remain comfortably in the same, otherwise overheated, environment. Clothing made with metallized threads could serve to screen out the radiation, mainly reflecting it, thereby reducing its effects on such active occupants.

The question of whether there are nonthermal effects that must be considered in the interaction of microwaves with tissue is a subject of debate. It is perhaps worth noting that microwave radiation contains only photons whose quantum energy is very much smaller than the mean energy of the pervasive thermal agitation and vibration of individual atoms and molecules of all matter at temperatures supportive of life. Microwaves form a part of the spectrum of radiations emitted by all objects at temperatures above about 1 K, and are present in the radiation from the sun. These photons, individually, have none of the penetrating and disruptive qualities possessed by gamma rays, x-rays, or energetic particles encountered in nuclear reactions.

The Group on Microwave Theory and Techniques, of the Institute of Electrical and Electronics Engineers, in 1971 devoted an issue of their transactions to the subject of the biological effects of microwaves. It seems that even advocates of the view that there are dangerous nonthermal effects accept the argument that the shallow penetration of 3-cm and shorter microwaves makes them unsuitable for use in testing for such effects (*3*). It is worth noting here that at short microwave wavelengths the penetration depth in tissue with a sizable water content is proportional to the square of the wavelength (*4*). With the principal warming occurring in the skin, it seems likely that there is little difference between being warmed by such microwaves and being warmed by more conventional infrared waves of, say, 100-μm wavelength. No great danger has been cited from the radiation from a fire on the grate or a stove. These traditional devices, as employed mainly prior to the spread of central space heating, did tend to be used to deliver heat to persons relatively more than to raise the temperature of the space itself, but most of them were highly inefficient and nonuniform.

Some fear of this proposed form of heating might arise from the association with microwave ovens for cooking. Of course, that application of microwaves makes use of the same ability to heat the desired object, with the development of very little heat in the air or the walls of the enclosure. However, wavelengths of 12 cm or more are used in ovens, and these penetrate more than ten times more deeply than does 3-cm radiation in tissue with a sizable water content. Also, cooking is a matter of degree. All forms of domestic heating have their counterparts in cooking, when the level of the heat is made sufficient. One may associate, for example, forced hot air (or a dry sauna) with baking, a damp sauna with steaming, and radiant heat with broiling. The open fire itself is also used for broiling, but that does not prevent a fireplace from serving as a pleasant source of warmth. The important factor in all cases is the limitation of the exposure to an appropriate level.

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4 December 1979; revised 19 February 1980

The Double Quasar 0957+561: Examination of the Gravitational Lens Hypothesis Using the Very Large Array

Abstract. *A full 12-hour synthesis at 6-centimeter wavelength with the Very Large Array confirms the major features previously reported for the double quasar 0957+561. In addition, the existence of radio jets apparently associated with both quasars is demonstrated. Gravitational lens models are now favored on the basis of recent optical observations, and the radio jets place severe constraints on such models. Further radio observations of the double quasar are needed to establish the expected relative time delay in variations between the images.*

One of the classic consequences of general relativity is the bending of light rays by the sun's gravitational field. A star's image is displaced outward by an angle $2R_s/b$, where R_s is the sun's Schwarzschild radius and b is the distance of closest approach of the ray to the center of the sun (the impact parameter). Einstein and others recognized that a corresponding gravitational lens effect might be seen in more distant astronomical objects [see Refsdal (*1*)]. A massive intervening object (the "gravitator"), so compact that it might act effectively as a point mass, would create two images of any object behind it and nearly on the same line of sight. The primary image is displaced outward from the gravitator with respect to the undeflected position of the object, while the weaker secondary image appears on the opposite side of the gravitator. The primary and sometimes (depending on the geometry) the secondary image is amplified by the lens effect. As the angle between gravitator and object is increased, the primary image and object merge, and the secondary image fades out. The more complicated gravitational lens properties of extended mass distributions can result in more (or fewer) images, and have been treated by Bourassa and Kantowski (*2*), Krolik and Kwan (*3*), and others.

Walsh *et al.* (*4*) discovered that the twin quasars associated with the radio source 0957+561 were so similar in their optical properties that they might well be an example of the gravitational lens effect. The A and B quasars, A being northernmost, exhibited emission-line and absorption-line redshifts that were identical, within their measurement accuracy. Their results have recently been confirmed by the higher resolution observations of Weymann *et al.* (*5*). If time variations could be neglected, the near equality of the fluxes implied that the gravitator and object quasar were aligned to within 0.3 arc sec and that the gravitator was within 0.1 arc sec of the midpoint of the line joining A and B. Assuming a conventional Friedmann cosmology, the 6 arc sec separation of the quasars and their redshift ($z_{em} = 1.4$) implied a massive gravitator ranging from 2×10^{11} solar masses ($M_\odot$) (the mass of a typical galaxy) to 2×10^{14} $M_\odot$ (more massive than any known galaxy) depending on the distance of the gravitator.

