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THE FAINTEST RADIO SOURCE YET: EXPANDED VERY LARGE ARRAY OBSERVATIONS OF THE GRAVITATIONAL LENS SDSS J1004+4112

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ABSTRACT

We present new radio observations of the large-separation gravitationally lensed quasar SDSS J1004+4112, taken in a total of 6 hr of observations with the Expanded Very Large Array. The maps reach a thermal noise level of approximately 4 μJy. We detect four of the five lensed images at the 15–35 μJy level, representing a source of intrinsic flux density, after allowing for lensing magnification, of about 1 μJy, intrinsically probably the faintest radio source yet detected. This reinforces the utility of gravitational lensing in potentially allowing us to study nJy-level sources before the advent of the Square Kilometre Array. In an optical observation taken three months after the radio observation, image C is the brightest image, whereas the radio map shows flux density ratios consistent with previous optical observations. Future observations separated by a time delay will give the intrinsic flux ratios of the images in this source.

Key words: gravitational lensing: strong – quasars: individual (SDSS J1004+4112) – radio continuum: galaxies

1. INTRODUCTION

Quasars which are gravitationally lensed by foreground galaxies are important for many different topics in astrophysics and cosmology. These range from determination of the Hubble constant (Refsdal 1964; see, e.g., Kochanek & Schechter 2004; Jackson 2007 for reviews) to the study of the individual lens systems. These studies can be divided into studies of the lensing galaxies, in particular the determination of their dark-matter content and distribution, and studies of the quasars, in which we can probe intrinsically faint objects because of the lensing magnification.

Studies of the lensing galaxies use the positions and flux densities of the lensed quasar images, which probe the gravitational potential at points where the corresponding light ray cuts the lens plane. In favorable cases, constraints on the lens potential can be obtained, notably in the case of CLASS B1933+503 where three components of the background object are lensed (Sykes et al. 1998; Nair 1998; Cohn et al. 2001). Often, however, it is found that smooth models fail to reproduce the observed image fluxes. This was first noted by Mao & Schneider (1998) in the case of CLASS B1422+231, and subsequently the effect was studied in samples of quadruple quasar lens systems (Dalal & Kochanek 2002; Kochanek & Dalal 2004; Metcalf 2002; Chiba 2002). The lack of a good fit is often ascribed to the presence of dark substructure, on scales ranging down to $10^6\,M_\odot$, which is predicted by cold dark matter (CDM) simulations (e.g., Diemand et al. 2008). Fluxes are more sensitive to small-scale irregularities in the mass field than image positions, because they are dependent on the second rather than the first derivative of the potential, although sometimes accurate position information cannot be well fit (e.g., CLASS B0128+437; Phillips et al. 2000; Biggs et al. 2004). The predicted substructure is apparently not seen in our own Galaxy, a phenomenon known as the "missing-satellites problem" (Moore et al. 1999; Klypin et al. 1999), and it may be that star formation in Galactic satellites is suppressed (Bullock et al. 2000). In lensing galaxies, the "substructure" detected through lensing actually exceeds that predicted by CDM, because in the central regions where lensing constraints are available, the substructure fraction is expected to be $<1\%$ (Mao et al. 2004; Xu et al. 2009).

The investigation of flux anomalies in lens systems is currently plagued by small-sample statistics because the most suitable lens systems for study are those relatively small numbers of objects where radio, or other low-frequency, measurements are currently obtainable. The low-frequency emission comes from regions of the source which are relatively extended, and consequently are not subject to microlensing by the stars in the intervening galaxy, which affects the optical fluxes (e.g., Schechter & Wambsganss 2002), or by optical extinction effects. The only effects present, if microlensing is excluded, are the effects of the mass distribution of the lens, together with the combined effect of variability in the source together with relative time delays in the images. There may also be mild effects of scattering (Koopmans et al. 2003). Unfortunately, however, only a dozen radio-loud, quadruply imaged quasars are known, mostly from the CLASS survey (Myers et al. 2003; Browne et al. 2003) but also from deep radio images of less radio-loud sources (e.g., Kratzer et al. 2011). Many authors have attempted to use mid-infrared fluxes instead (Chiba et al. 2005; Fadely & Keeton 2011) as an alternative waveband to study radio-quiet quadruple lens systems, and several further flux-anomalous systems have been detected in this way. In the future, however, the advent of very sensitive radio interferometers such as the Expanded Very Large Array (EVLA) and e-MERLIN, which have μJy sensitivity levels coupled with subarcsecond resolution, will allow study of hitherto "radio-quiet" radio sources. It has been shown by stacking of images from the Faint Images of the Radio Sky at Twenty cm (FIRST) survey (White et al. 2007) that typical radio-quiet quasars of optical I magnitudes of 18–20 should have radio flux densities of a few tens of μJy up to $\sim$150 μJy, very suitable for studies with the new radio arrays. In principle, nearly a hundred new lens systems with known radio flux densities could be found by radio follow-up of known radio-quiet lens systems.

