13. D. S. Robertson *et al.*, in preparation.
14. T. A. Herring *et al.*, in preparation.
15. A weighted-least-squares solution using all of the data from these (and other) experiments simultaneously yields consistent results (J. W. Ryan *et al.*, in preparation).
16. We thank the staffs of the participating observatories for their indispensable aid. We also thank R. J. Coates, E. A. Flinn, T. L. Fischetti, and especially P. B. Sebring for their support. The MIT experimenters were supported by Air Force Geophysics Laboratory contract F19628-81-K-0015; NASA contract NGR22-009-839; NSF grant EAR-7920253; and USGS contract 14-08-0001-18388. Haystack Observatory is operated by a grant from the National Science Foundation, and the National Radio Astronomy Observatory is operated by Associated Universities, Inc., under contract with the National Science Foundation.
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18 May 1982

Detection of a Compact Radio Source near the Center of a Gravitational Lens: Quasar Image or Galactic Core?

Abstract. *By use of a new, very sensitive interferometric system, a faint, compact radio source has been detected near the center of the galaxy that acts as the main part of a gravitational lens. This lens forms two previously discovered images of the quasar Q0957+561, which lies in the direction of the constellation Ursa Major. The newly detected source has a core smaller than 0.002 arc second in diameter with a flux density of 0.6 ± 0.1 millijansky at the 13-centimeter wavelength of the radio observations. This source could be the predicted third image of the transparent gravitational lens, the central core of the galaxy, or some combination of the two. It is not yet possible to choose reliably between these alternatives.*

Albert Einstein's theory of general relativity predicted that mass would deflect light rays and hence could form images. The theoretical properties of such gravitational lenses have been studied in detail over the past five decades (*1, 2*), but no astronomical examples were discovered until 1979 (*3*), a few weeks after the hundredth anniversary of Einstein's birth. The two images, A and B, of the quasar Q0957+561 then discovered are 6 arc sec apart on the sky, with A almost due north of B (*4*). They have the same emission features in their optical spectra, which yield redshifts of 1.4136, identical within their measurement uncertainties of 0.0002 (*5*). The imaging is caused by a cluster of very faint foreground galaxies (redshift ≃ 0.36) (*6*), with the principal role being played by a large elliptical galaxy (designated G1), the brightest member of the cluster, located 1.00 ± 0.03 arc sec north and 0.19 ± 0.03 arc sec east of the B image (*7*). The cluster is spread over a region about 4 arc min in diameter and comprises over 100 galaxies.

Because such a gravitational lens is transparent, one can predict (*2, 8*) from theory that, except for degenerate cases, there should be an odd number of images. After the discovery of the galactic lens, the central remaining question concerned the missing third image. Different models predicted that it would be very near to either the B image or the center of G1 (*6*). Observations with the Very Large Array (VLA) of radio telescopes near Socorro, New Mexico, showed pointlike emission which came from the positions of the A and B optical images and weaker emission (designated G) which came from a position 1.06 ± 0.02 arc sec north and 0.15 ± 0.02 arc sec east of the B radio image (*9, 10*) coincident, within the measurement uncertainty, with the apparent optical center of G1, referenced to the corresponding center of B. The angular resolution of these VLA measurements, about 0.3 arc sec FWHM (full width at half-maximum), was too crude to allow one to discern any structure within the images. The flux densities of the A, B, and G components, interpolated to our 13-cm observation wavelength (~ 2300 MHz), were 49 ± 1, 37 ± 1, and 3.3 ± 0.3 mJy, respectively (*9*). The spectral index of the radio emission from G differed significantly from those of the A and B images, suggesting that part, if not all, of this weak emission was from G1 (*11*).

Soon after the discovery of this gravitational lens system, we undertook a program of very-long-baseline interferometry (VLBI) observations of the region of the quasar images (*12*). Here we report on the first phase of analysis of our most recent observations, conducted on 15 and 16 March 1981 with a VLBI array more sensitive than any previously available, and within a factor of 2 of the highest sensitivity achievable with the VLA. This increase in sensitivity was brought about primarily by the use of the new Mark III VLBI terminals (*13*) in combination with the 100-m-diameter radio telescope at Effelsberg, Federal Republic of Germany; the 64-m-diameter telescopes at the National Aeronautics and Space Administration's radio tracking stations in Goldstone, California, and Madrid, Spain; and three other telescopes with smaller diameters. Our observations with these telescopes of right circularly polarized radiation covered about 12 hours for most baselines. Because the separation of 6 arc sec between the A and B images is small compared to the antenna beam widths, both images were observed simultaneously at each site.