Gravitational refraction should be frequency-independent, so radio measurements were immediately undertaken in an attempt to verify the double-image hypothesis. The first radio maps were made at a wavelength of 6 cm by two groups. Pooley *et al.* (*6*) used the Cambridge (England) 5-km telescope, with 2 arc sec resolution, and Roberts *et al.* (*7*) used the Very Large Array (VLA) of the National Radio Astronomy Observatory, with 0.8 arc sec resolution. With one small exception, the maps agreed in their main features. Both maps showed the A and B quasars, with intensities very similar in ratio to that observed optically. Since the frequencies differed from the

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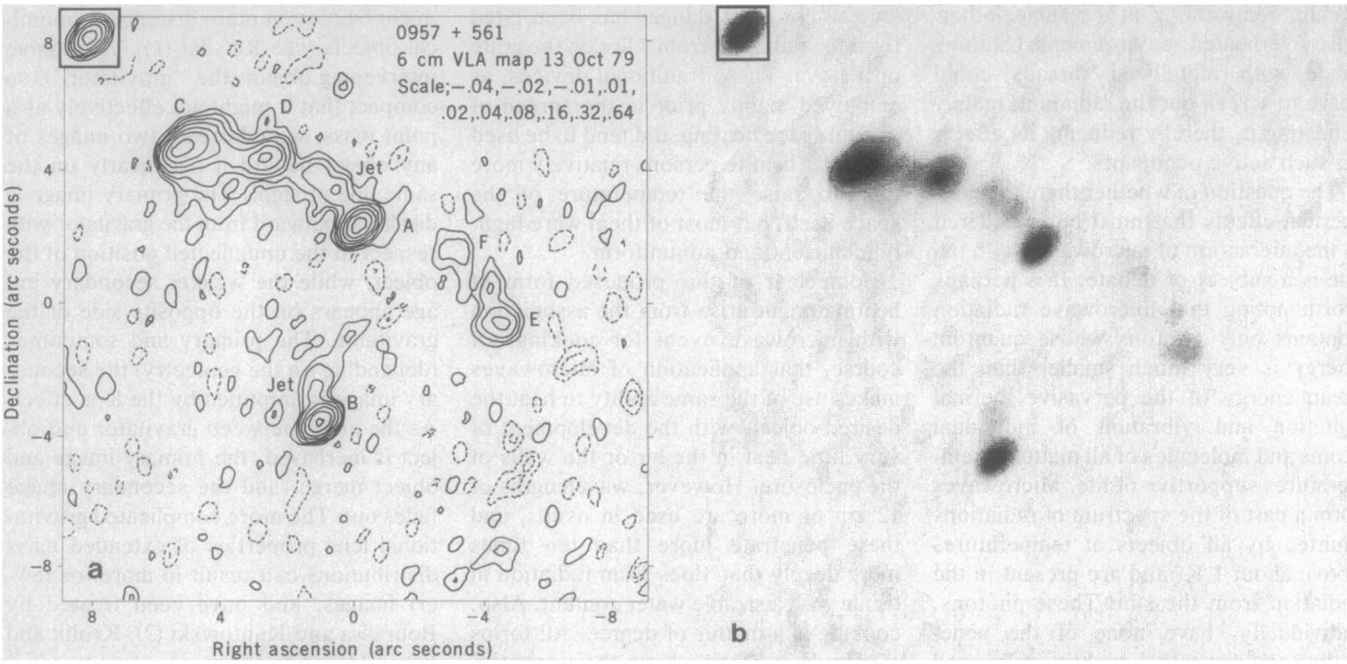

Fig. 1. Cleaned VLA map at 6-cm wavelength of the double quasar 0957+561 made 13 October 1979. The map center is right ascension 09 57 57.29, declination +56°08′19.99 arc sec (1950.0). (a) The contour levels are −4, −2, −1, 1, 2, 4, 8, 16, 32, and 64 percent of the peak flux of 37.6 mJy. The inset shows the clean beam of 0.45 by 0.80 arc sec (full width at half-maximum). (b) Linear gray scale reproduction of the same map. All zero and negative regions appear blank in this representation.

optical by a factor of 10^5, this was certainly evidence in favor of a gravitational lens. However, the radio maps were complicated by the presence of a complex of extra sources, apparently associated with the A quasar. Pooley *et al.* suggested that the B quasar might be extended by 1.5 arc sec, but the higher resolution data of Roberts *et al.* showed this not to be so. Although these data complicated the interpretation, they did not rule out a point-source gravitational lens model. The VLA data of Roberts *et al.* were taken with only 42 minutes of observing time, and a higher quality aperture synthesis was clearly indicated.