Studies of the sources are also potentially rewarding because the lensing magnification allows us to study quasars at flux density levels which we would otherwise not be able to reach. For example, it is not yet known whether the radio emission mechanism in radio-quiet quasars is similar to that in radio-loud quasars, with a compact core in which jet-like emission is collimated, or whether some other mechanism such as optically thin free–free emission is at work (Blundell & Kuncic

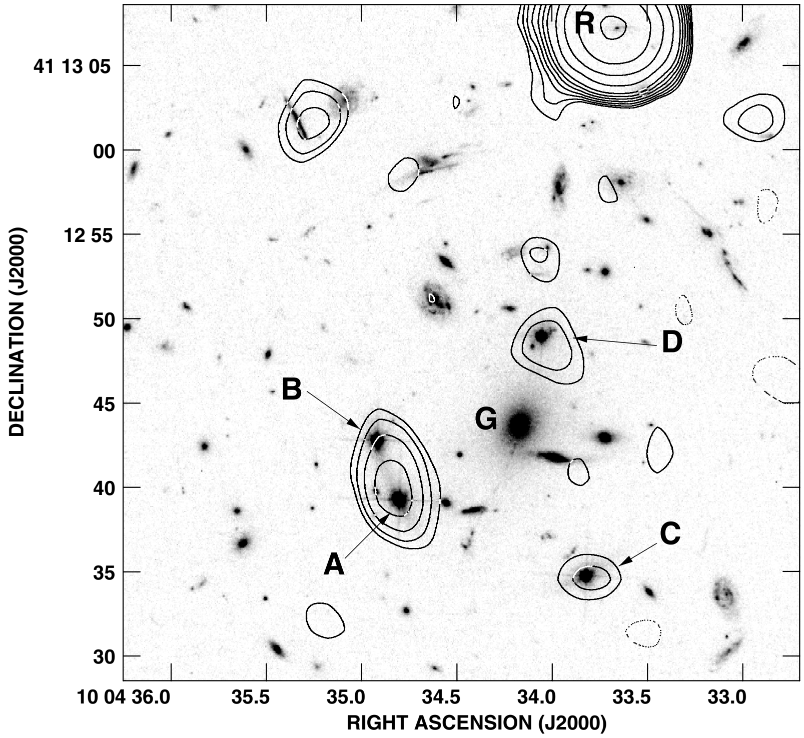

Figure 1. EVLA 4.959 GHz radio contours superimposed on the archival *HST* image of the SDSS J1004+4112 field. Contours are given with a base level of 10 μJy beam^{-1} (approximately 2.5σ) with multiples −1 (dotted), 1, 1.41, 2, 2.82, 4, 5.6, 8, 16, 32, . . . , 1024.

2007). Detailed studies of the radio emission, or comparison of variability properties in radio and optical, may help here. However, the radio faintness of many radio-quiet quasars is a challenge even for modern radio arrays such as the EVLA, and routine observations of these objects may be greatly assisted by choosing a lensed sample containing quasars which are magnified, typically by factors of 5–10.

