PMN J0134—0931: A GRAVITATIONALLY LENSED QUASAR WITH UNUSUAL RADIO MORPHOLOGY

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ABSTRACT

The radio-loud quasar J0134—0931 was discovered to have an unusual morphology during our search for gravitational lenses. In Very Large Array and MERLIN images, there are five compact components with a maximum separation of 0\,\prime\,7. All of these components have the same spectral index from 5 to 43 GHz. In a Very Long Baseline Array image at 1.7 GHz, a curved arc of extended emission joins two of the components in a manner suggestive of gravitational lensing. At least two of the radio components have near-infrared counterparts. We argue that this evidence implies that J0134—0931 is a gravitational lens, although we have not been able to devise a plausible model for the foreground gravitational potential. Like several other radio-loud lenses, the background source has an extraordinarily red optical counterpart.

Subject headings: gravitational lensing — quasars: individual (PMN J0134—0931) — radio continuum: galaxies

1. INTRODUCTION

Gravitationally lensed quasars are rare and valuable astrophysical tools. They can be used to determine the Hubble constant (Refsdal 1964) and place limits on the cosmological constant (Turner 1990; Fukugita, Futamase, & Kasai 1990). The image configuration reveals properties of the matter distribution of the foreground galaxy, including dark matter, and in some cases gravitational magnification reveals interesting details that would otherwise be too faint to observe (for reviews see, e.g., Blandford & Narayan 1992; Wambsganss 1998; Narayan & Bartelmann 1999).

Lenses are usually recognized as such by an unusual morphology in a high-resolution (< 1") image. A quasar that exhibits two or more components in an optical or infrared image is an excellent lens candidate. Likewise, a radio source with more than one compact flat-spectrum component or a radio lobe with a ringlike or arclike morphology is likely to be the result of gravitational lensing.

Such candidates are usually followed up with imaging at multiple wavelengths and/or higher resolution and with optical spectroscopy. The goals are to determine whether the components have identical spectra and surface brightness, as would be the case for lensed images, and to search for evidence of foreground objects that are responsible for the gravitational deflection.

This strategy has been employed by many lens surveys, including our own, which is a radio-based survey of the region 0° > δ > −40°. We used the Very Large Array (VLA) to search for characteristic lensing morphologies in a sample of approximately 4000 radio sources chosen to be flat spectrum between the 4.85 GHz Parkes-MIT-NRAO (PMN) catalog (Griffith & Wright 1993) and the 1.4 GHz NRAO-VLA Sky Survey catalog (Condon et al. 1998). This paper reports the discovery of PMN J0134—0931, the third object in our survey to date that we believe is gravitationally lensed; the other two are J1838—3427 (Winn et al. 2000) and J2004—1349 (Winn et al. 2001).

Independently, J0134—0931 was identified by Gregg et al. (2001) during a search for highly reddened quasars. In a companion paper, they present optical and near-infrared spectra exhibiting quasar emission lines at z = 2.216 and a K-band image revealing at least three components. These authors also argue that the quasar is being gravitationally magnified, and they examine the possible implications of the extreme redness of J0134—0931.

The next section describes the radio properties of J0134—0931. Section 3 describes the near-infrared and optical properties. Section 4 argues the case for gravitational lensing based on this evidence and points out complications of the lensing hypothesis. Section 5 contains a summary and suggests future observations to test the lensing hypothesis and to constrain lens models.

2. RADIO PROPERTIES

2.1. VLA, MERLIN, and ATCA Observations

We selected J0134—0931 as a lens candidate because of its unusual radio morphology. Table 1 provides a summary of our radio observations and also lists the coordinates of J0134—0931. Figure 1 presents radio images with the VLA and MERLIN at frequencies ranging from 5 to 43 GHz. The details of calibration and data reduction are as follows.