The new VLA observations were made on 13 October 1979 with a full 12-hour synthesis at 6 cm, broken periodically by observations of the phase calibrator, 1031+567, the amplitude calibrator, 3C286, and the polarization calibrator, 3C84. We adopted 7.4 Jy for the flux of 3C286 at 4885 MHz. The phase calibrator observations, approximately every 15 minutes, provided a continuous check on the performance of the 18 operating antennas. For preliminary editing we used the phase and amplitude stability of the calibrator as a guide. Following this stage of editing, a few spurious ring-type sidelobes could still be seen at the 2 percent level in the map, and these were eliminated by identifying and deleting unstable antenna pairs. The final data set was composed of 166,830 30-second averages, or effectively 11 antennas operating for 12 hours, giving dense coverage of the Fourier transform plane. The data were transformed and then processed with the standard CLEAN algorithm, as described in (7). The resulting "clean" map is shown as a contour plot in Fig. 1a and in half-tone reproduction in Fig. 1b. The improved Fourier coverage and longer integration time lead to a greatly improved dynamic range for the map, which exhibits a root-mean-square noise level of the order of 1 percent of the level of the highest peak. The resolution of the map is 0.45 by 0.80 arc sec, the size of the clean beam.

The C, D, and E features of the map in (7) are all verified, and the bridge between C and quasar A is also shown to be real. No bridge shows between A and E, although there is a condensation F that is certainly real. In the map of Fig. 1a, any feature several beam widths in size above the 2 percent contour level is real. The A and B fluxes are 37.6 and 28.3 mJy. The most important features of the map for the present discussion are the jets associated with the quasars. The A jet forms the bridge from A to D, although it appears to be distinct from D. Its mean position angle (measured counterclockwise from north) is 40°, although it is not strictly linear. This jet is 2.3 arc sec long and has a total flux of 4 mJy. There is also a B jet extending from the B quasar, at a mean position angle of 0°. Its length is about 1.5 arc sec and its total flux is 2 mJy. The B jet is unresolved in the transverse direction, and so is less than 0.4 arc sec wide.

The map shown in Fig. 1 immediately raises the question of whether or not the C-D source is a "double bubble" radio source close to the A quasar by a chance coincidence. The 6-cm source statistics of Pauliny-Toth *et al.* (8) show that there is a probability of only 3×10^{-6} that a 100-mJy source would be within 6 arc sec of either quasar. The alignment of the C-D source with A reduces the probability still further, and we conclude that a chance coincidence is highly unlikely.

With this caveat, the lack of a secondary image of the C-D complex [expected to be about 2 arc sec northwest of B (7)] eliminates the possibility that the twin quasar is caused by a point gravitator, such as a supermassive black hole, near the midpoint between A and B. The case against a compact massive gravitator is made still stronger by the existence of the radio jets associated with the A and B quasars. Given the observed flux and position angle of the A jet, there should be a secondary image next to the B quasar at approximately position angle −30°. The flux of the secondary image would be about 30 percent less than the flux of the A jet and should be easily observable. Similarly, the B jet should have a companion image next to the A quasar at position angle about −20°, with about 30 percent greater flux. Neither image is seen, so any compact gravitational lens model must be discarded. The jets are several kiloparsecs in size, and hence time variations cannot be invoked.

More complicated gravitational imaging can occur for extended mass distributions, with a single object being refracted into one or more primary images and zero or more secondary images, depending on the mass distribution and the object-gravitator-observer alignment. If the gravitator has spherical symmetry, such as the giant elliptical galaxy M87, the phenomena can be summarized as in Fig. 2. The condition that an image is seen relates the angle of deviation θ of the ray as a function of its impact parameter b to the distance D from observer to gravitator, the distance D' from gravitator to object, and the angle β on the sky between the gravitator and the undeflected image of the object. The observed angle between the gravitator and the ith image α_i is given by $\alpha_i = b_i/D$, and an image or images are seen if the deflection curve $\theta(b)$ intersects the straight lines $(1/D + 1/D')\ (b \mp \beta D)$, where the minus and plus signs apply to the primary and secondary images. The shape of the deflection function $\theta(b)$ depend on the mass distribution (*2, 3*); Fig. 2 shows the curve $\theta(b)$ appropriate to a mass distribution consistent with the $\exp(-r^{1/4})$ empirical brightness distribution of de Vaucouleurs and Capaccioli for elliptical galaxies (*9*). The solid lines (*a*) show a case where a single primary image and two secondary images are formed, the broken lines (*b*) show the limiting case of one primary and one secondary image, and the dotted lines (*c*) show a case where no secondary image formation occurs. The distinction among these cases depends on the intercept $\beta D(1/D + 1/D')$ of the secondary image line, and thus on β. The intensity amplification factor for the ith image is

$$\frac{b_i(D + D')/\beta D^2 D'}{(1/D + 1/D') - (d\theta/db)_{b_i}} \qquad (1)$$

In light of Fig. 2, the existence of the A and B jets eliminates the possibility of a gravitational lens composed of a spherical or nearly spherical mass distribution near the midpoint between the quasars.

