Reports

The Double Quasar 0957+561: A Radio Study at 6-Centimeters Wavelength

Abstract. *The optical double quasar 0957+561 has been interpreted as the gravitational double image of a single object. A radio map made with the Very Large Array of the National Radio Astronomy Observatory shows unresolved sources coincident with the optical images as well as a complex of related extended emission. Although the results cannot rule out the gravitational lens hypothesis, the complex radio structure is more easily interpreted as two separate quasars. The optical and radio properties of the two quasars are so similar that the two must have been formed at the same time with similar initial conditions.*

The radio source 0957+561 appears to be associated with a pair of quasars whose separation on the sky is only 6 arc sec. The identification was suggested by Walsh *et al.* (*1*), who showed that the optical spectra of the pair were similar and that the spectra of the A and B components (designating the northern component as A) were consistent with the emission redshifts being equal. Among the possible interpretations, Walsh *et al.* favored a gravitational refraction hypothesis, with the double quasar being a single object split into a pair of images by an intervening massive object acting as a gravitational lens. The optical data are consistent with this interpretation, since the small color difference between the two images could be explained by differential absorption (reddening) by dust along the separate optical paths. Since nearly identical absorption-line systems are also seen in the spectra of the two quasars, there is an intervening column of matter that could be associated with a gravitationally refracting body. The mean emission-line redshifts are 1.414, corresponding to a recession velocity of 212,000 km/sec for the pair. The absorption redshifts are both 1.3914, corresponding to the absorber being relatively close to the quasar or quasars, assuming the cosmological interpretation for all redshifts.

Little was known about the radio structure of the source, and in order to test further the gravitational lens hypothesis a set of observations were made with the Very Large Array (VLA) of the National Radio Astronomy Observatory near Socorro, New Mexico. The VLA is a multielement radio interferometer that, when complete, will consist of 27 25-m radio telescopes spaced along a Y-shaped set of railroad tracks, with a maximum dimension of 40 km (*2*). By cross-correlating all antenna pairs and by allowing Earth rotation to vary the effective antenna spacings, the array synthesizes a filled aperture whose diameter is approximately the size of the array, allowing the construction of radio "pictures" of the sky with an angular resolution comparable to that of optical telescopes. The array is partially completed and can be used for synthesis observation in its present state.

Our observations of 0957+561 were made on 23 and 24 June 1979 at a wavelength of 6 cm. We observed the source with $n = 14$ antennas for 6 minutes of time at each of seven hour angles, spanning a total range of 11 hours. The radio source 1031+567 was used as a phase calibrator, with 2 minutes of observation at each hour angle. The source 3C286 was used as a flux calibrator. Most of the $n(n-1)/2 = 91$ interferometer baselines were usable, covering spacings from 1000 to 300,000 wavelengths. Because of the finite sampling, there were narrow sidelobes at the 10 percent level radiating from the main beam with well-defined orientations, but the Fourier transform plane was reasonably well covered. The calibrated data were Fourier-transformed to produce a first-generation map, which was then processed with the standard CLEAN algorithm (*3*). This consists of successively subtracting point-source responses from the map, using the known beam pattern with all its sidelobes, and then reconstructing the map with a "clean" beam having no sidelobes. The resulting clean map is presented in Fig. 1, with the clean beam shown in the upper right-hand box. The peak flux in the map is 39 mJy, while the ± 2.5 percent levels, shown as the lowest-level solid and broken curves, are somewhat greater than the root-mean-square noise level of the map. Everything at and above the 6.3 percent contour is probably real.

The two unresolved sources, 2.5 arc sec north and 3.6 arc sec south of the map center, correspond to the optical A and B components, respectively. The radio source separation is 6.1 ± 0.1 arc sec, and the 1950.0 position and fluxes are given in Table 1. Table 1 also shows the optical positions of Walsh *et al.*, which are 0.5 arc sec north of our positions but probably well within their measurement errors. The radio positions are accurate to within ± 0.2 arc sec, and the identification is certain. The radio images show no broadening with a beam of 0.8 arc sec (full width at half-maximum), so we conclude that both A and B are less than 0.4 arc sec in size. In addition to these unresolved images corresponding to the optical quasars, a number of other features are visible in the map. A strong pair of resolved sources can be seen 5.8 and 3.6 arc sec northeast of the A source, embedded in an extended envelope of lower brightness, and we designate these C and D, respectively. A fifth region, ≃ 5.5 arc sec southwest of A, is less certain but probably is real, and we designate this as source E. The fluxes of these sources are also shown in Table 1. The short extensions immediately south and northeast of the A source cannot be regarded as real at this stage, and a more complete synthesis with lower sidelobes will be needed to confirm them. The same statement holds for the low-level extensions joining the C, D, and E sources to the A source. These faint extensions may be real, but their confirmation will also require synthesis to lower brightness levels.