The properties of the galactic gravitational lens lead to the prediction that the third image, if near G1, should be smaller and therefore dimmer than the A or B image, but of similar shape (*6, 14*). Analysis of the data obtained in 1980 with the Effelsberg-Goldstone interferometer (*15*) disclosed single compact radio cores with largest dimensions between 0.001 and 0.002 arc sec in both the A and B images. The corresponding flux densities in these parts of the A and B images were 23 ± 1 and 19 ± 1 mJy, respectively. In searching for a similar but fainter radio core in the vicinity of G we used the 1981 data from the most sensitive (Madrid-Goldstone) interferometer, whose fringe spacing was ~ 0.0035 arc sec. To increase detection sensitivity we used the technique of phase referencing to average together coherently all the data from 13 "scans," each 12 minutes in duration, obtained with this interferometer (*16*).

The region around G that we searched showed no radio radiation above the (5 standard deviation) noise level of 0.3 mJy, save for a spot less than 0.002 arc sec in extent with a flux density of ~ 0.6 mJy detected with a signal-to-noise ratio (SNR) of 10. This detection represents

Table 1. Positions of G1, G, and G′

Object	Method of observation	Resolution (FWHM arc sec)	Position relative to B image (epoch 1950.0)	
			Right ascension (arc sec)	Declination (arc sec)
G1	Optical (*7*)	0.5*	0.19 ± 0.03	1.00 ± 0.03
G	VLA (*10*)	0.3	0.15 ± 0.02	1.06 ± 0.02
G′	VLBI	0.002	0.181 ± 0.001	1.029 ± 0.001

*The resolutions for the optical and VLA observations are from the respective references; the VLBI resolution is given as one-half the fringe spacing on the long California-Europe baselines.

the first successful use of phase referencing with VLBI. The center of brightness of this new compact radio component, designated G′, is 1.029 ± 0.001 arc sec north and 0.181 ± 0.001 arc sec east of the B image, referred to the mean equinox and equator of 1950.0 (*17*). The average of the corresponding data from the 22 scans from the Effelsberg-Goldstone interferometer, also with fringe spacing ~ 0.0035 arc sec, confirmed the detection with an SNR of 9; the coherent average of all 35 scans yielded a flux density of 0.6 ± 0.1 mJy (*18, 19*) with an SNR of 13. The individual scans set only weak limits on any structure of G′ more complex than a single unresolved point source. For example, a second (unresolved) source with flux density half that of G′, located within 0.01 arc sec of G′, would be barely detectable.

Considering the closeness of G′ to G1, we must ask whether this new compact component is an additional image of Q0957+561 or the radio core of the galaxy. The flux density and size of G′ are consistent with either hypothesis. Simple lens models yield the ~ 30:1 demagnification relative to B needed to account for the flux density of G′ (*6*). Alternatively, lens models can be modified within existing constraints to yield a third image sufficiently dim to fall below our detection threshold. In this case the observed radio emission would be from G1, and its value would be well within the range expected from observations of the cores of other elliptical galaxies (*20*). Given the detection of cores about 0.002 arc sec in extent in the A and B images, the detection of a smaller core in G′ with the same interferometers is a necessary, although not sufficient, condition for G′ to be a third image. On the other hand, the limit on the size of G′ is also consistent with the higher observational bounds on the sizes of cores of other elliptical galaxies (*20*).

How can the precise position of G′ relative to the other relevant objects aid in resolving this issue? The vastly different resolutions of the instruments used to determine this position and, to a lesser extent, the differences in observing wavelengths complicate the answer. The positions of G1, G, and G′ were each determined with respect to the corresponding position of the B image (Table 1). The agreement among the coordinate differences seems to indicate that G1, G, and G′ all coincide and hence are the same object (*21*). The identification of G1 as the center of the galaxy then suggests that G′ is the radio core of G1. Moreover, it is difficult to reconcile this agreement if G′ is not the core of G1, but rather the third image: lens models that yield a ~ 30:1 demagnification of the third image relative to B also require the third image to be about 0.2 arc sec south of the center of the galaxy (*6, 9, 22*).