2. THE GRAVITATIONAL LENS SYSTEM SDSS J1004+4112

As a beginning to such a program, we present new, deep EVLA observations of the lensed quasar SDSS J1004+4112. This system consists of a $z_s = 1.73$ quasar being lensed by a galaxy cluster at $z = 0.68$ into five images, with a maximum separation of 14$''$.6, and was discovered in the Sloan Quasar Lens Survey (Inada et al. 2003; Oguri et al. 2004; Inada et al. 2005) using the catalog of quasars from the Sloan Digital Sky Survey (Schneider et al. 2007). It has been modeled by numerous authors (Williams & Saha 2004; Kawano & Oguri 2006; Saha et al. 2007; Fohlmeister et al. 2007; Liesenborgs et al. 2009; Oguri 2010) using constraints including multiple time delays (Fohlmeister et al. 2007, 2008), spectroscopy of galaxies in the cluster (Sharon et al. 2005), and *Chandra* X-ray observations (Ota et al. 2006). The magnifications of the images are likely to be considerable, with the exception of the central image, E: Oguri (2010) estimates the image magnifications to be 29.7, 19.6, 11.6, 5.8, and 0.16 for A, B, C, D, and E, respectively. Optical microlensing is known to exist in this system (Fohlmeister et al. 2008) and has been used to determine an approximate size for the accretion disk in the source quasar.

3. OBSERVATIONS AND RESULTS

Observations were obtained on four epochs: 2010 October 15, 2010 November 15, 18, and 20 using the EVLA in C-configuration. Each observation consisted of 9 × 370 s scans within a total observing time of 90 minutes, interspersed with observations of a phase calibrator (J0948+4039). This resulted in a total time on source of just under 4 hr. 3C286 was used as an absolute flux calibrator (Baars et al. 1977). All observations were carried out in two contiguous, 128 MHz IF bands, each divided into 64 channels, and centered at 4896 and 5024 MHz.

The data were processed in the NRAO AIPS package. Significant phase slopes across the bandpass were present, which were corrected by fringe fitting to the 3C286 observations. The resulting delay and rate solutions, consisting of delays of typically a few nanoseconds, were applied to the phase calibrator J0948+4039 to check their validity. A few channels at the edge of each IF were deleted, and a bandpass solution was made, again using 3C286. Phase calibration solutions were then derived using J0948+4039. In some epochs, the atmospheric phase varied by up to a radian during the observation, but this could be followed well by the phase calibration observations. Images were made using the AIPS IMAGR routine using Briggs ROBUST = 0 weighting; natural weighting was also attempted but this produced no noticeable improvement in the signal-to-noise while degrading the beam considerably. The final images have a resolution of 3$''$.95 × 3$''$.69 in position angle 58° and the off-source noise level is approximately 3.8 μJy beam^{-1}.

The cleaned map is reproduced in Figure 1, superimposed upon an archival *Hubble Space Telescope* (*HST*) image (GO-10509, PI: Kochanek). The four bright images of the quasar (A–D) are all clearly detected, although the A and B images are only marginally resolved from each other. All the radio components have flux densities between 15 and 35 μJy (Table 1). No radio emission is seen from the main lensing galaxy G, which is also known to contain a faint fifth optical image E. A much brighter radio source, R, is seen about 25$''$ north of G. This has a flux density of 1.4 mJy, but is only marginally visible, at about 0.5 mJy, in the FIRST 1.4 GHz image (Becker et al. 1995). It