For the VLA and MERLIN observations, we interleaved observations of J0134—0931 with the nearby source J0141—0928 in order to calibrate the antenna gains. To
calibrate the absolute flux density scale for the MERLIN data, we observed 3C 286 and assumed a flux density of 7.086 Jy on the shortest baseline. For the VLA observations in 2000 October, we observed J2355+4950 instead; this secondary flux calibrator is monitored monthly by G. Taylor and S. Myers of the National Radio Astronomy Observatory (NRAO) and has been found to have a stable flux density. We assumed the flux densities of this source (in jansky) to be 0.921, 0.602, 0.473, and 0.284 at 8.5, 15, 22.5, and 43 GHz, respectively. Calibration was performed using standard procedures within the software package AIPS. We applied gain-elevation corrections for data at 15 GHz and higher frequencies, based on gain curves prepared by S. Myers.

Imaging was performed with the software package DIFMAP (Shepherd 1997). Five radio components were apparent in each image, except in the 8.5 GHz image, in which four of the components were blended together. In Figure 1 these components are labeled A–E, in decreasing order of flux density. This order is the same in all five images; indeed, the visual appearance of the images suggests that all the components of J0134—0931 have approximately the same radio “color.”

To investigate this point quantitatively, we fit a model consisting of five point components to the visibility function of each data set. We used this model to perform phase-only self-calibration with a solution interval of 30 s. This process of model fitting and self-calibration was repeated (typically 5–10 times) until the model converged. In all cases, the relative separations of the five components (printed in Table 2) agreed within 2 mas.

The flux density of each component as a function of radio frequency is plotted in Figure 2. We computed the best-fit power law $S \propto \nu^p$ for each component. They are all consistent with $p = -0.69 \pm 0.04$ between 5 and 43 GHz. Evidently, the radio continuum spectra of all five components have the same slope. This comparison can be made more precise by comparing the flux density ratios between components at each frequency because these ratios are not affected by the uncertainty in the absolute flux scales. The ratios relative to component D are printed in Table 2. The differences between the ratios measured at different frequencies are less than 5%.

Also plotted in Figure 2 is the total flux density of J0134—0931 over a wider frequency range. The data were drawn from the literature, our VLA and MERLIN measurements described earlier, and our Australia Telescope Compact Array (ATCA) measurements of 2000 September 25. The ATCA measurements were performed when the array was in the 6D configuration and used PKS B1934—638 to set the flux density scale. The total flux density measurements reveal that J0134—0931 is a gigahertz-peaked spectrum (GPS) source with a peak at 2 GHz. The morphology of J0134—0931 is unusual for a GPS quasar, or indeed for any radio source. Although morphologies of GPS quasars are diverse, they are predominantly compact sources, core-jet sources, or linear triples

| Date          | Observatory | Frequency (GHz) | Bandwidth (MHz) | Duration (minutes) | Beam FWHM, P.A. (mas × mas, deg) | rms Level (mJy beam$^{-1}$) | Flux Scale Uncertainty (%) |
|---------------|-------------|----------------|-----------------|-------------------|----------------------------------|---------------------------|---------------------------|
| 1992 Dec 31   | VLA         | 8.440          | 100             | 2                 | 276 × 160, 11                   | 0.24                      | 3                         |
| 2000 Apr 1    | MERLIN      | 4.994          | 15              | 36                | 128 × 39.1, 17                  | 1.2                       | 5                         |
| 2000 Apr 24   | VLBA        | 4.975          | 64              | 60                | 7.3 × 1.5, 25                   | 0.4                       | 5                         |
| 2000 Sep 25   | ATCA        | 1.2–9.0*       | 128             | 2                 | ...                             | ...                       | 5                         |
| 2000 Oct 15   | VLA         | 8.46           | 100             | 10                | 297 × 195, 23                   | 0.15                      | 3                         |
| 2000 Oct 15   | VLA         | 14.94          | 100             | 28                | 139 × 100, 10                   | 0.40                      | 5                         |
| 2000 Oct 15   | VLA         | 22.46          | 100             | 28                | 96 × 76, -23                    | 0.44                      | 10                        |
| 2000 Oct 15   | VLA         | 43.34          | 100             | 28                | 56 × 35, -6                     | 0.68                      | 10                        |
| 2000 Oct 31   | VLBA        | 1.667          | 64              | 240               | 10.2 × 4.0, 5                   | 0.2                       | 5                         |

NOTE.—The J2000.0 coordinates of component A of J0134—0931 are 01°34′05′′667, −09°31′02′′89 within 0′15.

