THE ASTROPHYSICAL JOURNAL, 190:L105–L108, 1974 June 15

THE DOUBLE QUASAR 1548+115a,b AS A GRAVITATIONAL LENS*

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Received 1974 February 7; revised 1974 March 29

ABSTRACT

The two quasars 1548+115a (17th mag; $z = 0.4359$) and 1548+115b (19th mag; $z = 1.901$) are separated by only 5″ of arc. We consider the possibility that the light from the distant quasar is enhanced by the gravitational-lens effect of the nearby quasar and any galaxy in which it may reside. The observed separation allows one immediately to set a strict upper limit of $7 \times 10^{12}\mathfrak{M}_\odot$ on the mass of the system containing 1548a. If $\mathfrak{M}$ is between about 4 and $7 \times 10^{12}\mathfrak{M}_\odot$, gravitational-lens brightening of 1548b roughly doubles our probability of finding such a close pair. It is perhaps significant that this mass range is just that observed for giant elliptical galaxies (radio galaxies). It is likely that the lens forms a fainter but still observable secondary image of 1548b on the other side of 1548a. Identification of such a secondary image would verify the lens effect and indicate that the two quasars are seen in projection rather than being physically connected.

Subject headings: gravitation — quasi-stellar sources or objects

Wampler *et al.* (1973) have reported two QSOs with discordant redshifts separated by only 5″: 1548+115a (17th mag, $z = 0.4359$) and 1548+115b (19th mag, $z = 1.901$). They estimate the probability of finding such a pair among the 250 QSOs with known redshifts as about 1 in 100. They have taken this as evidence that the two are physically connected and that therefore their redshifts are noncosmological. We investigate here an alternative explanation for the close separation: namely, that light from the distant quasar is brightened through the gravitational-lens effect by passage near the nearby quasar and the galaxy in which it resides. Such gravitational-lens brightening of distant quasars should increase the counts of distant quasars in the vicinity of nearby quasars and increase the probability of finding such a close pair in the sky: an application in a different context of the gravitational-lens brightening mechanism originally proposed by Barnothy (1965).

Let us reevaluate the probability of finding a double quasar with a separation of 5″ due to random projection effects. Using count data from Schmidt (1972) with his favored $10^{5\tau}$ density evolution law, we find that the expected number of QSOs with $m_v < 20.0$ and $z < 4$ within a circle of radius 5″ centered on a random point in the sky is $\sigma_0 = 4.0 \times 10^{-5}$. Given a group of N known QSOs picked at random, what is the probability that the *closest* QSO pair involving a known QSO has a separation of $\lesssim 5''$? This probability, calculated from Poisson statistics assuming random distributions, is $P = 1 - \exp(-N\sigma_0)$. There are $\sim$250 QSOs with known redshifts, so taking $N = 250$ we find $P = 0.01$. There are, however, some selection effects at work. The study which uncovered 1548+115a,b was looking for pairs (Hazard *et al.* 1973). As the most interesting candidate, 1548+115 had its redshift measured, of course, before the great majority of the other candidates. Thus the number of known QSOs is at least $N \approx 300$ and possibly larger, of which 1548+115 is the best case. A second selection effect is that the calculated probability refers to a given group of N QSOs with N fixed in advance. Redshifts are measured in some sequence, so in such a group of N the closest pair will half the time be found before $N/2$ is reached and half the time will be found between $N/2$ and N. If each new record-breaking closest pair is published soon after its discovery and we use N as those known up to that time, we underestimate N by a factor of 2 over what we would find with a proper fixed sample. Therefore, we should use $N_{\text{effective}} \approx 600$ and calculate $P \simeq 0.024$. If one adopts $m_v = 21$, the plate limit of the Palomar *Sky Survey*, as the detectability limit for QSOs as suggested by Bahcall and Woltjer (1973), one would find $P \approx 0.07$.

If 1548+115a,b are at their cosmological distances, they are ideally situated to produce a gravitational-lens effect. Adopting the formalism of Press and Gunn (1973), we speak of the distance to a source in terms of the affine parameter of the light ray connecting it to us. For a definition of the affine parameter see Misner, Thorne, and Wheeler (1973). If the universe is open and $q_0 \approx 0$, then the affine parameter to a source is given by $\lambda = \frac{1}{2}cH_0^{-1}[1 - (1 + z)^{-2}]$, where $H_0 = 55$ km s^{-1} Mpc^{-1} is Hubble's constant and z is the redshift. Choice of this particular cosmological model is not critical to the results, as we shall see later. The affine parameter of 1548+115a (to be called Q_1) is $\lambda = 0.257\ cH_0^{-1}$, and the affine parameter of 1548+115b (to be called Q_2) is $L = 0.4405\ cH_0^{-1}$. Light suffers a gravitational deflection $\theta = 4Gm(r)/rc^2$, where r is the impact

* Supported in part by the National Science Foundation [GP-36687X].