The total flux from the complex was determined by adding all the CLEAN components (usually called the restored flux). Adopting a flux of 7.41 Jy for the 4885-MHz flux of 3C286, we obtain a total flux of 220 ± 11 mJy for 0957+561, where the quoted error refers to the internal consistency of the fringe amplitudes of the calibrators 1031+567 and 3C286.

The properties of a gravitational lens have been discussed by a number of authors (*4*). The effect is easily summarized for an intervening point mass and a time-independent object: if the gravitationally refracting mass is exactly on the line from the object to the observer, the observer sees a ring, with the total flux of

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Table 1. Positions, fluxes, and angular sizes of the radio components of 0957+561 as obtained from the VLA map (Fig. 1) at 6 cm.

Component	Optical position (1950.0)*		Radio position (1950.0)		Flux (mJy = 10^{-29} W/m²-Hz)	Angular size (RA × DEC)
	RA (hr min sec)	DEC	RA (hr min sec)	DEC		
A	09 57 57.3	+56°08′22″.9	09 57 57.27 ± 0.03	+56°08′22″.37 ± 0.2	36	< 0″.4
B	09 57 57.4	+56 08 16.9	09 57 57.41	+56 08 16.37	30	< 0″.4
C			09 57 57.90	+56 08 24.67	75	1″.2 × 1″.0
D			09 57 57.61	+56 08 24.47	28	0″.8 × 0″.8
E			09 57 56.74	+56 08 19.00	10	1″ × 2″
C and D (+ envelope at 5 percent brightness level)					110	3″.5 × 2″

*RA, right ascension; DEC, declination.

the object amplified by the lens effect. If the point mass is slightly off center, the image becomes a pair of crescents of approximately equal flux which will, in the limit of a point-source object, appear as a pair of unresolved sources. The radio nuclei of quasars are sufficiently compact to meet these requirements in the present observation. As the refracting body is moved farther off the center line, the fluxes S_A and S_B become progressively more unequal. If α_A and α_B are the angles between the respective images and the refracting mass, $S_A/S_B = (\alpha_A/\alpha_B)^2$. If the observed A and B sources are the separate and complete images of a single object, the observed flux ratio $S_A/S_B = 1.20$ requires that the refracting object is within 0.1 arc sec of the midpoint on the line joining A and B. Since the gravitational refraction should be wavelength-independent, the fact that the radio and optical double images have nearly the same flux ratios can be taken as support for the gravitational lens interpretation.

There is an absorption-line system at a redshift of 1.3914, compared to the emission-line redshift of 1.414. If the refracting object is associated with the intervening matter that causes the absorption lines, its mass would have to be $\simeq 2 \times 10^{14}$ solar masses ($M_\odot$) in order to give the observed images, assuming that both redshifts can be used as a metric distance measure in the conventional way. (Here and below we adopt a Hubble constant of $H_0 = 50$ km/sec-Mpc and a deceleration parameter $q_0 = 1/2$.) No such massive objects are known, so if the gravitational lens hypothesis is correct, a dramatic new class of object would be required. The refracting mass need not be at the distance of the absorbing matter, of course. If it is located at half the redshift, the mass requirement is $\simeq 5 \times 10^{12} M_\odot$. This is still a much larger mass than has been demonstrated for any galaxy, although there is some evidence that elliptical galaxies such as M87 may be this massive. The data of Walsh *et al.* (*1*) permit a refracting galaxy to be as close as a redshift $z \cong 0.1$, in which case the mass of the galaxy need be only $7 \times 10^{11} M_\odot$. A chance alignment of a quasar within 0.1 arc sec of a galaxy of redshift ≈ 1 has a probability of 10^{-5}, using the Tyson and Jarvis (*5*) value of 17,100 galaxies per square degree to magnitude 24. The probability decreases rapidly with the redshift of the galaxy and is $\approx 10^{-8}$ for $z = 0.1$. The chance that the alignment would occur for a galaxy of rare type such as M87 is two or three orders of magnitude smaller. One must conclude, therefore, that an alignment such as this is a rare event unless $10^{13} M_\odot$ objects are fairly common in the universe.