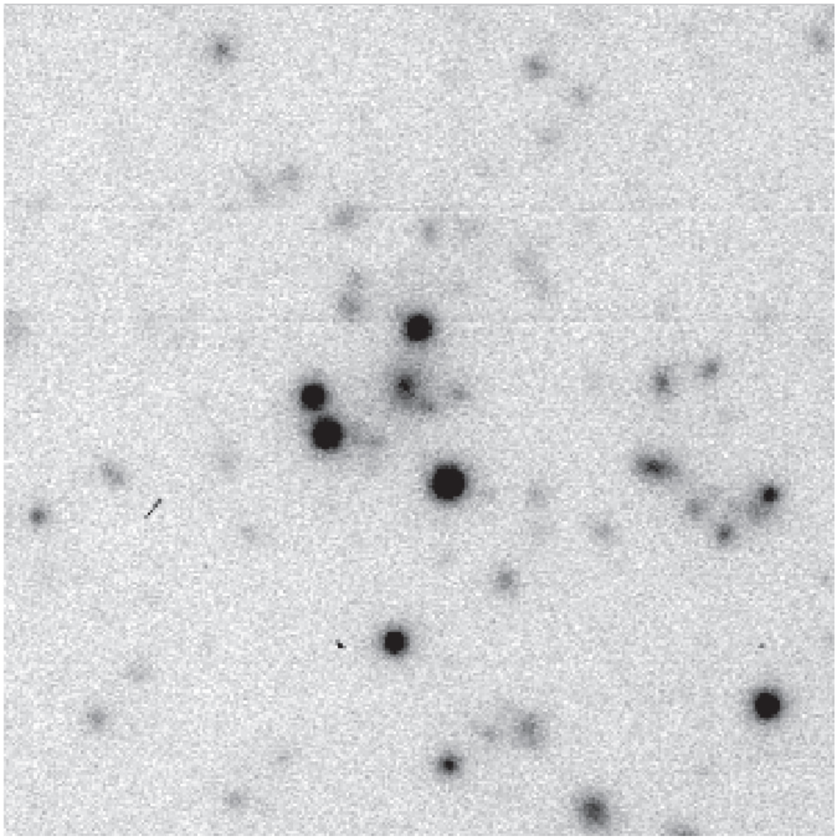

Figure 2. WHT r-band image of J1004+4112, taken on the night of 2011 February 25. Note the relatively much brighter image C compared to the radio image in Figure 1.

Table 1
Flux Densities of the Four Bright Components of SDSS J1004

Cpt.	EVLA $F_{5\,\mathrm{GHz}}/\mu$Jy	μ	Sloan m_g	Sloan m_r
A	34.6 ± 4.4	29.7	20.83 ± 0.03	20.27 ± 0.03
B	21.2 ± 4.4	19.6	21.26 ± 0.03	20.91 ± 0.03
C	16.1 ± 4.4	11.6	20.13 ± 0.03	20.03 ± 0.03
D	18.1 ± 4.4	5.8	20.99 ± 0.03	20.79 ± 0.03

Notes. EVLA 5 GHz flux densities are given in μJy, together with the magnification μ predicted for each image in the model of Oguri (2010). The WHT/ACAM optical fluxes in Sloan g and r magnitudes are also given in the last two columns.

is therefore either highly variable, or else an inverted-spectrum source with $\alpha \sim +0.8$.

Optical imaging observations of J1004+4112 were also made using the 4.2 m William Herschel Telescope on La Palma, on the night of 2010 February 25. The ACAM camera was used and images were obtained in two colors, corresponding to the Sloan g and r filters with 2×300 s exposure in each filter. The r image is presented in Figure 2 and the image flux densities, together with the EVLA radio flux densities, are shown in Table 1.

4. DISCUSSION AND CONCLUSIONS

The current observations are the first of a program which may tell us much both about the lenses and the lensed quasar. The lens can be probed by knowing the intrinsic long-wavelength flux ratios, together with other constraints from previous observations. The nature of the quasar's radio source can be probed by its flux density at different wavelengths, and also by its variability properties in the optical and radio wavebands.

4.1. Flux Ratios and the Lensing Galaxy

In principle, radio observations tell us the intrinsic flux ratios without interference from microlensing effects or extinction. If the radio source is not variable, then the radio flux ratios are consistent with models (see Table 1) except for component D, which is relatively bright. The picture can be complicated by the combined effects of variability and time delay, and in this case also by possible differences in variability characteristics in the two wavebands.

Fohlmeister et al. (2008) present optical monitoring of SDSS J1004+4112 for nearly four years from the end of 2003 until the middle of 2007. Flux variations in the five images are expected to proceed in the order C-B-A-D-E, where the C-A and B-A time delays have been measured by Fohlmeister et al. (2008) as 821.6 ± 2.1 days and 40.6 ± 1.8 days, respectively; they also obtained a lower limit on the A-D delay of 1250 days. Model predictions for this delay include 1218 days by Oguri (2010) and ~2000 days by Fohlmeister et al. (2008). Fohlmeister et al. obtain delay-corrected flux ratios of B to A that vary from 0.283 to 0.460 mag due to microlensing, and in C to A of 0.59 mag. Comparison of the William Herschel Telescope (WHT) optical photometry of 2011 February with Fohlmeister et al. (2008), whose photometry covers the period 2004–2007, implies that components A and B have continued to decline in brightness by about half a magnitude in the last three years. It will be important to use radio observations to derive intrinsic flux ratios free from the effects of microlensing, using further observations separated by the C-B and C-A time delays in the system.