* The ATCA was used to measure total flux densities only, with 2 minute observations at 1.216, 1.344, 1.472, 1.728, 2.240, 2.496, 4.800, 6.080, 8.640, and 9.024 GHz.

| Component | ΔA.R.A. (mas) | ΔDecl. (mas) | Flux Ratio |
|-----------|---------------|--------------|------------|
| A         | −539.62 ± 1.20 | 414.71 ± 1.51 | 5.34 ± 0.13 |
| B         | −618.80 ± 0.84 | 264.02 ± 1.58 | 1.317 ± 0.043 |
| C         | −448.76 ± 1.48 | 382.18 ± 0.69 | 1.140 ± 0.048 |
| D         | 0             | 0            | 1          |
| E         | −263.47 ± 0.67 | 632.79 ± 1.91 | 0.3178 ± 0.0073 |

NOTE.—Figures reported here are the average of the modeling results applied to the VLA and MERLIN data. Each quoted uncertainty is the standard deviation of these results. Flux ratio is relative to D.
Fig. 1.—Radio contour plots of J0134–0931 with the VLA and MERLIN. In all cases, the field of view is $2'' \times 2''$, the image is based on uniform weighting, and the synthesized beam is inset in the lower left of each panel. Contours begin at $3\sigma$ and increase by factors of 2, where $\sigma$ is the rms noise level (see Table 1).
with an angular extent of 10–100 mas (see, e.g., O’Dea 1998; Stanghellini et al. 1997).

Two other characteristics of typical GPS sources are a low level of centimeter-wavelength polarization and low or nonexistent variability of total flux density. The lack of a polarized signal in the MERLIN observations implies that the fractional polarization of the brightest component of J0134−0931 is less than 3%. (The VLA observations were performed from the VLA and MERLIN data, to provide a wide-field overview of the system.

To summarize the main conclusions that we have drawn from the VLA and MERLIN data: (1) J0134−0931 is a GPS radio source. (2) It consists of five compact components in an unusual triangular arrangement with a maximum separation of 0.1”. (3) The spectral indices of the components are the same from 5 to 43 GHz.

2.2. Very Long Baseline Array Observations

We observed J0134−0931 with the Very Long Baseline Array (VLBA) on two separate occasions. On 2000 April 24, we observed for 1 hr at 5 GHz, using eight antennas (the Mauna Kea and Hancock antennas were unavailable). On 2000 October 31, we observed for 4 hr at 1.7 GHz with all 10 antennas. The key parameters of these observations are printed in Table 1. In both cases, the total observing bandwidth of 64 MHz was divided into eight intermediate frequency bands of width 8 MHz, each of which was subdivided into 16 channels of width 500 kHz. The sampling time was 1 s.

Calibration was performed with standard AIPS procedures. We solved for phase delays and rates using a fringe-fit interval of 2 minutes. After fringe fitting, we averaged the data into frequency bins of width 2 MHz and time bins of width 6 s. These values were chosen to reduce the data volume as much as possible while keeping the amount of bandwidth smearing and time-average smearing below 1% over the required field of view.

For imaging, we employed standard AIPS procedures. The process of “cleaning” (deconvolution) and phase-only self-calibration (with a 30 s solution interval) was iterated three times. Figure 3 presents the final images, using uniform weighting. The central panel is not an image; it is merely an illustration of the five-component model developed from the VLA and MERLIN data, to provide a wide-field overview of the system.

