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ARE QUASAR REDSHIFTS COSMOLOGICAL?

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ABSTRACT

Recent observations on gravitational lensing of quasars by intervening galaxies strongly support the cosmological interpretation of quasar redshifts against the far more exotic proposals. The lensing model predicts correctly the angular separation and time delay between different images and the frequency of quasars that are lensed by galaxies only if the quasars lie at the large cosmological distances that are inferred from their redshifts.

Subject headings: cosmology — gravitational lenses — quasars

1. INTRODUCTION

In the standard hot big bang model of the universe (see, e.g., Weinberg 1972, and references therein) the expansion of the universe redshifts the light from distant objects. The redshift factor $z \equiv (\lambda - \lambda_0)/\lambda_0$, where λ_0 and λ are, respectively, the emitted wavelength in the rest frame of the distant object and the presently observed wavelength, increases with distance, or equivalently, with look-back times. For $z \ll 1$ the distance D to the object is given by the Hubble law, $D \approx cz/H_0$, where H_0 is the present value of the Hubble constant. For larger redshifts the relation between distance and redshift in a Robertson-Walker universe depends also on the values of the mass-energy density of the universe and the cosmological constant which are not known very well. Although the cosmological origin of the redshift of light from distant galaxies and clusters of galaxies has been fairly well established from their angular sizes and apparent brightness, this is not the case for quasars, which have large redshifts up to values of $z > 4$ making them the most luminous objects in the universe if their redshifts indicate their distance.

The inferred very high luminosity of the quasars, which comes from a very compact region whose size is set by the time scale of variability, and their other peculiar properties have led some authors to question the cosmological origin of their large redshifts (see, e.g., Arp 1987, and references therein). Evidence in support of the cosmological origin of quasar redshifts which came mainly from the absorption features in quasar spectra does not seem to have settled the controversy, as is evident from a recent paper by Arp et al. (1990) where the authors have summarized what they claim to be the observational evidence that the quasars do not lie at large cosmological distances as inferred from their large redshifts. Their main argument is that the number of quasars which are found within a few arcminutes from bright galaxies is much larger than expected on statistical grounds. Therefore, they conclude that quasars lie in or near companion galaxies which have much smaller redshifts, that is, they are not at large cosmological distances, and their large redshifts are largely intrinsic in origin and not cosmological. However, in this *Letter* I show that strong evidence in support of the cosmological origin of quasar redshifts is provided by recent observations on gravitational lensing of quasar images by intervening galaxies. Although the success of the gravitational lensing explanation of some striking objects that contain multiple quasar images (for recent reviews see, e.g., Moran, Hewitt, & Lo 1989; Blandford 1990, and references therein) has been proposed as supportive evidence for the standard Friedmann cosmology (e.g., Schneider et al. 1988), to the best of our knowledge the above argument has never been worked out in detail nor given any particular emphasis or prominence.

Thus, in this *Letter* I show that the angular separations and the time delays between the multiple images of high-redshift quasars, caused by the gravitational bending of the light that passes near galaxies that lie on or very near the line of sight to the quasar, are correctly predicted by general relativity *if the quasars lie at their redshift distance* (Dar 1991; Peebles et al. 1991). If, on the other hand, the quasar redshifts are largely intrinsic and they lie near or in the lensing galaxies, then the observed angular separation and time delay between quasar images should be smaller by many orders of magnitude. Our argument, of course, applies only if the objects that we consider are formed by gravitational lensing. But the impressive success of the lensing interpretation and the agreement between the number of lens candidates that was discovered (e.g., Blandford 1990) and the number that was predicted (Turner, Ostriker, & Gott 1984) strongly support the lensing interpretation against the far more exotic proposals (e.g., Arp et al. 1990).

2. EVIDENCE FROM GRAVITATIONAL LENSING

2.1. *General Evidence*

Einstein's theory of general relativity predicts that light which passes at an impact parameter b from a spherical symmetric mass distribution is deflected by an angle which for small angles is given approximately by (see, e.g., Weinberg 1972)

$$\alpha \approx \frac{4GM(b)}{c^2 b}, \tag{1}$$

where G is Newton's gravitational constant and $M(b)$ is the mass interior to b. The mass $M(r)$ enclosed within a distance r from the center is given by Kepler's third law

$$M(r) \approx \frac{v_{\rm cir}^2 r}{G}, \tag{2}$$

where $v_{\rm cir}$ is the circular velocity of a mass orbiting at a distance r from the center.