4.2. Flux Level, Variability and the Lensed Object

The detection of significant radio flux density, albeit at a low level, from SDSS J1004+4112 vindicates the prediction of White et al. (2007) that hitherto "radio-quiet" quasars should display significant radio flux when imaged with noise levels of a few μJy, which are now within reach using new radio interferometer arrays such as the EVLA and e-Merlin. It also suggests that the correlation between the *I* band and centimeter-wave radio flux density inferred by White et al. continues down to considerably lower flux density levels than can be probed by FIRST. Moreover, the high magnification of this lens system implies that the intrinsic flux of the radio source is between 1 and 2 μJy, using the model of Oguri (2010). This is probably the lowest intrinsic flux density of any source yet detected in the radio. The current faintest radio sources include the lensed submillimeter galaxy SMMJ16359+6612, detected in deep Westerbork Synthesis Radio Telescope observations by Garrett et al. (2005) and a lensed radio source in the cluster MS0451.6–0305 (Berciano Alba et al. 2010), both of which have unlensed flux densities of about 3 μJy. Similar, or slightly brighter, detections have been reported in other lensed submillimeter galaxies (e.g., Ivison et al. 2010). Other faint radio lenses may emerge from candidates in the COSMOS field (Faure et al. 2008; Jackson 2008) in which deep radio maps have been made (Schinnerer et al. 2007) but no other lensed quasars are yet reported with such low intrinsic radio fluxes. Such a radio source, if unlensed, would require about a week of observing time using the EVLA when it is fully completed with the full 2 GHz bandwidth, in order to achieve a significant detection. In this object, we can therefore use gravitational lensing for detailed study of an intrinsically weak radio source at a level which will only become routine in unlensed sources with the advent of the Square Kilometre Array in the next decade.

One immediate objective that can be resolved soon is the variability of the radio source. The pattern of the radio source variability depends on the nature of the radio source, and in particular whether radio-quiet quasars such as SDSS J1004+4112 produce radio emission with a standard black hole/jet, as in stronger sources, or with a different mechanism such as optically thin free–free emission (Blundell & Kuncic 2007) from a disk wind. In the latter case we might expect radio variability to be associated with the variability of the optical emission from and around the disk. Variability properties of such faint quasars are unknown, although Barvainis et al. (2005) find similar variability properties in samples of radio-loud quasars and quasars with radio flux densities $\sim$1 mJy.

A remarkable feature of the present observations is the relative brightness of C compared to the other components in the 2011 February optical observations, being then 0.24 mag brighter than A, despite the 2010 November radio flux being less than that of A by a factor of approximately two. A 1 mag brightening in such a short period has not previously been seen in optical monitoring data. Either C is currently undergoing a high-magnitude microlensing event or a high-amplitude episode of intrinsic variability is currently taking place.

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Facilities: EVLA, ING:Herschel(ACAM)

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Erratum: "The Faintest Radio Source Yet: Expanded Very Large Array Observations of the Gravitational Lens SDSS J1004+4112" (2011, ApJL, 739, L28)

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The flux scale of the radio measurements of SDSS J1004+4112 is in error, being low by a factor of 1.85. The source of the error is almost certainly the inclusion of an extra solution table in the overall calibration, which had the effect of leaving the flux calibrator, 3C286, unaffected, but affected the bootstrapping of the point-source calibrator flux and hence the flux density of the target. This has the following consequences:

Both in the abstract and in Section 3, the thermal noise level of the maps is about 7 μJy, the lensed images are detected at the 30–65 μJy level, and the intrinsic flux density of the source is about 2 μJy, rather than 4 μJy, 15–35 μJy, and 1 μJy, respectively. In Section 3, the radio source R is 2.8 rather than 1.5 mJy, and the bottom contour of Figure 1 is 18.5 μJy beam^{-1} rather than 10. The ratios of the image fluxes are unchanged.

Finally, the correct version of Table 1 is shown here.

Table 1
Flux Densities of the Four Bright Components of SDSS J1004

Cpt.	EVLA ($F_{5\mathrm{GHz}}/\mu$Jy)	μ	Sloan m_g	Sloan m_r
A	64 ± 8	29.7	20.83 ± 0.03	20.27 ± 0.03
B	39 ± 8	19.6	21.26 ± 0.03	20.91 ± 0.03
C	30 ± 8	11.6	20.13 ± 0.03	20.03 ± 0.03
D	33 ± 8	5.8	20.99 ± 0.03	20.79 ± 0.03

Note. EVLA 5 GHz flux densities are given in μJy, together with the magnification μ predicted for each image in the model of Oguri (2010). The WHT/ACAM optical fluxes in sloan g and r magnitudes are also given in the last two columns.

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