We first discuss the 5 GHz data. The four components A–D were detected. Components B and D are nearly unresolved, whereas component A is highly elongated. Component C is barely visible in the image and has a larger angular size (and lower surface brightness) than the other components. Table 3 lists the parameters of a simple model consisting of four elliptical Gaussian components that fits the data fairly well. In this model, component A was represented by two elliptical Gaussians. Component E is absent from the image, although it does appear faintly when the data are reweighted so as to emphasize the shortest baselines.

In general, radio structure that is smooth on an angular scale of greater than 25–30 beamwidths is “resolved out” and will be invisible in VLBA images. In order to gauge whether any of the components are significantly resolved out, we divided the total 5 GHz flux of each component as measured by the VLBA by its 5 GHz flux as measured by MERLIN. The results are 1.00, 0.88, 0.50, and 0.95 for components A–D, respectively, confirming that C is largely

| Component | RA (mas) | Dec (mas) | Flux Density (mJy) | b_{maj} (mas) | b_{min}/b_{maj} | Position Angle (deg) |
|-----------|---------|----------|-------------------|--------------|----------------|---------------------|
| A         | -539.93 | 415.04   | 269.22            | 7.7          | 0.28           | 46                  |
| A         | -542.66 | 409.43   | 78.02             | 20.7         | 0.19           | 30                  |
| B         | -619.64 | 262.95   | 82.47             | 3.7          | 0.21           | 20                  |
| C         | -446.58 | 382.72   | 35.62             | 11.2         | 0.63           | -23                 |
| D         | 0       | 0        | 63.98             | 2.6          | 0.37           | 18                  |

Note: Each component is an elliptical Gaussian with the specified position, flux density, FWHM major axis (b_{maj}), ellipticity (b_{min}/b_{maj}), and position angle (degrees east of north).
resolved out. The nondetection of E implies that its angular size must be larger than about 35 mas. Because E was unresolved in the 5 GHz MERLIN image, the angular size cannot be much larger than 80 mas.

We next discuss the 1.7 GHz image. Figure 3 contains radio contour plots, and Figure 4 is a wide-field gray-scale image. Components B and D are compact, but C and E are completely absent. Component A is very extended and is
connected to B by a curved arc of emission. Furthermore, a dim sixth component is evident to the southwest of D, labeled F in Figures 3 and 4.

In Figure 4, a dotted circle has been drawn through components A, B, D, and F. This illustrates that all four components lie on the same circle and also that the arc joining A and B lies on the circle. Both these properties are strongly suggestive of gravitational lensing (see §4.1).

Table 4 lists the parameters of a simple model consisting of four elliptical Gaussian components. This model provides a decent fit to the image but does not account for most of the flux in the arc. The total flux density of the model is 0.635 Jy, which is 91% of the total flux density in the image (0.696 Jy). Components D and F are elongated toward one another. It is possible that components D and F are connected by an arc, as are A and B, but that the arc is too dim to be evident.

Judging from the total flux densities plotted in Figure 2, the total flux density of J0134—0931 at this frequency is about 1.0 Jy. The 0.3 Jy that is missing from the 1.7 GHz VLBA image is mainly due to the absence of components C and E. These two components would be expected to contribute about 0.2 Jy at 1.7 GHz by extrapolating their flux densities measured at higher frequencies. For these components to be resolved out by the VLBA, their angular sizes must be about 120 mas or larger.

