15 GHz MONITORING OF THE GRAVITATIONAL LENS MG 0414+0534

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ABSTRACT

We report the results of monitoring the four images of the gravitational lens MG 0414+0534 at 15 GHz. In 35 VLA maps spanning 180 days, we measure root mean square variations in the image light curves of ~3.5% mostly due to variations in the flux density calibration. The flux ratios, which are independent of flux density calibration variations, show root mean square variability of 1%–3%. Extensive simulations of the data analysis process show that the observed variations in the flux ratios are likely to be due entirely to errors in the deconvolution process. It is possible that some of the observed variation is due to the source; however, the signal-to-noise ratio is too small to make a time delay determination using a data set of this size.

Subject headings: cosmology: observations — gravitational lensing — quasars: individual (MG 0414+0534)

1. INTRODUCTION

Well before the first gravitational lens was discovered,Refsdal (1964a, 1964b) pointed out that, given a model of the lensing potential and the redshift of both the source and the lens, a measurement of the difference in optical path length between two images in a gravitational lens could be used to determine the Hubble parameter. More recently, Narayan (1991) has shown that a time delay measurement combined with a model of the lensing potential provides a measure of the angular diameter distance to the lens that is independent of the redshift of the source and cosmological assumptions other than local isotropy and homogeneity transverse to the line of sight. Thus, lens models combined with time delay measurements and lens redshifts can be used to measure the relationship between angular diameter distance and redshift. The measurement of the angular diameter distance–redshift relation at a variety of lens redshifts will allow the comparison of the measured relation to that predicted by cosmological models. Large-scale structure may contribute to the deflection and time delays in strong lensing (Seljak 1994; Bar-Kana 1996), raising the interesting possibility of detecting the effect of large-scale structure in a sample of lenses.

For a time delay measurement we have selected the gravitational lens MG 0414+0534, a source that was culled from the MIT–Green Bank survey (Bennett et al. 1986) in a gravitational lens search (Hewitt et al. 1988) and followed up with optical and radio observations. The object consists of four bright, highly reddened images with very similar radio spectra and optical colors. These characteristics, along with the morphology and relative brightnesses of the images, were taken as early evidence that the object is indeed a gravitational lens (Hewitt et al. 1992). Further study has supported that finding. Katz & Hewitt (1993) confirmed that the close double (components A1 and A2) is indeed a double as predicted by lens models. Optical (I-band) observations at the Michigan-Dartmouth-MIT observatory at Kitt Peak have detected the lensing galaxy at nearly the expected position (Schechter & Moore 1993). Spectroscopy by Angonin-Willame et al. (1994) shows that the spectra of images A1 + A2 and B are similar. Infrared spectroscopy by Lawrence et al. (1995) suggests that the source is a fairly typical quasar that is highly reddened by dust in the lensing galaxy (but see Vanderriest, Angonin-Willame, & Rigaut (1995) and Annis (1993) for other views). A 15 GHz radio image of MG 0414 is displayed in Figure 1.

MG 0414 is well suited to relating time delay measurements to angular diameter distances since the morphology of the system argues for a relatively simple lensing potential (particularly compared to QSO B0957+561). Furthermore, Hubble Space Telescope, VLA, and VLBI studies of the object are underway which have revealed structure that may be used to place constraints on models of the lensing potential (Falco, Lehar, & Shapiro Wilson 1997; Trotter Wilson 1997; Katz, Moore, & Hewitt 1997; Ellithorpe 1995; Patnaik & Porcas 1995).

1.1. Lens Models

Kochanek (1991) has fitted five simple models of the lensing potential in MG 0414 using only the positions of the images as constraints for reasons of computational speed and lack of reliable data on the flux ratios. The models fall into two classes: those in which image B is at a minimum of the time delay surface (models 2, 3, and 4) and those in which it is at a saddle point (models 1 and 5). In order to illustrate the difference between the two classes of models, we show Kochanek’s model 1 (singular isothermal sphere + internal quadrupole) and model 3 (singular isothermal sphere + external quadrupole). Since Kochanek does not publish the fitted source positions, we estimate the source position by computing the source position implied by each observed image. Images A1, A2, and B give consistent estimates of the source position, and we take their average as our estimate (0'0:053, -0'0:050 from the lens center for model 1 and -0'0:13, 0'0:046 for model 3). Figure 2 shows the lensing potentials for both models (from Kochanek’s fits) and our estimated source position. Even though the position angles of the potentials differ by approximately 90°, the radial deflections and therefore the Einstein rings generated by these models are nearly aligned.