There is also a possibility that the double image is caused by a cylindrical lens, such as a massive spiral galaxy nearly edge-on in the line of sight. A somewhat larger mass would be needed, and this is at least ten times more mass than has been seen in any spiral system.

The remaining sources in the map of Fig. 1 give the gravitational lens hypothesis its most severe test. The objects C, D, and E are roughly aligned with the A quasar. Jetlike and hierarchical source structures are common radio phenomena among extragalactic radio sources. The jet of the quasar 3C273 is a classic case, but numerous other examples are known (*6*). Almost always, the extended radio sources seem to radiate from the active nucleus, whether it is a radio galaxy or a quasar, and the A-C-D-E complex bears a strong resemblance to such structures [one can refer to the examples given in (*6*) for a number of similar instances]. Therefore, it seems very likely that the C-D-E structure is physically associated with A and is not simply a chance superposition. Thus, under the gravitational lens hypothesis, all the structure in the map must be the result of imaging a single (perhaps complex) source. One possibility, that A-D-C is one image and B is the other, may be discarded. The refracting object would have to lie ~ 2 arc sec north of B to satisfy the observation that $(S_A + S_C + S_D)/S_B \approx 5$, and then B

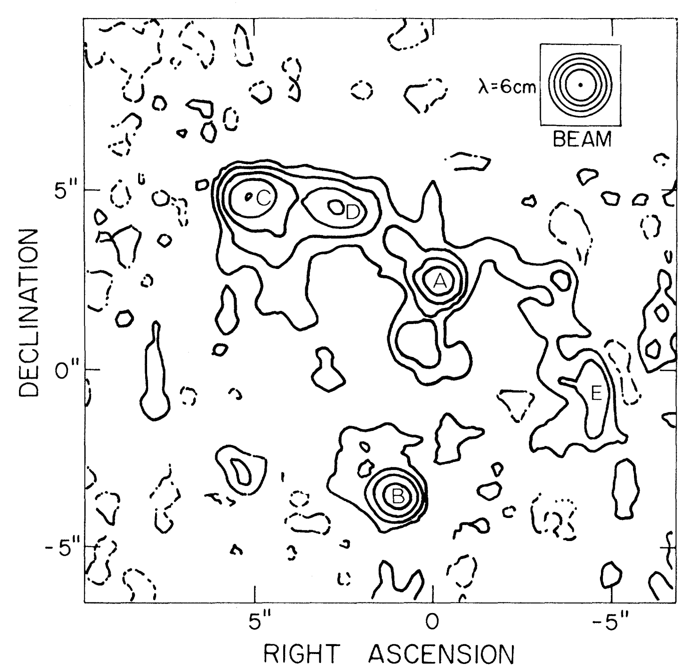

Fig. 1. Cleaned VLA map at 6 cm of the double quasar 0957+561 (24 June 1979). The map center is at right ascension 9 57 57.29, declination +56°08′20″.0 (1950.0). The contour levels are −2.5, 2.5, 6.3, 15.6, 39.1, and 97.7 percent of the peak flux of 39 mJy, chosen to emphasize the low-level extended features. The inset shows the clean beam.

would be ~ 2 arc sec across, which is ruled out by the data. However, it may be possible to concoct a source structure that, when imaged, resembles the radio map in both angular structure and intensity distribution. Consider a compact object nearly on the midpoint of the line joining A and B, and an extended object located ~ 1 arc sec southeast of C-D. The compact object would be imaged as A and B. One image of the extended object would be C-D, and the other would be located ~ 2 arc sec northeast of B and contain ~ 3 percent of the flux of C-D. This second image would be at the limit of the present map and could not be ruled out. A full-synthesis VLA map should be able to determine the viability of this model.

It is clear that the existence of the extended radio structure in 0957+561 severely strains the gravitational image hypothesis. Consider instead the possibility that A and B are separate quasars, quite possibly gravitationally bound, with A undergoing an active phase, sending out bursts or beams of relativistic particles. The difference in the radial velocities of the emission-line systems should be measured more carefully. A difference of 270 km/sec (the maximum allowed by the optical observations) implies somewhat high masses if the system is bound—at the emission redshift of 1.414, the projected separation is 52 kpc, and the masses would be of the order of 10^{12} $M_\odot$ each. Given the uncertainty in the radial velocity difference and our poor understanding of quasars, such masses do not rule out this interpretation. It is also suggestive that the line of sources C-D-A-E is slightly bent in the sense that would arise from the gravitational attraction of B.