**Figure 4.—Radio image of J0134—0931 with the VLBA at 1.7 GHz. Based on the same data as the left panels of Fig. 3, but here the entire field is shown. The expected positions of components C and E are marked. A dotted circle has been drawn to illustrate the discussion of §2.2.**

| Component | ΔR.A. (mas) | ΔDecl. (mas) | Flux Density (mJy) | $b_{\text{maj}}$ (mas) | $b_{\text{min}}/b_{\text{maj}}$ | Position Angle (deg) |
|-----------|-------------|-------------|-------------------|-----------------|-----------------|------------------|
| A .......... | -540.90     | 412.20      | 406.39            | 51.1            | 0.29            | 43               |
| B .......... | -618.83     | 266.58      | 117.48            | 15.4            | 0.13            | 14               |
| D .......... | 0           | 0           | 100.24            | 3.8             | 0.56            | 28               |
| F .......... | -30.95      | -39.14      | 10.82             | 8.9             | 0.00            | 53               |

**TABLE 4**

*Radio metric Model Based on 1.7 GHz VLBA Data*

Note.—Each component is an elliptical Gaussian with the specified position, flux density, FWHM major axis ($b_{\text{maj}}$), ellipticity ($b_{\text{min}}/b_{\text{maj}}$), and position angle (degrees east of north).
3. OPTICAL AND INFRARED PROPERTIES

3.1. Near-Infrared Counterparts

We obtained an $H$-band image of J0134—0931 on 2000 October 13 at Las Campanas Observatory, using the Cambridge Infrared Survey Instrument (CIRSI) camera mounted on the Cassegrain focus of the du Pont 2.5 m telescope. Four exposures of 30 s were taken at each of five dither positions, making for a total integration time of 10 minutes in the final stacked image. The pixel scale is 0\textquoteleft200, and the resolution in the stacked image is 0\textquoteleft46. A subraster of the stacked image is shown in Figure 5, along with a contour representation.

The $H$-band counterpart is obviously elongated. There is also a dim object 3\textquoteleft to the southwest, which is radio silent in all our radio images. We used the DAOPHOT routines in the software package IRAF\textsuperscript{11} to construct an empirical point-source function (PSF) of diameter 10\textquoteleft using a star 50\textquoteleft west and 78\textquoteleft south of J0134—0931. A contour representation is displayed in the lower right panel of Figure 5. We used this empirical PSF to find the best-fit positions and

\textsuperscript{11} IRAF is distributed by the National Optical Astronomy Observatories, which are operated by the Association of Universities for Research in Astronomy, Inc., under cooperative agreement with the National Science Foundation.

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**Fig. 5.** Top panel: Stacked $H$-band image (30\textquoteleft $\times$ 30\textquoteleft) of J0134—0931 (centered). Lower left panel: Contour plot of the 6\textquoteleft $\times$ 6\textquoteleft region surrounding J0134—0931. Contours begin at 3 $\sigma$ and increase by factors of 2, where $\sigma$ is the rms noise level. Lower right panel: Contour plot of the empirical PSF (see § 3.1).
fluxes of a model with three components (two for J0134−0931 and one for the dim object to the southwest).

In this model, the double representing J0134−0931 had a separation of 613 ± 75 mas, position angle of 126° ± 7°, and flux ratio of 6.3 ± 0.5. The corresponding radio values for components A and D are 681 ± 2 mas, 127:3 ± 0:2, and 5.4 ± 0.1. The other pairings of radio components that agree with the H-band separation are A/F, C/D, and C/F, but in those cases the radio flux ratios do not match the H-band flux ratio at all.

The simplest conclusion is that A and D, at least, have near-infrared counterparts. It is possible that components B and C also have near-infrared counterparts that are merged with A in our image. Indeed, Gregg et al. (2001) present an analysis of a K'-band image of J0134−0931 that supports this interpretation. After performing a maximum entropy deconvolution, these authors conclude that components A, B, and D (at least) have K'-band counterparts.

If J0134−0931 is indeed gravitationally lensed, it is also possible that the foreground galaxy contributes significantly to the total light. These possibilities would complicate the interpretation of the near-infrared images. For the purpose of evaluating possible lensing scenarios, it is important to obtain higher resolution optical or near-infrared images, using adaptive optics or the Hubble Space Telescope.

