta_S)/(\beta - \theta_S)]$ with the image at $\theta_2$ fainter. In the HST survey the detection limit for two images depends on the image separation angle. For the typical separation angle 1.7 arcsec for $L^*$ galaxies (for $z_S \sim 2$ and $z_L \sim 1$) the detection limit is $\Delta m \leq 3.5$ mag (Bahcall et al. 1992a). This means the survey would miss a lensing event if the difference $\Delta A(\theta_S)$ of obscuration of the images at the smaller and larger impact parameters satisfied

$$\Delta m(\theta_S) + \Delta A(\theta_S) \gtrsim 3.5.$$  \hfill (5)

We find that in our dust model obscuration in an $L_*$ galaxy makes the magnitude difference larger than this detection limit at $\theta_S \lesssim (0.5$ to $0.6)\beta$, leaving a survival probability $\sim 0.3$ for observed lens events.

The expected lensing frequency is the sum of the unobscured rate, $\tau(0;0.5)$, for low redshift lenses, and the obscured rate for larger redshift, $0.4 \times 0.3 \times \tau(0.5; z_s)$, the first
factor being the suppression of the magnification bias (eq. [4]), the second the effect of the difference of extinction of the images (eq. [5]), and the last the unobscured rate. The results are presented in the fourth entry of Table 1, along with the results of a similar calculation for the Einstein-de Sitter universe.

V. Discussion

The gravitational lensing rate is a remarkably sensitive test of cosmological models, but, in common with the other tests, it does require an understanding of the astronomy of the objects. The HST results are in line with earlier samples in indicating that the distribution of angular separations $\theta$ in lensing events is broader than might have been expected in an Einstein-de Sitter universe. This is not a serious problem, of course, because it is easy to imagine lensing events at large $\theta$ has been enhanced by massive dark halos while the lensing frequency at small $\theta$ have been slightly obscured by dust. An open cosmological model with negligible $\Lambda$ and $\Omega = 0.1$ predicts lensing rates only modestly greater than in the Einstein-de Sitter model. This would seem to be easy to accommodate by adjusting the parameters in the same manner. The $\Omega = 0.1$ cosmologically flat model requires a considerably larger adjustment. We have attempted to show, however, that the adjustment is not unreasonable in view of the expected properties of the active young galaxies observed at $z \gtrsim 0.5$.

Observations in the infrared may test the hypotheses that optical lensing events have been obscured by dust. Since dust may be ignored in radio-selected gravitational lenses, the radio surveys may offer a key test (Turner 1993). For example, the optical images of the lensed quasar in MG0414+0534 are unusually red ($g - r \approx 2.3$), and the color varies from image to image ($r - z \approx 2.4$ to 1), suggesting obscuration as much as 5 mag in the B-band, if the unusual colors are to be ascribed to dust in the lensing galaxy (Hewitt et al. 1992). It may be significant also that radio-selected lenses generally are rather faint in the optical band, compared with optically selected lenses, as would be expected if there were appreciable dimming by dust. The preliminary report from the VLA lens survey (Hewitt et al. 1989) presents four lenses out of 4000 sources. The rate is comparable to
that of optically selected lenses (2 to 9 out of 4300 in the Hewitt & Burbidge 1987, 1989 catalog). However, redshifts of quasars in radio surveys are known only for a part of the sample, and the average redshifts are not as high as those in the optical sample, which makes the interpretation more sensitive to astronomy and less sensitive to cosmology. Since the identification of radio lensing events is complicated by the intrinsic structures of the objects, it will not be easy to identify the abundance of objects capable of being imaged as double images. One must look for objects with more complicated geometry, or the characteristic radio “Einstein rings”. The progress in the radio surveys for these events certainly will be followed with great interest.

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TABLE 1
Models for the HST Lensing Statistics

|                | $\Omega = 1, \lambda = 0$ | $\Omega = 0.1, \lambda = 0.9$ |
|----------------|----------------------------|-------------------------------|
|                | $N(< 1''')$  | $N(1 - 2'')$ | $N(> 2'''$) | $N(< 1''')$ | $N(1 - 2'')$ | $N(> 2'''$) |
| Observed       | 1             | 1              | 2            | 1             | 1              | 2            |
| No Dust        | 0.9           | 0.9            | 0.9          | 5.8           | 5.9            | 6.1          |
| No events at $z > 0.5$ | 0.2        | 0.3            | 0.7          | 0.3           | 0.6            | 1.6          |
| Dust model     | 0.3           | 0.4            | 0.7          | 0.9           | 1.1            | 2.1          |