When the A-C-D-E complex is compared to a known quasar-jet source such as 3C273, there are interesting parallels. The total 6-cm radio luminosity densities 3C273 (*7*) and 0957+561 are nearly equal for any reasonable q_0, even though the flux of the jet is a larger fraction of the total flux in the case of 0957+561. The total linear extent of 3C273 is about 110 kpc, compared to the A-C separation of 52 kpc.

In the above discussion, we have assumed that the brightness does not vary with time. Most quasars are time-variable, and it is not unreasonable to expect that 0957+561 also varies. If the gravitational lens hypothesis can be maintained, the time variation in the single object would be manifest in similar light curves of the double image, with a time lag corresponding to the difference in light travel times for the two images. If the light travel time to the refracting object is t_R and the ratio of the distances to the refracting mass and to the object is f, the time lag will be of order $(\alpha_A + \alpha_B)(\alpha_A - \alpha_B)t_R/(1-f)$. This characteristic time depends sensitively on the alignment of object, refracting mass, and observer, and on the distance to the refracting mass: it ranges from months if the bender is close to the observer to decades if it is at the absorption-line redshift. One could imagine that the difference in brightness of the two objects is actually greater, and that an unlucky coincidence in the time lag of a brightness variation accidentally makes the fluxes nearly equal at the moment. [Note that the optical flux ratio S_A/S_B appears to have been unchanged between the epoch of the Palomar sky survey (around 1950) and the present (*1*).] However, the range of intrinsic luminosity variations in quasars is limited, so the refracting mass is still constrained to be near the midpoint of the line joining A and B. More complicated geometry of the refracting mass is another possibility, but would seem to be artificial.

In summary, the 6-cm map of the double quasar 0957+561 derived from the VLA observations shows unresolved sources coincident with the optical images, and a complex of related extended emission. The suggestion that the double optical sources are actually a single quasar refracted into two images by the gravitational field of an intervening massive object is severely constrained, but not ruled out, by the complex of other related sources. The observations are consistent with the source being a true double object, with the north component actively ejecting relativistic plasma. The near identity of the radio and optical spectra of the compact objects is still remarkable. We suggest that the two objects had a common origin, are similar in their basic physical parameters, and are evolving in similar fashions. The average radio and optical properties of the compact objects are thus characteristic of this stage in their evolution. The outburst phenomenon, so common in quasars, is then seen as a sporadic phenomenon, with only one of the objects being active at the present time.

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References and Notes

1. D. Walsh, R. F. Carswell, R. J. Weymann, *Nature (London)* **279**, 381 (1979).
2. D. S. Heeschen, *Sky Telesc.* **49**, 344 (1975).
3. J. Högbom, *Astron. Astrophys. Suppl. Ser.* **15**, 417 (1974).
4. S. Liebes, Jr., *Phys. Rev. B* **133**, 835 (1964); S. Refsdal, *Mon. Not. R. Astron. Soc.* **128**, 295 (1964); *ibid.* **132**, 101 (1966).
5. A. J. Tyson and J. F. Jarvis, *Astrophys. J. Lett.* **230**, L153 (1979).
6. J. F. C. Wardle and G. K. Miley, *Astron. Astrophys.* **30**, 305 (1974); R. I. Potash and J. F. C. Wardle, *Astron. J.* **84**, 707 (1979).
7. S. von Hoerner, *Astrophys. J.* **144**, 483 (1966).
8. We thank A. K. Dupree and M. Davis for early information about the double quasar, R. Perley for rearranging his observing schedule to accommodate our program, and D. Staelin for helpful discussions. 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.

12 July 1979

Market Penetration Characteristics for Energy Production and Atmospheric Carbon Dioxide Growth

Abstract. *Estimates are given for the maximum rate at which fossil fuel consumption can be reduced by the introduction of noncarbon-based energy sources, according to the market penetration time concept. These estimates indicate an immediate need to implement a revised energy policy if major climatic changes induced by increased amounts of carbon dioxide are to be avoided in the next century. However, application of market penetration ideas to energy consumption is new and may not be valid for the prediction of future trends.*

The long-acknowledged potential for large climatic change arising from atmospheric release of increasing amounts of fossil fuel–generated CO_2 has only recently been recognized as posing an immediate environmental control problem. The reasoning behind the altered attitude is as follows. It is claimed that serious climatic consequences will result from the "greenhouse warming" associated with increasing atmospheric CO_2 concentration when the concentration doubles, some 50 or 60 years from now (*1*), although with large probable error. Even though the uncertainty in this doubling date is large, it was believed to be sufficiently distant for the problem to be one of academic concern only, but introduction of the market penetration time concept (*2*) radically altered this