Figure 3 displays the time delay surfaces corresponding to the two models. By the Fermat principle, images are
The models that are consistent with the measured flux ratios predict that flux variations should be observed first in image B, then in images A1 and A2, and finally in image C. The model of the system by Hewitt et al. (1992) predicts (for $H_0 = 80$ km s$^{-1}$ Mpc$^{-1}$, $q_0 = 0.5$, empty beam) that images B and A2 lead A1 by 12 and 0.3 days, respectively, and that image C lags A1 by 19 days. It should be noted that the model upon which these estimates are based should be taken to be illustrative only, since it assumes a lens redshift ($z_l = 0.47$) and does not exactly reproduce the observed geometry and flux ratios of the system.

2. OBSERVATIONS

We observed MG 0414 at 15 GHz with the Very Large Array (VLA) starting on 1992 November 8 in its most extended (A-array) configuration, continuing through the second most extended (B-array) configuration, and ending on 1993 May 3. The central frequencies for the two observing bands were the standard VLA $U$-band values of 14.9649 and 14.9149 GHz, each with 50 MHz bandwidth. Each band was observed in both senses of circular polarization, bringing the total observed bandwidth to 100 MHz in each polarization. There were a total of 63 individual observations, each of 0.5–1.5 h duration. The total time spanned by the observing program and the sampling interval of the observations were chosen so that for a reasonable range of the (unknown) lens redshift, at least one delay would be detectable. This program was scheduled into small interstices in the VLA schedule, resulting in observations occurring over a wide range of hour angle and with no particular sampling pattern (see Table 1). We have found that, in practice, an irregular sampling pattern is desirable because it minimizes windowing effects in the time delay analysis.

The VLA is part of the National Radio Astronomy Observatory, which is operated by Associated Universities, Inc., under cooperative agreement with the National Science Foundation.
Some of the observations took place when the source was at very low elevation. These data are problematic, since the projection of the baselines of the array and the resulting large synthesized beam makes deconvolution difficult, and because the atmospheric contribution to phase errors and flux calibration errors is much larger.

3. DATA REDUCTION

The data were reduced using the National Radio Astronomy Observatory's Astronomical Image Processing System (AIPS). After the initial excision of raw data that were clearly corrupted by interference or hardware problems, all data sets were processed by AIPS with a "run file" that applied the same processing to each observation. Complex antenna gains were determined by observations of J0423+013. Refined estimates of the antenna phases were obtained by self-calibration (Cornwell & Fomalont 1989). Observations of 3C 48 were used to set the flux density scale, but in order to use as many of the available baselines as possible, we used a model of the source based on 4 minutes of A-array observation kindly provided by C. Katz.

We used the CLEAN (Hög bom 1974) algorithm implemented within the AIPS task MX (Clark 1980; Schwab 1984) to deconvolve each image. CLEAN is an iterative procedure that, for each iteration, selects the brightest pixel in the map and subtracts a fraction of it multiplied by the dirty beam. As a result, when two point sources are very close together, components tend to fall spuriously between them. This effect becomes particularly troublesome for the B-array data, in which the A1-A2 doublet is barely resolved. Our initial attempts to clean these data resulted in a single bright source located between the two images with flux extending from the center toward the true image positions. When we instead used the knowledge of the relative positions of the components as measured from our A-array maps to constrain CLEAN so that it only attempted to place clean components in 0'12 square boxes centered on each component, we found that the quality of the deconvolution improved as evidenced by comparison of the B-array maps to the A-array maps.