Consequently, spiral galaxies, which have flat rotation curves ($v_{cir} \approx$ constant independent of r) up to the largest distances where measurements are available, have $M(r) \propto r$, $\rho(r) \propto 1/r^2$, and $M(b)/b \approx \pi v_{cir}^2/2G$, which gives rise to a constant deflection angle independent of impact parameter,

$$\alpha = 2\pi\left(\frac{v_{cir}}{c}\right)^2 . \quad (3)$$

Thus, the constant deflection angle for a typical spiral galaxy with a flat rotational curve of $v_{cir} \sim 250$ km s^{-1} is $\alpha \sim 1''$. In elliptical galaxies, or clusters of galaxies, whose total mass densities are well described by singular isothermal sphere distributions, $\rho(r) \approx (1/2\pi G)(\sigma_{\parallel}/c)^2$, the circular velocity is given by $v_{cir}^2 = 2\sigma_{\parallel}^2$, where $\sigma_{\parallel}$ is the one-dimensional line-of-sight velocity dispersion in the galaxy or the cluster, respectively. For a typical elliptical galaxy with $\sigma_{\parallel} \sim 200$ km s^{-1} the constant deflection angle is $\alpha \sim 1\farcs5$, while for a rich cluster with $\sigma_{\parallel} \sim 1000$ km s^{-1} the constant deflection angle is $\alpha \sim 30''$.

The angular positions of a source and its images, $\boldsymbol{\theta}_S$ and $\boldsymbol{\theta}_I$, respectively, relative to the center of the lensing galaxy are related via simple geometry to the deflection angle at the lens (see, e.g., Turner et al. 1984),

$$\boldsymbol{\theta}_I = \boldsymbol{\theta}_S + \frac{D_{LS}}{D_{OS}}\boldsymbol{\alpha} , \quad (4)$$

where D_{OS} and D_{LS} are the angular distances from the observer to the source (the quasar) and from the lens (the galaxy) to the source, respectively. These angluar distances may be calculated from the redshifts z_L and z_S of the lensing galaxy and the lensed quasar, respectively, using the standard cosmological redshift-distance relations in a Robertson-Walker universe.

If a lensing galaxy with a radially symmetric surface density happens to lie on or very near the line of sight to a distant quasar, ($\theta_S \approx 0$), it forms in the sky a ring image (Einstein 1936; Cholson 1924) of the quasar around the center of the lensing galaxy. Such an Einstein Ring, MG 1654+1246, was discovered by Langston et al. (1989, 1990). The angular diameter of an Einstein Ring, $\Delta\theta$, which follows from equation (4) is (see, e.g., Turner et al. 1984),

$$\Delta\theta \approx 2\frac{D_{LS}}{D_{OS}}\alpha \approx 4\pi\frac{D_{LS}}{D_{OS}}\left(\frac{v_{cir}}{c}\right)^2 , \quad (5)$$

and from equation (1) it also follows that

$$\Delta\theta \approx \left[\frac{16G}{c^2}\frac{D_{LS}}{D_{OS}}\frac{M(b)}{D_{OL}}\right]^{1/2} . \quad (6)$$

When the lensing galaxy has an elliptical surface density and the line of sight to the source passes very near its center, the Einstein Ring degrades into four images that are located symmetrically along the two principal axes (see, e.g., Blandford et al. 1988) (and a faint fifth image at the center), as observed by Schneider et al. (1988) and by Yee (1988) and De Robertis & Yee (1988) in the case of Q2237+0305. The angular separation between the two images along the major axis is given approximately by equations (5) and (6).

If quasars lie at the large cosmological distances that are inferred from their large redshift, that is, if $D_{OS} \gg D_{LS}$, then $D_{LS}/D_{OS} \sim 1$, and the angular separation between opposite images (the diameter in the case of an Einstein Ring) formed by an intervening galaxy should be of the order of 2″, in good agreement with the observations, for example, $\Delta\theta = 1\farcs97 \pm 0\farcs04$ for MG 1654+1346, and $\Delta\theta = 1\farcs80 \pm 0\farcs04$ for Q2237+0305. On the other hand, if quasars do not lie at the large cosmological distances that are inferred from their large redshifts, but rather lie within or near the lensing galaxy, that is, if $D_{LS} \leq 50$ kpc, then $D_{OS} \approx D_{OL}$, $D_{LS}/D_{OS} \leq 50$ kpc/D_{OL}, and the diameter of the Einstein Ring, or the angular separation between opposite images that follows from equation (5), would be less than 2×10^{-4} arcsec for MG 1654+1346 and less than 1×10^{-3} arcsec for Q2237+0305, which vastly contradict the observations.