On the other hand, the reference point in B may well depend significantly on the technique used. VLBI observations made with a lower resolution at a radio wavelength of 18 cm revealed a radio feature about 0.040 arc sec in extent centered about 0.046 and 0.056 arc sec north of the cores of the A and the B images, respectively (*23*). The flux densities of these "jets" were equal to those of their respective cores within the ~ 50 percent uncertainties of the determinations. Hence the reference point in B for the VLA measurements may be about 0.03 arc sec north of the corresponding point for our observations, thus placing G′ 0.06 ± 0.02 arc sec south of G. Even if significant, the offset of 0.06 arc sec could be interpreted either as a possible location for the third image or as evidence for an asymmetric brightness distribution for G. The issue could be settled if we could detect or rule out the presence of a jet in the region of G′ consistent with the jets accompanying the A and B images. Detection of such a jet in the region of G′ would be convincing evidence that G′ is a third image of the quasar; conversely, a significant limit on extended emission would rule out this possibility (*24*). Our present weak limits on the presence of any extended emission near G′ and the large uncertainty in the flux density of any demagnified jet preclude this elimination.

It is also unlikely that we will be able to resolve this issue after complete analysis of our present data. More sensitive VLBI observations with submillijansky sensitivity in the G′ region seem to be required.

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4. The quasars are named after their coordinates: 0957+561A is at 09 hours 57 minutes 57.324 seconds right ascension (α) and 56°8′22.344″ declination (δ). The second quasar image 0957+561B is offset from the A image by Δα = 0.149866 ± 0.000004 second and Δα = −6.04662 ± 0.00004 arc sec (M. V. Gorenstein *et al.*, in preparation) with all coordinates referred to the standard equator and equinox of 1950.0.
5. The value quoted is for Mg II emission features [R. Weymann, F. H. Chaffee, M. Davis, N. P. Carleton, D. Walsh, R. F. Carswell, *Astrophys. J. Lett.* **233**, L43 (1979)]. The equivalent "angular-size" distance of the source may be written approximately as 1.2 h^{-1} Gpc, that is, about 4×10^{27} h^{-1} cm, if we use values of 100 h km sec^{-1} Mpc^{-1} and 0 for the Hubble constant, H_0, and deceleration parameter, q_0, respectively. The dimensionless constant h is thought to be bounded by $0.5 \le h \le 1$.
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11. The spectral index α is the exponent of the (assumed) power law dependence of the flux density, S, on frequency, ν: $S \sim \nu^{\alpha}$. Here $\alpha = -0.51 \pm 0.01$ for A, -0.43 ± 0.01 for B, and -0.7 ± 0.1 for G, as deduced from VLA observations at 6 and 18 cm (*9*).
12. M. V. Gorenstein *et al.*, *Bull. Am. Astron. Soc.* **12**, 498 (1980).
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14. If the lens is transparent, surface brightness is conserved and the apparent luminosity of an image of Q0957+561 is proportional to its (magnified) size [see, for example, C. W. Misner, K. S. Thorne, J. A. Wheeler, *Gravitation* (Freeman, San Francisco, 1973), p. 589].
15. This experiment involved the same three large antennas used in March 1981, but the time interval was much shorter, and the much less sensitive Mark II VLBI system was used for the interferometers involving Madrid (M. V. Gorenstein *et al.*, in preparation).
16. The time interval over which VLBI data from observations at 13 cm can be averaged coherently is normally limited to about 30 minutes because of random contributions to the interferometer ("fringe") phase. These contributions stem from the receiver systems and from the troposphere and ionosphere over the sites of an interferometric array. But these contributions, common to the fringe phases for two sources that are observed simultaneously and are sufficiently close together in the sky, cancel in the difference between these phases. We took advantage of this cancellation in a straightforward manner to search for other compact radio components in the vicinity of the B image by using as a reference the measured values of the fringe phase of the B image, obtained from each scan. For a grid spacing of 0.0015 arc sec, commensurate with the resolution of the interferometers, we searched a region extending 0.2 arc sec north, 0.2 arc sec east, 0.2 arc sec west, and 0.6 arc sec south of G. We also searched a region centered on the B image and extending 0.4 arc sec north, 0.3 arc sec west, and 0.1 arc sec east; however, we have not yet corrected for the contributions to the fringe phase from the strong sidelobes due to the beam pattern of the synthesis array and the presence of B, thus marring the otherwise negative results of our search in that region.
17. M. V. Gorenstein, I. I. Shapiro, A. E. E. Rogers, N. L. Cohen, *Int. Astron. Union Circ.* *3644* (1981).
18. The uncertainty in flux density represents a combination of statistical and systematic calibration errors; the latter are estimated to be 15 percent.
19. Data from the Effelsberg-Madrid interferometer (fringe spacing 0.020 arc sec) were not used because of contamination problems, due to radi-