When two point sources are barely resolved, it is difficult to measure their flux densities independently. We attempted to use the AIPS task JMFIT to fit two Gaussians to the A1-A2 double and found a strong covariance between the measured flux densities. Since we have already fitted for the flux densities of each component in the image deconvolution step, we instead measure the flux density of each image by summing the flux density of the CLEAN components in the box centered at the image position. This CLEAN flux density does not reliably measure the total flux density when the clean components do not reliably represent the total flux distribution (e.g., for extended sources). Since all four images in MG 0414 are nearly point-like, the CLEAN components contain essentially all of the flux and can be used directly to get the flux densities. Our flux density measurements were compared to the results of JMFIT by creating artificial data sets with the same uv sampling as typical data and four Gaussian components with parameters measured from our A-array images. Gaussian white noise was added to all visibilities, so that the noise in the image was comparable to the noise measured in the real images. The artificial data sets were deconvolved in exactly the same way as the real data and the resulting images then measured with JMFIT and by our technique. The results are comparable for the case when all images are well resolved (A-array) but in the B-array data, the A1-A2 pair is marginally resolved and our flux densities for those images had a variance smaller than those of JMFIT by a factor of ~ 50.

Weather conditions can make flux calibration at 15 GHz very difficult. The most important effects are varying absorption due to the proximity to the water absorption line at 22 GHz and wind-induced pointing errors of the individual array antennas. For example, we have measured variations in calibrator flux density of a factor of ~ 1.5 over a period of 25 minutes at the beginning of a snowstorm.
(The data from that particular observation are omitted from our analysis.) Since flux calibration errors can substantially affect the results of the analyses to be discussed below, these analyses are carried out using only those observations made when the wind speed was less than 10 m s\(^{-1}\), the object was above 30° elevation, there was no precipitation, and the phase stability of the atmosphere allowed reliable calibration of the complex antenna gains. Of the original 63 observations, three were lost to equipment failures at the VLA site, calibrations for two
were lost to human error at operations, and one was lost to snow filling the dishes. Of the remaining 57 observations, we exclude from analysis five for high wind, eight for precipitation, two for atmospheric phase instability, and seven for low elevation, leaving 35 observations. Table 2 lists the measured flux densities for all components for each of the 35 observations.

Figure 4 displays the measured light curves for all four images in MG 0414. The variability is still clearly dominated by the flux calibration errors caused by variable atmospheric water content, differences in source and calibrator elevations, flux calibrator modeling errors, and weather conditions. Even with these effects, the rms variability in the resulting four light curves (without any adjustment for possible source variability) is only 3.3%−3.9%. Since this includes both source variability and flux calibration errors, the relative flux calibration is at least this good over the whole data set.

4. ANALYSIS

4.1. Variability in the Source

Source variability is prerequisite to the determination of a time delay, but the uncertainties in the flux calibration obscure any evidence for source variability in the light curves of Figure 4. In order to determine whether there is source variability, we compare the variations in the ratios of various images. Figure 5 displays "ratio light curves" in which the flux density of each component is normalized to component B. For comparison, we generated an artificial data set with the same $uv$-sampling as the real data, the average fluxes for the four components of MG 0414 that we measure, and no source variability (created by the AIPS task UVMOD). An estimate of the rms noise (per visibility) was obtained from the phase calibrator observations in the real data, and Gaussian noise of this amplitude was added to the visibilities in the artificial data. This complete artificial data set was then processed with the same run file as the real data. Table 3 displays the rms variability in each flux ratio for both the real data and the artificial data described above. These results demonstrate that uncertainties in the map computation and flux estimation procedures are comparable to the uncertainties in the calibration of the overall flux density scale. Thus, there is no evidence here that any source variability has been detected.

Another measure of variability is the first-order structure function (Simonett, Cordes, & Heeschen 1985),

$$V(\tau) = \frac{1}{T} \langle [s(t) - s(t + \tau)]^2 \rangle,$$

where $s(t)$ is the image flux density at time $t$, $\tau$ is the difference in time between two observations, and the angle brackets indicate the average. We fit the structure function of the log of the radio data in decibels (referred to 1 Jy), adopting a structure function of the form

$$V(\tau) = C \tau^{1.0}.$$

We expect that the structure function of instrumental errors will be that of white noise, so we take the power-law part of the structure function as an estimate of the maximum possible variability in the source and find

$$V(\tau) = \left(0.000139 \text{ decibels day}^{-1}\right) \tau.$$

This implies that the signal-to-noise ratio for a single measurement of a change in flux density on timescales of interest (~20 days) is at most ~0.3.

4.2. Time Delays and Correlated Variability

The data presented above provide no evidence that we have detected variability in MG 0414. However, it is possible that some of the variability in the data is due to the quasar and that such "real" variability would manifest itself as itself in the form of a correlation between flux density measurements separated by the lens time delay. To investigate this, we computed discrete correlation functions (Edelson & Krolik 1988) for pairs of our light curves. No evidence for correlations was found in this analysis.

