The double quasar 0957+561 A, B: a gravitational lens?

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1. INTRODUCTION

In May 1979 Walsh *et al.*[1] announced their discovery of a unique object: a pair of quasars, designated by its equatorial coordinates as 0957+561 A, B; since that time it has been kept under study at many observatories. The quasars have now been investigated over a large part of the spectrum, from radio frequencies to the ultraviolet, and considerable information has been gathered, probably enough to permit some fairly definite conclusions to be drawn about the nature of the phenomenon. Walsh *et al.* reported that the two quasistellar objects 0957+561 A, B are nearly equal in brightness ($I_B/I_A \approx 0.8$); the components are separated by an angular distance of only 5.7″ and have the same redshift $z = 1.41$ as well as nearly identical spectra. Thus it was quite natural to inquire whether we might in fact be viewing not two distinct quasars but just one, whose image is split in two by a gravitational lens. Exactly what is a gravitational lens?

2. PRINCIPLE OF THE GRAVITATIONAL LENS

One remarkable implication of general relativity theory, brilliantly confirmed by the observations, is the prediction that the trajectories of light rays should become curved in the gravitational field of a massive object. The gravitational-lens effect is based entirely on this phenomenon. Einstein[2] was the first to point out that such an effect might operate.

To illustrate the principle of the gravitational lens, consider the following simple model (see Fig. 1). Suppose that light is traveling from the point source I toward the observer N, but that near the line IN (at an angle $\theta_I \ll 1$) there is a massive gravitational object G. The gravitational field of G will deflect the ray trajectories by the angle α, so that instead of a single light beam IN arriving from the source I, the observer may perceive several beams.

If the object G is spherically symmetric, the deflection angle α of light passing at distance b from the center of G will be

$$\alpha(b) = 4\gamma M(b)\, b^{-1} c^{-1}, \quad \alpha \ll 1, \tag{1}$$

where $M(b)$ represents the mass within b as viewed in projection, γ is the gravitational constant, and c is the speed of light. We also readily see from Fig. 1 that the simple geometrical relation

$$(L_1 + L_2)\,\theta_I + \alpha(b)\,L_1 = \theta\,(L_1 + L_2) \tag{2}$$

will hold, provided $\alpha,\ \theta,\ \theta_I \ll 1$. Since $b = L_2\theta$, Eqs. (1), (2) yield the following equation for θ:

$$\theta^2 - \theta_I\theta - \frac{4\gamma}{L_2(L_1+L_2)\,c}\, M(L_2\theta) = 0. \tag{3}$$

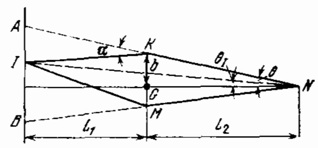

FIG. 1. Schematic configuration of a gravitational lens. The gravitating object G deflects light rays from the source I to the observer N along the two trajectories IKN and IMN, forming two separate images A, B of the same source I.

In the event that G is a point mass we will have $M(L_2\theta) = M_0 = \text{const}$; Eq. (3) will then be quadratic and have two solutions. Light from I will reach the observer along the two trajectories IMN, IKN, and the observer will see two images A, B of the same source I. If the gravitating object should not lie exactly on the line joining the source and the observer, the image of the quasar I will clearly take the form of a ring. As G shifts away from the direct line of sight, asymmetry will transform the ring into a pair of severely astigmatic images lying in the plane that passes through I, N, and G.

However, if G is an extended object the situation will be considerably more complicated. Equation (3) will, in general, be transcendental, since $M(L_2\theta)$ can be an arbitrary function. Calculations demonstrate[3] that in the case of a galaxy having the most plausible model density distribution, the number of solutions of Eq. (3), and accordingly the number of images, will be odd (there will be one, three, ... images, rather than two).

Another distinction is that, unlike the point-mass case, where in order that the images A, B may be of comparable brightness G must be located almost precisely midway between them (for the double QSO 0957+561 any displacement should be $\lesssim 0.1''$), for an extended object the constraints on the lens geometry are relatively weak.[4,3] Indeed, the likelihood that a lens similar to 0957+561 A, B can develop increases by three orders of magnitude.

We now proceed now to describe some recent observations of the double quasar. It is worth emphasizing at the outset that Weymann *et al.*[5] and B. J. and D. Wills[6] confirm the spectra of the two components to be remarkably identical.

3. RADIO OBSERVATIONS

A direct test of the gravitational-lens hypothesis is furnished by the radio observations of 0957+561 A, B which Roberts *et al.*,[4] Pooley *et al.*,[7] and Porcas *et al.*[8] have carried out. The two radio components show a complex structure extending as far as 12″ from the

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quasars. The brighter member of the pair, component A, lies almost at the center of a lineament comprising four well-defined radio structures. Quasar B is a compact radio source, perhaps slightly distended ($\approx 1.5''$) along the line Ab in the direction toward A, whereas A appears to be a point radio source of angular size $\lesssim 1''$.

