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INTERSTELLAR BROADENING OF IMAGES IN THE GRAVITATIONAL LENS PKS 1830−211

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ABSTRACT

The remarkably strong radio gravitational lens PKS 1830−211 consists of a 1″ diameter Einstein ring with two bright compact (milliarcsecond) components located on opposite sides of the ring. We have obtained 22 GHz Very Long Baseline Array (VLBA) data on this source in order to determine the intrinsic angular sizes of the compact components. Previous VLBI observations at lower frequencies indicate that the brightness temperatures of these components are significantly lower than 10^{10} K (Jauncey et al.), less than is typical for compact synchrotron radio sources and less than is implied by the short timescales of flux density variations. A possible explanation is that interstellar scattering is broadening the apparent angular size of the source and thereby reducing the observed brightness temperature. Our VLBA data support this hypothesis. At 22 GHz, the measured brightness temperature is at least 10^{11} K, and the deconvolved size of the core in the southwest compact component is proportional to ν^{-2} between 1.7 and 22 GHz. VLBI observations at still higher frequencies should be unaffected by interstellar scattering.

Subject headings: galaxies: individual (PKS 1830−211) — gravitational lensing — scattering

1. INTRODUCTION

The Einstein ring gravitational lens PKS 1830−211 is one of the strongest compact radio sources in the sky, nearly 2 orders of magnitude brighter at radio frequencies than any other known gravitational lens (Rao & Subrahmanyan 1988; Jauncey et al. 1991). The source consists of a pair of bright compact (milliarcsecond) components on opposite sides of a 1″ diameter ring of emission. Both compact components have been imaged with VLBI at 1.7 GHz (D. L. Jones, unpublished), 2.3 GHz (Jauncey et al. 1991; King et al. 1993), 5 GHz (Jones et al. 1993; Jones 1994), and 22 GHz (Jones et al. 1995 and this paper). Variations in the morphology of both compact components have been seen between two VLBI epochs at 5 GHz (Jones 1994). The extragalactic nature of PKS 1830−211 was confirmed by Galactic H I emission and absorption measurements (Subrahmanyan, Kesteven, & te Lintel Hekkert 1992).

The large radio flux density of PKS 1830−211 has allowed a large quantity of high signal-to-noise ratio single-dish and interferometric data to be obtained (e.g., Subrahmanyan et al. 1990; Jauncey et al. 1992, 1993; van Ommen et al. 1995; Lovell et al. 1995). This wealth of observational information provides strong constraints on the geometry of the lens system and may lead to an accurate estimate of the large-scale value of H_0 when combined with redshifts and the differential time delay between the two images.

The overall morphology of the source has been modeled successfully as a background core-jet radio source lensed by a single medium-mass galaxy (Kochanek & Narayan 1992; Nair, Narasimha, & Rao 1993). An optical redshift for the background source is still unavailable because the position of PKS 1830−211 is close to the Galactic center ($l = 12\overset{\circ}{.}2$, $b = -5\overset{\circ}{.}7$) in a region crowded with foreground stars (Djorgovsky et al. 1992; Jauncey et al. 1993). However, the redshift of the lensing galaxy has been determined recently from radio absorption line observations (Wiklind & Combes 1996). The time delay between the two compact components has been estimated as 44 ± 9 days by van Ommen et al. (1995) based on multiepoch VLA images. Proposed observations with the Japanese VSOP spacecraft could improve the accuracy of the time-delay determination.

One of the aspects of this source that has been difficult to explain is the unusually low brightness temperatures of the two compact components. The total flux density varies by factors of more than 2 on timescales of months and years (Lovell et al. 1995), which implies a smaller angular size and higher brightness temperature than seen in VLBI images at frequencies ≤ 5 GHz. Since the line of sight to PKS 1830−211 passes close to the Galactic center, it is plausible that significant interstellar scattering (ISS) within our Galaxy may occur along this line of sight. Scattering by the interstellar medium (ISM) in the lensing galaxy will be far less significant than ISS within our Galaxy (Walker 1996). The effects of ISS decrease rapidly with frequency and should be significantly smaller at 22 GHz.

2. OBSERVATIONS

We observed PKS 1830−221 with the full Very Long Baseline Array (VLBA) at 22 GHz in 1994 May. The data were correlated twice in Socorro, using phase centers corresponding to the locations of the two compact components, which we designate the northeast (NE) and the southwest (SW) components. The observations were inadvertently made in dual-polarization mode, which resulted in much less suppression of the component far from the phase center (by decorrelation over the observing bandwidth) than expected. As a result, it was necessary to include both compact components in the imaging process. After manual phase calibration,

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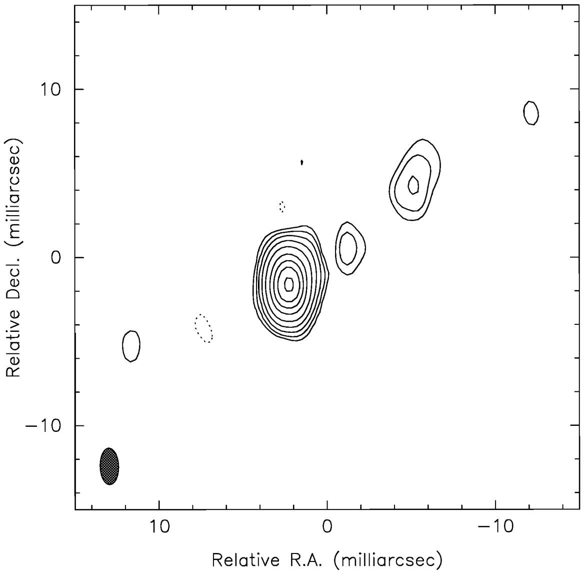

FIG. 1.—VLBA image of the NE compact component in PKS 1830−211 at 22 GHz. The contours are −1%, 1%, 2%, 4%, 8%, 16%, 32%, 50%, 70%, and 95%, and the restoring beam (*bottom left-hand corner*) is an elliptical Gaussian with FWHM of 2.2 × 1.1 mas and the major axis along position angle 1°.5. The absolute flux density scale is not well calibrated, but this changes only the peak brightness level of the image and not the morphology of the source.