ation from the B image, that require further analysis to solve. These problems are serious only on this baseline, where the contamination in the region to be searched is typically about 0.5 mJy; the contamination for the two longer baselines is typically below 0.05 mJy.
20. The luminosity per unit bandwidth of the radiation from G, as deduced from the VLA measurements at 6 cm, is about $4 \times 10^{23}\ h^{-2}$ W Hz^{-1} ($H_0 = 100\ h$ km sec^{-1} Mpc^{-1}), a value in the midrange of those found for the cores of 34 elliptical galaxies by G. Colla *et al.* [*Astron. Astrophys.* **38**, 209 (1975)] at 6 cm. However, lack of detection with the VLA of radio radiation from G1 would also be consistent with the results of Colla *et al.* In our measurements, the radiation from G′ arrives from a region under 0.002 arc sec in extent, implying a surface brightness of at least 3×10^8 K, consistent with values measured for cores of galaxies [see, for example, P. C. Crane, *Astron. J.* **84**, 281 (1979)].
21. This G′ core must then contribute to the flux density of the G component; the other part of the 3.3-mJy flux density from G presumably comes from a region too extended to be detected at the high resolution of our interferometers and could form another part of the third image or of the G1 galaxy, or of both.
22. If the prediction that the third image is 0.2 arc sec south of G1 is correct, then it is unlikely that the detected radiation from G′ arises partly from the galaxy core and partly from the third image. At a separation of 0.2 arc sec, the emissions from G1 and from a third image would be easily separable with the resolution obtained in our observations.
23. R. W. Porcas, R. S. Booth, I. W. A. Browne, D. Walsh, P. N. Wilkinson, *Nature (London)* **289**, 758 (1981).
24. As an image at the G′ location would resemble an inverted demagnified image of the quasar, we would expect to see a dim radio feature, located some 0.010 arc sec south of the core of G′, which should be visible with the intercontinental interferometers were their sensitivities increased severalfold. If G′ were an image, the demagnified "jet" would tend to further bias the measured position of G slightly southward by at most 0.005 arc sec. Correction for this bias would place the true radio center of the galaxy a corresponding amount further northward of G′.
25. We thank the staffs of the participating observatories for their indispensable aid and J. Capece, J. Caplin, and E. Raphael for technical and administrative support. The MIT experimenters were supported in part by NSF grants PHY-8106036 and AST-8022229. Haystack Observatory is operated with support from the National Science Foundation. This work also represents one phase of research at Jet Propulsion Laboratory performed under NASA contract NAS7-100.
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18 May 1982

Lines of T Lymphocytes Induce or Vaccinate Against Autoimmune Arthritis

Abstract. *The pathophysiology of autoimmune arthritis was studied by selecting and isolating lines of effector T lymphocytes from rats administered an arthritogenic dose of* Mycobacterium tuberculosis *in complete Freund's adjuvant to induce adjuvant arthritis. Irradiated rats were intravenously inoculated with a cell line characterized by proliferative reactivity to* Mycobacterium tuberculosis *and, to a lesser degree, to rat collagen type II. This produced arthritis in all the irradiated rats. Nonirradiated recipients failed to develop arthritis. However, such rats, and those recovering from cell-mediated arthritis, were resistant to subsequent attempts to induce adjuvant arthritis. Lines of T lymphocytes selected for responsiveness to other antigens had no effect. Therefore, a line of T lymphocytes responsive to bacteria or to collagen type II could either induce autoimmune arthritis or serve as an agent of vaccination against it.*

Rheumatoid arthritis is characterized by a chronic proliferative and inflammatory reaction in synovial membranes, producing pain, disability, and eventual destruction of joints (*1*). Although the etiology of this disease is unknown, it is thought that autoimmune processes are involved (*2*).