The lack of any radio structure near B similar to that found in the vicinity of A is hard to reconcile with the simple gravitational-lens model. If, however, the object G (Fig. 1) should be extended (a galaxy, say), then interpreting the radio data would pose no problem. The extension observed in the source B might be due to the lens galaxy G, while the asymmetric shape of G and perhaps the presence of an intervening cluster of galaxies along the path IN could well account for the observed asymmetry of the radio structure.[3]

4. OPTICAL OBSERVATIONS

A second test of the lens hypothesis would, of course, be to detect and investigate the gravitating object G (presumably a galaxy). But observations of that sort are extremely difficult. If the galaxy were located roughly halfway between the quasar and us, its image ought to be very faint. Yet a search with the 200-inch telescope has been crowned with success. A group of American astrophysicists report[3] that $0.8''$ from image B is a slightly elongated $18-19^m$ galaxy whose redshift[1)] is equal[6,3] to $z\approx 0.4$. The presence of any other objects between A and B can be ruled out at the 25^m level. From the redshift of a galaxy one can find its distance and hence its luminosity. In this instance $z\approx 0.4$ implies a total luminosity of order $2\cdot 10^{11}$ L , which matches the luminosity of typical giant elliptical galaxies.

Close to the double quasar Young *et al.*[3] find an aggregation of galaxies which, they believe, form a cluster one of whose members is the lens galaxy. Calculations of the lens effect that allow for the existence of an entire cluster of galaxies are very complicated and do not give definite results. Nevertheless, by making a reasonable choice of parameters one can arrive at a picture similar to that observed. We have mentioned (Sec. 2) that an extended lens galaxy will more likely produce three images of the distant quasar than two. In a model examined by Young *et al.* one image of the pair would comprise two close ($\lesssim 0.2''$), unresolved components.

5. INFRARED AND ULTRAVIOLET DATA

Infrared observations of the object 0957+561 A, B have been reported by Soifer *et al.*[9] and Lebofsky *et al.*[10] Close to B is a strong infrared source which these authors interpret as a galaxy. Its characteristic properties, such as its infrared spectrum and luminosity ($L\approx 2\cdot 10^{11}\ L_\odot$), are consistent with the parameters of a giant elliptical galaxy located at $z\approx 0.4$. Furthermore, the peculiarity and mutual resemblance of the infrared spectra of the quasars themselves serve as indirect support of the gravitational-lens idea.

The model of the gravitational lens predicts that the flux ratio of the observed components A and B should remain constant throughout the spectrum, unless the light beams representing the two images of the quasar have experienced significant differences in absorption. Studies of the QSO at ultraviolet wavelengths indicate that absorption evidently is not an important factor.[11] The I_B/I_A flux ratio remains surprisingly unchanged at ≈ 0.8 as one passes from the radio to the infrared, optical, and ultraviolet ranges—further emphatic support for a gravitational lens.[3-11]

6. FUTURE OBSERVATIONS

While there are a variety of indications that the double quasar 0957+561 A, B does represent a lens effect, further observations will be needed if all the questions that arise are to be answered with confidence. These observations should proceed along several lines.

If the variations in the light from quasars A and B should prove to be correlated, the hypothesis might be confirmed directly. Such measurements are currently under way with the 6-m telescope of the Special Astrophysical Observatory, USSR Academy of Sciences, at Zelenchukskaya in the Caucasus.[2)] Another test of great importance would be to study the radio structure of component B in an effort to decide whether B itself is double.

Observations of a different kind would concern exploration of the lens galaxy and the cluster to which it is presumably belongs. In particular, the redshift of the cluster members ought to be measured more accurately.[3)] It also will be most valuable to determine the velocity dispersion of the cluster members including the lens galaxy, as well as the geometry and other properties of the cluster, to aid in evaluating the unknown parameters of the lens.

7. CONCLUSIONS

At present we can say with a good deal of assurance that the first gravitational lens in the universe has finally been discovered. In fact it would be surprising if

[1)]The redshift of this galaxy is not very accurate. Young *et al.*[3] and Wills and Wills[6] regard the galaxy as responsible for certain differences observed between the spectra of quasars A and B at red wavelengths; they determine z by interpreting the break in the spectrum of B as due to Ca II lines in the intervening galaxy. However, as B. V. Komberg points out, the spectra of A and B may differ because of an absorption line produced by dust near B. In view of these matters one should treat redshift measurements of the galaxy with caution.

[2)]Observations carried out by G. M. Beskin, S. I. Neizvestnyĭ, and V. F. Shvartsman now show that in terms of brightness the components of the double quasar have changed places, as a result of the slow variability of this object and the time lag between the images. In October 1980, component B was brighter than component A; during 1979 and the first half of 1980 the reverse was true.

[3)]Before long it should be feasible to determine a more reliable redshift for the lens galaxy by using the Mg II absorption line, which unfortunately is quite weak.

our interpretation of the double QSO 0957 + 561 A, B should undergo any radical change.

In a qualitative sense this discovery of a gravitational lens provides just as much support for the general theory of relativity as does the deflection of light rays by the sun. It forthwith demonstrates that quasars lie at cosmological distances. More than that, gravitational lenses—if enough of them should be found[4)]—give us a powerful new tool for measuring such cosmological parameters as the Hubble constant.

4)Weymann *et al.*[12] have recently announced the discovery of a triple quasar system, PG 1115 + 08. The angular separation of the components is $\approx 2-3''$, the redshift $z = 1.71$, and all three spectra are much alike. Weymann *et al.*, believe this system represents another gravitational lens.

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