2.2. *Detailed Tests*

In fact, quite accurate tests of equation (5) with the cosmological interpretation of quasar redshifts are possible without specific knowledge of Ω and H_0, using the observations on the gravitational lenses and the lensed images in 2237+0305 and 1654+1346.

2.2.1. *Redshift Dependence*

If the observed redshifts, z_L of the lensing galaxy and z_S of the lensed quasar, are cosmological, then one may use the standard cosmological redshift-distance relations to calculate the angular distances D_{OL}, D_{OS}, D_{LS}. In a Robertson-Walker universe

$$D_{OX} = \frac{2c}{\Omega^2 H_0(1+z_x)^2}\left[\Omega z_x - (2-\Omega)(\sqrt{1+\Omega z_x} - 1)\right] , \quad (7)$$

where Ω is the present density of the universe in units of critical density and H_0 is the present value of the Hubble parameter. The expression for D_{LS} is more complicated; its value for two common world models are

$$D_{LS} = \frac{1}{2}\frac{c}{H_0}\left(\frac{1+z_S}{1+z_L} - \frac{1+z_L}{1+z_S}\right)\frac{1}{1+z_S} \quad \text{for } \Omega = 0 , \quad (8)$$

$$D_{LS} = 2\frac{c}{H_0}\left(\frac{1}{\sqrt{1+z_L}} - \frac{1}{\sqrt{1+z_S}}\right)\frac{1}{1+z_S} \quad \text{for } \Omega = 1 . \quad (9)$$

Although the distance for large redshifts depends strongly on the cosmological model, the ratio D_{OS}/D_{LS} is independent of H_0, and for $z_L \ll z_S$ it is close to 1 and depends very weakly on the cosmological model. This is demonstrated in Table 1 for MG 1654+1346 (Langston et al. 1989, 1990), Q2237+0305 (Huchra 1985), and Q0957+561 (Walsh, Carswell, & Weymann 1980; Weymann 1980).

2.2.2. *Angular Separations*

MG 1954+1346: The ring image MG 1654+1346 of a radio lobe of a quasar at redshift $z_S = 1.75$ is formed by a bright elliptical galaxy at redshift $z_L = 0.254$ in nearly perfect alignment with the lobe (Langston et al. 1990). In their high-resolution radio interferometric observations Langston et al. (1990) obtained an angular diameter of $\Delta\theta = 1\farcs97 \pm 0\farcs04$. Unfortunately, no published measurements are available either of the circular velocity or of the one-dimensional velocity dispersion in the lensing galaxy. However, Langston et al. (1990) measured a total B-band luminosity of the galaxy of $L_B = (1.87 \pm 0.18) \times 10^{10} h^{-2} L_{\odot}$, where h is the Hubble parameter in units of 100 km s^{-1} Mpc^{-1} and $L_{\odot}$ is the luminosity of the Sun. The luminosities of bright elliptical galaxies were found by Faber & Jackson (1976) to be correlated with the velocity dispersion within the inner few kiloparsecs of the galaxies through (Faber & Jackson 1976; Dressler et al. 1987) $\sigma_{\parallel} \approx 190(L_B/10^{10}\ h^{-2}\ L_{\odot})^{1/4}$ km s^{-1}. Thus, for MG 1654+1346 the Faber-Jackson relation yields $\sigma_{\parallel} \approx 223 \pm 15$ km s^{-1}, and equation (5) predicts an angular diameter of $\Delta\theta \approx 2\farcs09 \pm 0\farcs27$

TABLE 1

OBJECT REDSHIFTS[a]