† Alfred P. Sloan research fellow, 1972–1974.

parameter and $m(r)$ is the mass within a radius equal to the impact parameter. This relation holds for all power-law distributions of projected surface density. Press and Gunn (1973) have developed a simple formalism for the gravitational-lens problem in expanding cosmologies. The geometry of the light deflection is shown in figure 1, which serves to define all the angles involved. A critical angle is reached when $x^* = 0$ (Q_2 directly behind Q_1). Then the image of Q_2 becomes a thin bright ring having an angular radius of

$$\beta_{\rm crit} = \left[\frac{4Gm(<b_{\rm crit}^*)(1+z_1)(L-\lambda)}{c^2\lambda L}\right]^{1/2}, \quad (1)$$

where $b_{\rm crit}^* = \beta_{\rm crit}\lambda$ and $m(<r)$ denotes the projected mass interior to projected radius r; z_1 is the redshift of Q_1.

We shall see that the observed separation must be larger than $\beta_{\rm crit}$: if we take $\beta_{\rm crit} = 5''$, $b_{\rm crit}^* = 34$ kpc and $m(<b_{\rm crit}^*) = 7.2 \times 10^{12}\mathfrak{M}_\odot$. Thus an *upper limit* on the combined mass of Q_1 and the galaxy containing it is $7.2 \times 10^{12}\ \mathfrak{M}_\odot$.

We consider two cases for the mass distribution: first that of a point mass $m(<r) = m_0$ and second a distributed mass with $m(<r) = m_0 r/b_{\rm crit}^*$. Motivation for the second case is provided by the accumulating evidence that galaxies have extended halos which roughly obey this law (Roberts 1974; Ostriker and Peebles 1973). Then if we let $b = b^*/b_{\rm crit}^*$, $x = x^*/b_{\rm crit}^*$, we have the relations

$$\frac{1}{b} = b - x \quad \text{for point mass}, \quad (2)$$

$$1 = b - x \quad \text{for } m(<r) \propto r. \quad (3)$$

The ratio of the total brightness of an image seen at b to one with no lens mass present is $I_b/I_0 = |b/x| \times |db/dx|$, from which we have (see fig. 2)

$$\frac{I_b}{I_0} = \frac{1}{|1 - b^{-4}|} \quad (4)$$

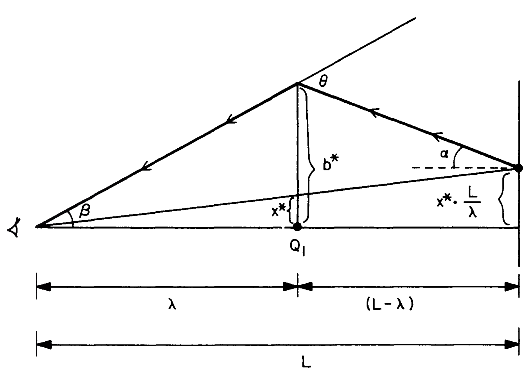

FIG. 1.—Geometry of the light deflection. Q_1 represents 1548+115a at a redshift $z = 0.4359$ and Q_2 represents 1548+115b at a redshift $z = 1.901$.

for a point mass, with primary image at $b_+ > 1$; secondary image at $b_- = 1/b_+$.

For $m(<r) \propto r$,

$$\frac{I_b}{I_0} = \frac{1}{|1 - b^{-1}|}, \quad (5)$$

with primary image at $b_+ > 1$; secondary image at $b_- = 2 - b_+$ provided $b_+ < 2$. The position of the secondary image is computed by changing the sign of x in equations (2) and (3). The image of Q_2 that has been observed must be the primary (brightest) image; therefore $b > 1$, and the earlier remarks about the upper limit on the mass of Q_1 apply.