A dramatic new development, however, has come through the observation by Gunn *et al.* (*10*) that there is a slightly elongated 19^m galaxy about 0.8 arc sec almost due north of the B quasar. An extended nonspherical gravitator in this location could, indeed, create the A and B images, and most of the features of our map are consistent with the interpretation of Gunn *et al.* In this picture, the complex C-D-A-E is the primary image while the secondary quasar image B has been formed near the limiting case (*b*) in Fig. 2. The near equality of intensity of the A and B quasars (despite the fact that $\alpha_A >> \alpha_B$) is understood as a consequence of the enhanced secondary image magnification that occurs near this limiting case, where $d\theta/db = 1/D + 1/D'$ (see Eq. 1). The cluster probably can shift the apparent positions of the images by up to 10 arc sec (*10*).

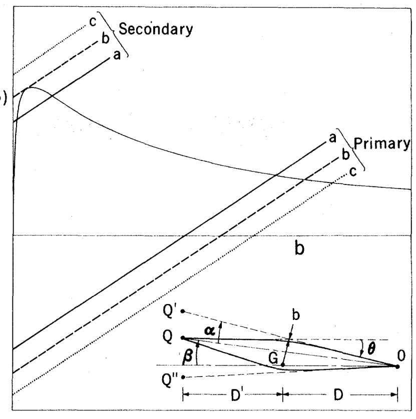

Fig. 2. Construction for the formation of gravitational lens images with an extended spherically symmetric gravitator. The intersections of the pairs of straight lines with the $\theta(b)$ curves give the impact parameter b_i and bending angle $\theta(b_i)$ of the ith image. The number of secondary images formed is (*a*) two, (*b*) one, and (*c*) zero, while one primary image is formed in each case. The diagram in the lower right-hand corner shows the geometry of the gravitational lens. The observer is at O, the gravitator at G, and the quasar at Q with images Q' and Q''.

In the model of Gunn *et al.*, B would probably be composed of two comparable closely spaced images oriented north-south. Our data constrain such a pair of images to be separated by no more than 0.2 arc sec. The absence of prominent secondary images corresponding to primary images C, D, and E is ascribed to their angles β being sufficiently large that no secondary images are formed by the extended mass distribution of the galaxy (case *c* in Fig. 2). The A and B jets provide the most severe difficulties and the sharpest tests of lens models. Since the A jet appears to continue all the way to the A quasar, it should have one or two secondary images. Since the jet flux is only about 0.1 that of the A quasar, and the images should be only about 0.3 arc sec long, they would be only marginally resolved from the B quasar by our current observation. It seems unlikely that the B jet is in fact this secondary image. A more intriguing possibility is that the B jet is the secondary image corresponding to C and D, formed not by the extended mass distribution of the galaxy but by a compact massive object in its nucleus. On the other hand, the B jet could simply be a small radio source associated with the foreground galaxy itself. The hypotheses that the B jet is the secondary image corresponding to the A jet or to C and D predict that the B jet does not extend northward of the center of the foreground lens galaxy. Observations with angular resolution spanning the range 0.01 to 1 arc sec are needed to determine the nature of the B jet and to search for the secondary image corresponding to the A jet. Since the radio intensities of the A and B quasars may vary with time, it should be possible to test the gravitational lens model by using the expected time delay (of the order of 1 year) between the arrival of the two images. This plus the detailed information on the structure (or absence) of secondary images will lead to severe constraints on the mass distribution of the foreground lens galaxy and on the location of any missing mass in the cluster.

Note added in proof: An improved 6-cm map of 0957+561 was obtained by us in February 1980, using the VLA. The B jet is clearly shown as an unresolved 2-mJy source 0.98 arc sec north and 0.18 arc sec east of the B quasar. This is within 0.02 arc sec of the center of the foreground galaxy seen by Gunn *et al.* (A. Stockton, private communication). Thus there is no radio jet associated with the B quasar, the foreground galaxy is probably a radio galaxy, and the most serious objection to the gravitational lens hypothesis is removed.

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11. The National Radio Astronomy Observatory is operated by Associated Universities, Inc., under contract with the National Science Foundation. The research at Massachusetts Institute of Technology was supported by a grant from the National Science Foundation. We thank J. Krolick for discussions about the gravitational lens effect and P. Young for early communication of the Palomar results.

26 December 1979; revised 19 February 1980