To establish the zero point for the H-band magnitude scale, we measured the flux of star 9106 described by Persson et al. (1998) within an aperture of diameter 10". The resulting total H-band magnitude of J0134−0931 is given in Table 5 along with the results from measurements through other filters.

### 3.2. Optical Counterpart

On 2000 July 26, we obtained BVRI images of J0134−0931 with the Mosaic II CCD camera at the prime focus of the Blanco 4 m telescope at the Cerro Tololo Inter-American Observatory (CTIO). Each exposure lasted 10 minutes. The seeing varied from 0.8 to 0.9. The images were processed with standard IRAF routines, and the I-band image was deconvolved using a template kindly provided by R. C. Dohm-Palmer. In the I-, R-, and V-band images, the optical counterpart was detected but unresolved. In the B-band image, the counterpart was not detected. A synthetic circular aperture of radius 7" was used to compute instrumental magnitudes of J0134−0931 (after subtracting all neighboring objects within 14").

To place the instrumental magnitudes on a standard photometric system, we also observed the standard stars 355, 360, and 361 from field SA 110 described by Landolt (1992). Our photometric solutions took the form

$$m_{\text{std}} = m_{\text{inst}} + c_1 + c_2 (B_{\text{inst}} - R_{\text{inst}}),$$  \hspace{1cm} (1)

where

$$m_{\text{inst}} = -2.5 \log \left( \frac{\text{counts}}{\text{time}} \right) - k_m \times \text{air mass}.$$  \hspace{1cm} (2)

We adopted “typical” CTIO coefficients of $k_I = 0.06$, $k_R = 0.11$, $k_V = 0.15$, and $k_K = 0.28$. Star 355 was not used for the $I$-band solution because it was overexposed.

Table 5 lists the optical and near-infrared total magnitudes of J0134−0931 in seven filters from B to K, using the observations described in this section and entries from the Two Micron All Sky Survey (2MASS) catalog. Evidently, J0134−0931 is very red, with $V - R = 1.8$, $V - I = 3.7$, and $B - K = 10.8$ (the latter is confirmed by the spectrophotometry of Gregg et al. 2001, who find $B - K \approx 11$). Because the $V - R$ colors of the standard stars range only from 0.36 to 0.72, we caution that the quoted uncertainties in the BVRI magnitudes in Table 5 (which are based only on Poisson noise and do not include errors due to the extrapolation of color terms) may be underestimates.

### 4. GRAVITATIONAL LENSING HYPOTHESIS

#### 4.1. The Case for Lensing

The case that J0134−0931 is gravitationally lensed relies mainly on its near-infrared and radio morphology. Given the spectra of Gregg et al. (2001), which reveal the source to be a quasar, the observation that the H-band counterpart is double (§ 3.1) is by itself powerful evidence for lensing. At optical and near-infrared wavelengths, quasars are almost always observed as unresolved points. Quasars that appear double (with separation of < 3") are the result of (1) a chance superposition between a quasar and a star, (2) a chance superposition of quasars at different redshifts, (3) a binary quasar, or (4) a gravitational lens.

The first possibility is ruled out by the observation that both components are radio loud. The second and third hypotheses are a priori unlikely because radio-loud quasars constitute a minority (<10%) of quasars generally. The observation that components A–E all have the same continuum radio spectrum from 5 to 43 GHz makes the chance superposition hypotheses untenable and casts serious doubt on the binary quasar hypothesis. By contrast, the identity of spectral indices is a natural consequence of gravitational lensing. The maximum component separation of 0:7 is also in the range of angular sizes that are characteristic of gravitational lensing by galaxies (0:5–2"). This angular scale is set by the Einstein ring radius of medium-redshift $L_*$ galaxies.