The gravitation-lens effect brightens background QSOs, thereby increasing the surface density of detectable QSOs in the vicinity of Q_1 and making discovery of a close pair more likely. This density enhancement is

$$\frac{\sigma}{\sigma_0} = \frac{1}{N(m_v < 20.0)}\frac{1}{\pi b_0^2}$$

$$\times \int_0^{b_0}\left(\frac{I_0}{I_b}\right) N\left[m_v < 20.0 + 2.5\log\left(\frac{I_b}{I_0}\right)\right] 2\pi b\, db\,. \quad (6)$$

The factor I_0/I_b is due to the magnification of surface areas by the lens. To take a specific example, take $\beta_{\rm crit} = 3''.5$ and calculate the density enhancement within a circle of $5''$ radius ($b_0 = \sqrt{2}$). First we will take $N(m_v)$ from Schmidt's (1971) projected counts of QSOs ($z < 4$) using his favored $10^{5\tau}$ density evolution law. We find density enhancements of 1.1 and 1.6 for the point mass and the distributed mass models, respectively. While Schmidt's counts are the most reliable ones available, it is important to emphasize that they are projected rather than observed counts and that the density enhancements are quite sensitive to $N(m_v)$. As an example, for $\log N(m_v) = \text{const.} + 0.6m_v$ (homogeneous model), we obtain density enhancements of 1.6 and 3.3 for the point mass and distributed mass, respectively; for $\log N(m_v) = \text{const.} + 0.7m_v$ (fits observed QSO counts between $m_v = 18$ and 19) we obtain enhancements of 2.6 and 7.2, respectively. From these considerations it is clear that a density enhancement from 1.6 to 2 would not be unexpected while an enhancement of as much as 5 could not be ruled out. This raises the probability of finding such a $5''$ pair to $P \approx 0.04$–0.05 and possibly as high as $P \approx 0.12$. Such probabilities are appreciably larger than those originally estimated by Wampler *et al.* (1973) and are not so low as to preclude the pair being a chance event. We note in passing from inspection of figure 2 that the true angular separation of the two quasars is even less than the observed angular separation of their images. But as we have seen, the lens brightening effect bringing faint background quasars into view more than compensates for this and, through the density enhancements, increases the probability of observing such a close pair. There are significant density enhancements only if $\beta_{\rm crit}$ is comparable in

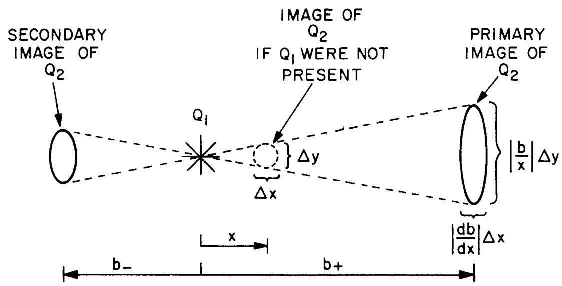

FIG. 2.—Images as seen by the observer. The gravitational lens conserves surface brightness. The image of Q_2 is brightened by a factor $(I_b/I_0) = |b/x| \times |db/dx|$.

magnitude to 5″. Since the pair is unusually close, this is an argument that the lens enhancements are in effect and that $\beta_{\rm crit}$ is of the order of 3″.5 or greater. Indeed there is weak evidence that the image of Q_2 has been brightened by a gravitational lens. Q_2 is 19th magnitude with $z = 1.901$. Less than one-quarter of 19th-magnitude QSOs show a redshift as large as Q_2's: we have to go to 21st magnitude before the median redshift is $z \approx 1.9$ (Schmidt 1972). This also argues in favor of $3''.5 \lesssim \beta_{\rm crit} < 5''$ and $3.6 \times 10^{12}\mathfrak{M}_\odot \lesssim m < 7.2 \times 10^{12}\mathfrak{M}_\odot$.

Sandage (1972) has argued from photometric data that quasars are exceptionally active nuclei in giant elliptical galaxies, i.e., that the parent galaxies of quasars are essentially the same as those that become strong radio galaxies. QSO counts by Schmidt (1972) are consistent with this hypothesis. Sandage (1972) estimates the mean absolute magnitude of radio galaxies as $M_v = -22.77$ (for $H_0 = 55$ km s^{-1} Mpc^{-1}). With a standard $\mathfrak{M}$/L = 30–50 this is $\mathfrak{M} = 3$ to $5 \times 10^{12}\mathfrak{M}_\odot$, in good agreement with the estimate of the probable mass of the galaxy harboring Q_1 based on the gravitational-lens effect. Such an average radio galaxy would have $m_v = 20$ and would probably be undetectable around the much brighter (17th magnitude) Q_1.