An animal model of arthritis that has features similar to human rheumatoid arthritis is adjuvant arthritis (AA) (*3*). Adjuvant arthritis can be induced in rats by a single intradermal injection of a suspension of killed *Mycobacterium tuberculosis* in complete Freund's adjuvant (CFA). Experimental evidence suggests that an autoimmune process involving T lymphocytes is responsible for the generation of AA. Another form of autoimmune arthritis can be induced in rats (*4*) and mice (*5*) by immunization with type II collagen, component of joint cartilage. The development of this arthritis is associated with both cell-mediated and humoral immunity to type II collagen (*6*). Immunity to type II collagen has also been detected in human rheumatoid arthritis (*7*) and in AA (*8*).

We investigated the means by which *M. tuberculosis* induces the autoimmune joint damage seen in AA and the role that reactivity to type II collagen might play in the process by isolating and propagating arthritogenic effector cells as T lymphocyte lines. This approach is based on the observation that T cell lines reactive against the basic protein of myelin can both induce and vaccinate against experimental autoimmune encephalomyelitis (*9*). Accordingly, we isolated three T cell lines. From Lewis rats immunized with CFA we selected one line (designated Z1c) for its proliferative reactivity to the purified protein derivative of *M. tuberculosis* and a second line (designated A2) for its reactivity to the whole bacterium. A third line (designated D1) was selected for its reactivity to type II collagen from Lewis rats that had been immunized with rat type II collagen in incomplete Freund's adjuvant.

Table 1 shows the proliferative responses of the three cell lines. Line A2 reacted strongly to *M. tuberculosis*, to a lesser extent to purified protein derivative, and weakly to collagen type II. Despite its low magnitude, the response of line A2 to collagen type II was similar to that of line D1, which was directly selected for reactivity to type II collagen. These relatively low proliferative responses may be the result of the physicochemical properties of collagen fibers (*10*), which could make them weak activators of T cells in vitro. Line D1 did not show any reactivity to *M. tuberculosis* or the protein derivative. Line Z1c showed reactivity to the protein derivative, and to a lesser extent to the bacterium, but not to type II collagen.

We then investigated whether line A2 can induce arthritis or be used to vaccinate against subsequent induction of active AA. Because total body irradiation before inoculation with adjuvant increases the susceptibility of rats to AA (*11*), we inoculated the A2 line into both nonirradiated and irradiated rats. Intravenous inoculation with 2×10^7 untreated A2 cells did not lead to development of arthritis in rats that had been irradiated with 200 R (Table 2). However, inoculation of the A2 cells into rats irradiated with 750 R led to polyarthritis within 6 to 12 days. This arthritis lasted for up to 3 weeks and was characterized by the inflammation and histological features of AA. Irradiation of A2 cells with 1500 R abrogated their ability to cause arthritis in irradiated rats. Control T cell lines selected for their reactivity to the protein derivative (Z1c), to ovalbumin (Cla), or to the basic protein of myelin (Z1a) did not cause arthritis.

These results indicate that specific T lymphocytes reactive against *M. tuberculosis* can induce autoimmune arthritis and that suppressor mechanisms sensitive to radiation can participate in the regulation of arthritis (*11*). Although antibodies to collagen type II may be capable of transferring arthritis to recipient rats (*12*), it is unlikely that the transferred T lymphocytes (negative for immunoglobulin markers) or the heavily irradiated recipients could have produced arthritogenic antibodies. Thus, it appears that the A2 cells themselves mediated the arthritis.

To test whether the A2 line can also vaccinate rats against active AA, we challenged rats with CFA 35 days after they had been inoculated with A2 or

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