Furthermore, the milliarcsecond morphology of J0134−0931 is unusual for a GPS quasar, or indeed for any radio source. GPS sources are usually a single core, a compact double, a linear triple, or a core-jet structure (O’Dea 1998). Examples of VLBI observations of GPS

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12 CTIO is operated by the Association of Universities for Research in Astronomy Inc., under a cooperative agreement with the National Science Foundation as part of the National Optical Astronomy Observatories.

13 2MASS is a joint project of the University of Massachusetts and the Infrared Processing and Analysis Center/California Institute of Technology, funded by the National Aeronautics and Space Administration and the National Science Foundation.
sources are given by Snellen, Schilizzi, & van Langevelde (2000). The total angular extent is usually less than 100 mas. By contrast, the five components of J0134—0931 have a much larger separation and are not collinear, which prevents any obvious assignment of the components as cores, lobes, and jets.

The curved arc between components A and B in the 1.7 GHz VLBI image (§ 2.2) is particularly suggestive because the arc is nearly perpendicular to the line from A to D. The magnification due to gravitational lensing often results in lensed images that are stretched tangentially, i.e., stretched along the circular or elliptical critical curve that runs approximately through the images. Some examples are B0218 + 357 (Patnaik et al. 1995), B1422 + 231 (Patnaik et al. 1999), MG 0414 + 0534 (Trotter, Winn, & Hewitt 2000), and B2016 + 112 (Garrett et al. 1997).

In addition, the line joining D and F is nearly perpendicular to the line joining A and D, suggesting that D and F may also be an example of tangential stretching. As pointed out in § 2.2, it is possible that D and F are connected by an arc. In fact, if the A/B arc is extrapolated into a full circle (to approximate a critical curve), the circle intersects both D and F, as shown in Figure 4.

Finally, Gregg et al. (2001) present an additional piece of circumstantial evidence that J0134—0931 is being gravitationally lensed: based on its observed redshift and K-band magnitude, the object would be among the most intrinsically luminous quasars known. This high inferred luminosity is consistent with gravitational magnification.

4.2. Problems with Gravitational Lens Models

An important step in the analysis of newly discovered gravitational lens systems is to devise a plausible model of the gravitational potential of the foreground galaxy and of the background source structure that can account for the observed image configuration. The most common configurations by far are those with two and four lensed images, which can often be modeled by an isothermal elliptical potential that is lensing a single background source. However, the radio morphology of J0134—0931, with at least six components, cannot be produced by such simple models, and we have not been able to devise a completely satisfactory alternative model. In this section, we describe some possible lensing scenarios and the unsatisfactory aspects of each one.

Is it possible that J0134—0931 is a simple two- or four-image gravitational lens and that some of the additional radio components are actually due to the foreground object(s) rather than to the background source? Any such scenario is unsatisfactory because A–E have the same spectral index (§ 2.1), suggesting that they are all related. Furthermore, even if the lens galaxy is assumed to be centered on one of the radio components, or between any two of them, the remaining radio components are not arranged in a typical lensing configuration.

Could all the radio components be images of a single background source? This is unsatisfactory because lensing conserves surface brightness, whereas two of the components (C and E) apparently have a lower surface brightness than the other components (§ 2.2). One would have to invoke a propagation effect that acts differently along the various image paths. For example, interstellar scattering (by plasma that is in either a foreground galaxy or our own Galaxy) might be causing differential scatter broadening of the images. In this scenario, the comparatively large angular sizes of C and E, which caused them to be largely resolved out of our VLBA images, are due to a larger column density of electrons along those image paths. This hypothesis is testable because the angular sizes of the components would be expected to vary as \( \lambda^2 \), where \( \lambda \) is the observing wavelength. Multifrequency VLBI observations that include some short baselines (<10\( \lambda \)) would be helpful.

The other problem with identifying all six components as images of a single background source is that the image configuration cannot be produced with simple lens models consisting of a single galaxy. Nor have we been able to produce the image configuration with models consisting of more than one lens galaxy, although the phase space of parameters in such models is too large to explore comprehensively without at least some prior constraints (e.g., the galaxy positions).