Take $m = 3.6 \times 10^{12}\ \mathfrak{M}_\odot$ (half the allowed maximum) as perhaps a reasonable value. Then in addition to the primary image of Q_2 with $m_v = 19.0$ there will be a secondary image of Q_2 on the other side of Q_1. For the point mass model the secondary image is $m_v = 20.5$ at 2″.5 from Q_1 while for the distributed mass model it is $m_v = 20.0$ at 2″.0 from Q_1. The primary and secondary images suffer distortions (see fig. 2) of at most 3.4 to 1 in these cases. The distortions would be undetectable since the original image of Q_2 was undoubtedly less than 10^{-3} arc sec in size. If we can find the secondary image of Q_2, and Q_2 is variable, then we can measure the time delay between the two images:

$$\Delta t = \tfrac{1}{2}[(b_- + x)^2 - (b_+ - x)^2]\beta_{\rm crit}{}^2 \frac{\lambda L}{(L-\lambda)c}\,. \qquad (7)$$

For the distributed mass $m(r) \propto r$, $\Delta t = 0$ because the two deflection angles are the same. For the images given above, the point mass model gives $\Delta t = 2.4$ years (for $q_0 = 0$). For $q_0 = \frac{1}{2}$, $\lambda = \frac{2}{5}[1 - (1+z)^{-5/2}]$, so λ and L are slightly different and $\Delta t = 2.6$ years. In principle, measurement of Δt could give a test of q_0. In practice it is only a 10 percent effect, and all the angles and H_0 would have to be measured to a better accuracy. An even more serious difficulty is that Δt is also dependent on the mass distribution. Presumably we could determine y in $m(r) \propto r^y$ by comparison of b_+, b_-, and I_{b+}/I_{b-}, but irregularities in the mass distribution could easily invalidate any cosmological significance for Δt. There is no known radio source associated with Q_2. Of course, it would be most interesting if such a radio source (and its secondary image) could be found. This would allow another opportunity to make the above tests.

Observation of a secondary image allows us to place constraints on local models for quasars. In such models quasars are taken to lie at distances of the order of 10–100 Mpc and their redshifts are taken to be intrinsic, so λ and L can be taken as free parameters. It has been argued that Q_1 and Q_2 are found close to each other because they are physically connected. On such a model $(L - \lambda)/L \sim 2.5 \times 10^{-4} = \beta$ (angle of separation). If we see a secondary image, $\beta_{\rm crit} \approx 3''.5$. Let $(L - \lambda)/L \ll 1$ for Q_2 and Q_1. Now for distant sources far behind the quasar Q_1 we have $(L' - \lambda)/L' \approx 1$, and for these sources $\beta'_{\rm crit} \approx \beta_{\rm crit}[L/(L - \lambda)]^{1/2}$. The *Sky Survey* prints reveal four faint galaxies within 40″ of Q_2, the closest being only 10″ away. These galaxies are 19th and 20th magnitude and are likely to be at redshifts of at least $z = 0.3$. Clearly these are background objects if Q_1 is local. Then $\beta'_{\rm crit} < 10''$ since otherwise the nearest background galaxy at 10″ would have an even brighter image on the other side of Q_1 with separation greater than 10″. Also the nearby galaxies would have image distortions. No such effects are seen. So $\beta'_{\rm crit} \lesssim 3\,\beta_{\rm crit}$ and $(L - \lambda)/L > 1/9$. Thus $(L - \lambda)/L$ must be roughly of order unity and the observed angular separation must be due to a projection effect. We can still use equation (1) to put a strict upper limit on the mass $m < 1.3 \times 10^{11}\ \mathfrak{M}_\odot\ (d/10$ Mpc$)$ where $d = \lambda$ is the distance to Q_1. If Q_2 is variable, we can observe the time delay between the two images. Now $L/(L - \lambda) < 9$, so $\Delta t_{\max} \sim \frac{1}{2}\beta^2 \times 9\lambda c^{-1} \sim 22$ days $(d/10$ Mpc$)$. Observation of a short time lag would not prove the local hypothesis since a short time lag can be produced by the cosmological model with $m(r) \propto r$. However, the local model is incapable of producing a long time lag. If we observe a $\Delta t \sim 2$ years, it will prove that 1548+115a is not a local object but lies at a distance comparable with that inferred from a cosmological interpretation of its redshift.

It is a special pleasure to thank Dr. Maarten Schmidt for a number of stimulating discussions.

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