A time delay detection technique with greater statistical efficiency than cross-correlation techniques has been developed by Press, Rybicki, & Hewitt (1992a, 1992b; see also Rybicki & Press 1992). Here we examine their $\chi^2$ statistic (hereafter PRH $\chi^2$). To apply their method, one assumes (or better, fits for) a flux ratio between two images and then, for each trial delay, creates a combined light curve that consists
of the union of the two light curves with one of them shifted and scaled relative to the other. For each trial delay, we ask how likely (in a $\chi^2$ sense) the combined light curve is to have originated from a process whose variability is described by the assumed structure function. We have performed Monte Carlo simulations by generating 500 trials using the sampling of the data from this work, the delays predicted by the Hewitt et al. (1992) models, the noise measured from the data (assumed to be white Gaussian), and assuming the source variability to be generated by a Gaussian process with the same structure function as that estimated from the data. For comparison, we also performed the same simulation assuming no gravitational lens (i.e., every image is an independent source of Gaussian noise again with the same structure function as that estimated from the data but uncorrelated with the other images). Figures 6 displays a histogram of the absolute minimum of the PRH $\chi^2$ curve on the interval $[-45, 45]$ for every image pair in the presence of the modeled gravitational lens. The simulations show that, given the quality and quantity of the available data and the small (if present) variability of the source, extraction of a time delay is not possible by this technique. Only 22%–31% of the measurements are within $\pm 5$ days of the simulated delay. However, it is clear that the technique is detecting the presence of correlated variability, since the correlated simulations show 3–6 times more measurements within 5 days of the simulated delay than the uncorrelated (no gravitational lens) simulations.

Even given the low signal-to-noise ratio of the present data, the PRH $\chi^2$ method is interesting since it uses all available lag pairs and is thus a very sensitive way to measure correlated variability. Given sufficiently large data sets, one can expect to detect correlated variability even when the signal-to-noise ratio for a single lag pair is less than unity (Hewitt, Chen, & Messier 1995).

From the measured MG 0414 data, one can compute a distinct PRH $\chi^2$ curve for every pair of images using the average flux ratio as an estimate of the true flux ratio. The six curves computed from the present data are displayed in Figure 7. It is clear from examining the PRH $\chi^2$ curves that there is a strong correlation between the light curves at zero lag due to unmodeled errors in the absolute flux calibration and that none of them presents a convincing argument for any particular time delay. This is not surprising. The signal-
Fig. 7.—PRH $\chi^2$ curves for all pairs of components (69 degrees of freedom). Note the prominent feature at zero lag due to flux calibration errors. Also note that some of the curves, particularly those in the right column, exhibit a strong preference for a particular sign of the delay. For ease of comparison, the curves are all plotted with the same vertical scale.

to-noise ratio of 0.3 for the variability as measured in a single lag pair (see § 4.1 above) can be compared to the case of Hewitt et al.'s (1995) MG 1131 + 0456 data for which the same ratio is 0.7. Their simulations of time delay observations in MG 1131 show that 50–100 flux measurements are required for a measurement of the time delay. Clearly this study of MG 0414 suffers because there are too few measured points, given the small signal-to-noise ratio. It is interesting to note that in the cases where the PRH $\chi^2$ curves show a particular preference for the sign of the delay, it is consistent with the predictions of Kochanek's models 2, 3, and 4 (Kochanek 1991) and the Hewitt et al. (1992) model.

5. CONCLUSIONS

Measurement of a time delay from these data is difficult at best because the variability is very small, the small size of the data set gives few lag pairs, and the zero lag correlation caused by errors in flux calibration dominates the PRH $\chi^2$ curves. One could, in principle, modify the statistical model of the data used in the $\chi^2$ analysis to account for the zero-lag correlation of the flux density calibration errors. However, given the limited expectation of a determination of a time delay, we postpone such analysis until a better data set is available. Our current analysis does not provide a convincing case for source variability or for any particular value of a time delay in MG 0414.

Improved experiments for measuring this time delay might use one or more of the following strategies: obtaining a larger dataset, observing at a lower frequency where flux calibration is more precise, or (conversely) observing at a higher frequency where the source is more likely to be strongly variable.

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