MODEL	Q2237+0305 $z_L = 0.0394$ ($\Omega = 0$)	Q2237+0305 $z_S = 1.695$ ($\Omega = 1$)	MG 1654+1346 $z_L = 0.254$ ($\Omega = 0$)	MG 1654+1346 $z_S = 1.75$ ($\Omega = 1$)	Q0957+561 $z_L = 0.36$ ($\Omega = 0$)	Q0957+561 $z_S = 1.41$ ($\Omega = 1$)
$(H_0/c)D_{OL}$	0.03719	0.03682	0.1820	0.1707	0.2298	0.2096
$(H_0/c)D_{OS}$	0.4313	0.2900	0.4339	0.2887	0.4139	0.2954
$(H_0/c)D_{LS}$	0.4097	0.2758	0.3158	0.2109	0.2506	0.1770
D_{OS}/D_{LS}	1.053	1.051	1.374	1.369	1.652	1.669

[a] Redshifts and angular distances (in c/H_0 units) of the galactic lenses and the quasar images for three simple gravitational lensing systems, in a Robertson-Walker universe with $\Omega = 0$ and with $\Omega = 1$, respectively.

for the Einstein Ring in good agreement with the observed diameter.

Q2237+0305: In the case of 2237+0305 the galaxy has a redshift $z_L = 0.0394$ and a rotational velocity of 260 km s^{-1} (Huchra 1985). The quasar has a redshift $z_S = 1.695$. The diameter of the ring (the angular separation between opposite images) is predicted by equation (5) to be $\Delta\theta = 1''.85$. This prediction agrees very well with the high-resolution CCD images of Schneider et al. (1988) which gave $\Delta\theta = 1''.7 \pm 0''.1$ and of Yee (1988) and De Robertis & Yee (1988) which gave $\Delta\theta = 1''.82 \pm 0''.03$, and with recent observations from the *Hubble Space Telescope* with the JPL wide field camera which gave $\Delta\theta = 1''.78 \pm 0''.05$. Note that *Q2237+0305* was presented by Arp et al. (1990) as an example where a high-redshift quasar lies very near the center of a low-redshift galaxy. However, this would produce an angular separation between opposite images smaller than that observed by at least three orders of magnitude.

In the other known cases of gravitational lensing of quasar images the angular separations have the expected magnitude, although in most of these cases the lens has not been identified or it is not a single galaxy. Because of lack of information on the lens or a complicated geometry, the analysis requires additional assumptions, and the tests become less conclusive. However, in the case of 0957+561, the object is relatively simple and well understood (see, e.g., Falco, Gorenstein, & Shapiro 1985).

0957+561: The object is a quasar at a redshift of $z_S \approx 1.41$ lensed by a giant elliptical galaxy at redshift $z_L \approx 0.36$ embedded in a large cluster (Stockton 1980; Young et al. 1980). The lens produces two quasar images, A and B, at angular distances $|\boldsymbol{\theta}_A| = 5''.24 \pm 0''.05$ and $|\boldsymbol{\theta}_B| = 1''.00 \pm 0''.05$, respectively, from the center of the galaxy with an angular separation of $\Delta\theta = |\boldsymbol{\theta}_A - \boldsymbol{\theta}_B| = 6''.17 \pm 0''.02$ between them. The measured positions of the two images and their relative magnification yield a deflection angle (Falco et al. 1985) $\alpha = 3''.4 \pm 0''.1$ at the giant elliptical galaxy. With cosmological redshifts equation (5) implies that $\sigma_{\parallel} = 344 \pm 6$ km s^{-1}, while from a recent measurement of the line-of-sight velocity dispersion for the giant galaxy Rhee (1991) reported $\sigma_{\parallel} = 303 \pm 50$ km s^{-1}, in satisfactory agreement.

2.3. *Mass-To-Light Ratios*

The masses interior to the Einstein Rings that follow from equation (6) are $M(b) \approx (1.12 \pm 0.04) \times 10^{10} h^{-1}\ M_{\odot}$ interior to $b \approx 0.5h^{-1}$ kpc for 2237+0305 (Schneider et al. 1988; Yee 1988; De Robertis & Yee 1988) and $M(b) \approx (9.0 \pm 0.4) \times 10^{10} h^{-1}\ M_{\odot}$ interior to $b \sim 2.5h^{-1}$ kpc for MG 1654+1346 (Langston et al. 1990). These masses and the measured luminosities inside the rings give (Langston et al. 1990) $M/L_B \approx (16 \pm 2)h\ M_{\odot}/L_{\odot}$ for MG 1654+1346 and (Schneider et al. 1988; Yee 1988; De Robertis & Yee 1988) $M/L_B \approx (10 \pm 3)h\ M_{\odot}/L_{\odot}$ for 2237+0305, in good agreement with the best dynamical M/L_B measurements for the cores of bright elliptical galaxies (Lauer 1985).