We are therefore led to consider models in which the background source has more than one radio component. GPS quasars commonly have more than one radio component, so this scenario is reasonable. Because the near-infrared counterpart is double, it is tempting to try models in which each background source is doubly imaged. From the 1.7 GHz image alone (Fig. 3), such a model appears plausible. In one scenario, the background source consists of a core and a jet with a hot spot at its end. In one image, the core is B and the hot spot is A; in the other parity-reversed image, the core is D and the hot spot is F.

A lens model consisting of a single isothermal sphere can reproduce the positions of A, B, D, and F almost exactly. However, the predicted magnification ratios in this model are not even close to the observed flux density ratios; the problem is that A is much brighter than F, whereas B and D are of comparable brightness. Any lens model of this type would need to produce a very large magnification gradient between the source locations corresponding to A/F and B/D, which is possible for a source almost perfectly aligned with the foreground galaxy. The main problem with this scenario is that it ignores components C and E.

This situation of having compelling evidence for gravitational lensing but an inability to model the system adequately is frustrating but not unique. For example, the correct model for the well-established three-image lens B2016 + 112 (Lawrence et al. 1984) has been a mystery for over 15 years and may involve two lens galaxies at different redshifts (Nair & Garrett 1997). The lensing scenario for the six-image system B1359 + 154 became clear only after an image with the Hubble Space Telescope revealed that the foreground mass was actually a compact group of three galaxies (Rusin et al. 2001).

5. SUMMARY AND DISCUSSION

We have presented an extensive set of radio, near-infrared, and optical observations of the GPS quasar J0134—0931. The radio morphology is unusual, with at least five components sharing the same radio continuum spectrum between 5 and 43 GHz. At least two of the components have H-band counterparts, strongly suggesting that they are lensed images of a single source. A curved arc of radio emission between two of the components appears to be an example of the tangential stretching that is characteristic of gravitational lensing.

Neither the lensing correspondences between the components nor the foreground mass distribution is clear from
the present data. We suggest three lines of observational inquiry to obtain this information:

Multifrequency high-resolution radio imaging.—Images at many frequencies will allow the angular sizes of components C and E to be measured as functions of wavelength in order to see whether they scale as $\lambda^2$, characteristic of scatter broadening. Images at higher frequencies will further resolve components A, B, and possibly D; the detailed morphology may be valuable in devising lens models. Finally, sensitive images at multiple frequencies will allow the spectral index of the dim component F to be compared to the other components.

Higher resolution optical/near-infrared imaging.—This will establish exactly which radio components have optical counterparts and will test for the presence of a foreground galaxy or galaxies. Finally, it may establish the nature of the dim component southwest of J0134—0931 that was detected in our near-infrared image (Fig. 5).

Optical/near-infrared spectroscopy of the individual components.—Separate spectra of components A and D should verify that they are both quasars at the same redshift. Deep spectra may also reveal the presence of foreground absorbing material and provide its redshift.

Separating the various components at optical wavelengths will probably require the Hubble Space Telescope. Adaptive-optics imaging is a more challenging prospect because there are no particularly bright stars within 30'' to serve as a guide star.

Finally, we note that the optical counterpart of J0134—0931 is extremely red, with $B-K > 10.8$. This places J0134—0931 among the recently recognized population of red quasars that appear in radio surveys but have been missed in optical surveys (see, e.g., Francis, Whiting, & Webster 2000). Several other gravitationally lensed radio sources are also extremely red (e.g., MG 0414 + 0534, MG J1131 + 0456, JVAS B1938 + 666). Gregg et al. (2001), Kochanek et al. (2000), Webster et al. (1995), and Becker et al. (1997), among others, have argued that these quasars are red owing to mechanisms intrinsic to the quasar or host galaxy rather than to foreground objects along the line of sight, and they are connected to a large population of optically obscured active galactic nuclei.

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