2.4. *Lensing And Time Delay*

One may also compare the observed time delay between the different images of a lensed quasar and the time delay predicted by general relativity for quasars that lie at their redshift distances. The time delay between the light arrival times from an image with and without the intervening lens, in the thin lens approximation, is composed of two terms (Cook & Kantowski 1975). One is due to the difference in the geometrical path lengths along which the light travels from the image to the observer. The second is due to the gravitational potential time delay produced by the mass distribution of the lens. For a galaxy with a constant deflection angle α, even when embedded in a large cluster, the total time delay between two images A and B reduces to the simple expression (Borgeest 1986)

$$\Delta t_{A,B} \approx \alpha(1 + z_L)(|\boldsymbol{\theta}_A| - |\boldsymbol{\theta}_B|)\frac{D_{OL}}{c}. \tag{10}$$

If one substitutes equation (5) with $b = D_{OL}|\boldsymbol{\theta}_A - \boldsymbol{\theta}_B|/2$ into equation (10) one obtains

$$\Delta t_{A,B} \approx 4\pi(1 + z_L)(|\boldsymbol{\theta}_A| - |\boldsymbol{\theta}_B|)\left(\frac{\sigma_{\parallel}}{c}\right)^2 \frac{D_{OL}}{c}. \tag{11}$$

The only object where a time delay between different images of a lensed quasar has been well established is Q0957+561 where identical flux variations with a relative time delay of 1.4 ± 0.1 yr in the radio band (Roberts et al. 1991) and ~ 1.48 yr in the optical band (based on a new analysis by Press, Rybicki, & Hewitt 1991 of the optical data of Vanderriest et al. 1989 and of Schild 1990) have been measured.

The measured line-of-sight velocity dispersion and a Hubble constant $50 \leq H_0 \leq 100$ km s^{-1} Mpc^{-1} yield a time delay of $0.5 < \Delta t < 2$ yr in a universe with $0 \leq \Omega \leq 1$ (using the values $H_0 = 67 \pm 8$ km s^{-1} Mpc^{-1} for the Hubble constant, which van den Bergh 1990 finds in a recent review, and $\sigma_{\parallel} = 330 \pm 50$ km s^{-1}, which follows from applying the Faber-Jackson relation [1976] to the measured luminosity of the lensing galaxy, I find that $\Delta t = 1.35 \pm 0.30$ yr). Thus, equation (11) predicts a time delay consistent with the observed time delay of 1.4 ± 0.1 yr. If, however, the quasar lies within a typical galactic distance from the lens, the deflection angle would be smaller by more than four orders of magnitude, and the time delay would be smaller by eight orders of magnitude, than their observed values, respectively.

3. CONCLUSIONS

In the two most striking known cases of gravitational lensing of quasar images by intervening galaxies, MG 1654+1346 and Q2237+0305, the angular separations between the quasar images agree well with those predicted by the lensing model if the quasars lie at their redshift distances. The predicted diameters are neither sensitive to the specific values of the cosmological parameters Ω, H_0, Λ, nor do they depend on free parameters. In the case of the double quasar Q0957+561, both the angular separation and the time delay between the two images have been measured and both are consistent with the values predicted by the lensing model provided that the quasar lies at its large redshift distance. In all the other known cases of gravitational lensing of quasar images by galaxies and clusters of galaxies (see, e.g., Moran et al. 1989; Blandford 1990, and references therein) the angular separations between the multiple images have roughly the magnitude expected if the quasars lie at their redshift distances. On the other hand, if the quasars lie near or within galaxies, then the observed angular separations and time delays between quasar images should be smaller by many orders of magnitudes than those observed. It could be argued that, perhaps, only some quasars lie at large cosmological distances and only those quasars are lensed by high-redshift galaxies. However, the number of lensed quasars that have been observed is consistent with the expected number (Turner et al. 1984) provided that most of the quasars lie at the large cosmological distances inferred from their large redshifts. The lensing argument, of course, applies only if the objects that were interpreted by gravitational lensing are indeed formed by gravitational lensing. However, the impressive success of the lensing interpretation and the agreement between the expected number (Turner et al. 1984) and the number of lens candidates that were discovered (e.g., Blandford 1990) strongly support the lensing interpretation against the far more exotic proposals (e.g., Arp et al. 1990).

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