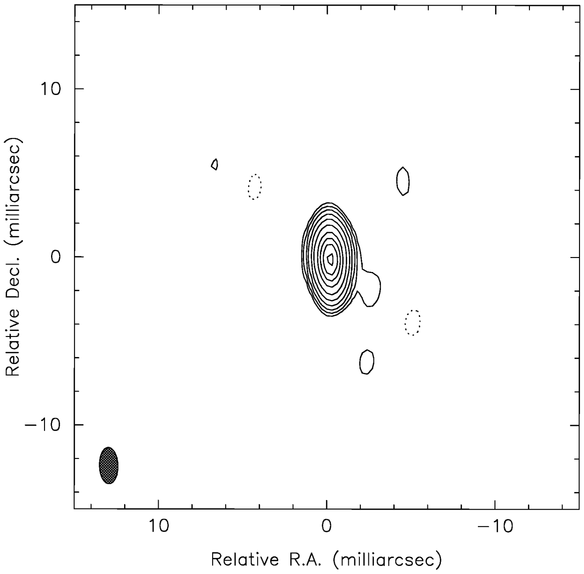

FIG. 2.—VLBA image of the SW compact component in PKS 1830−211 at 22 GHz. The contours are −0.5%, 0.5%, 1%, 2%, 4%, 8%, 16%, 32%, 50%, 70%, and 95%, and the restoring beam is the same as in Fig. 1.

amplitude calibration, and fringe fitting in AIPS,[5] we used the Caltech program DIFMAP (Shepherd, Pearson, & Taylor 1994) for editing, self-calibration, imaging, and deconvolution. The data were coherently averaged to 15 s, and the errors were estimated from the scatter of the 1 s data points within each averaging interval.

Phase-only corrections were applied during each cycle of self-calibration, Fourier inversion, and deconvolution until the model flux density matched that of the visibility data on the shortest baselines to within a few percent. At that point, time-independent antenna gain corrections were allowed (these corrections were ≤12% for all antennas) for several cycles, followed by time-dependent gain corrections with decreasing timescales, until full point-by-point amplitude self-calibration was applied. The self-calibration solutions remained very stable from one cycle to the next. The final agreement factor (reduced χ^2) between our model and the self-calibrated data was 0.86.

3. RESULTS

Figures 1 and 2 show our VLBA images of the NE and SW components of PKS 1830−211, respectively. The NE component appears to have a jet extending at least 12 mas toward the NW, and a bright core that is slightly extended toward the NW as well. The SW component appears to be very nearly unresolved. Recent 15 GHz VLBI observations by Garrett et al. (1995) confirm that the NE component has a well-defined jet as well as a core, while the SW component is essentially unresolved (see also Patnaik & Porcas 1995). The SW component in PKS 1830−211 is the more compact of the two bright components at all frequencies and, consequently, is the best one to use as a test for ISS broadening. The 22 GHz image of the SW component shown in Jones et al. (1995) has slightly higher angular resolution but significantly lower dynamic range than the image in Figure 2.

The angular separation between the brightest peaks in Figures 1 and 2 is 972 ± 1 mas. VLBI observations of PKS 1830−211 at 5 GHz in 1990 November and 1991 September indicated angular separations of 975 ± 2 and 973 ± 2 mas, respectively (Jones et al. 1993). Thus, we find no evidence for a significant change in separation over 3.5 yr. As Williams & Saha (1995) point out, centroid shifts caused by microlensing should not be detectable in radio images.

Figure 3 shows the deconvolved minor axis width of the SW component at four frequencies: 1.7 GHz (unpublished data from an ad hoc VLBA experiment in 1990), 2.3 GHz (King

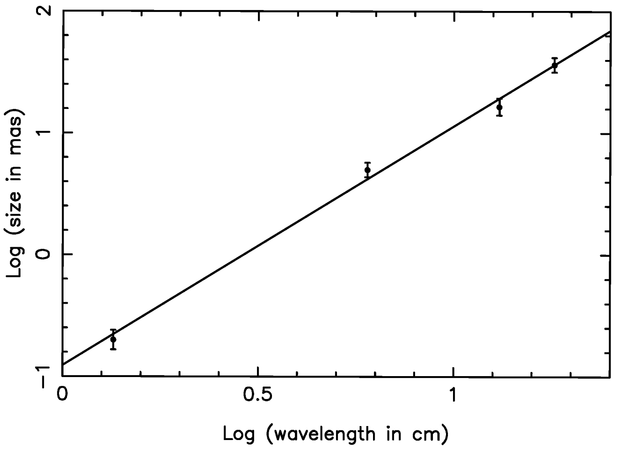

FIG. 3.—The deconvolved minor-axis angular size of the SW component core at 22 GHz (λ = 1.3 cm), 5 GHz (λ = 6 cm), 2.3 GHz (λ = 13 cm), and 1.7 GHz (λ = 18 cm). The deconvolved sizes and their (formal) errors at 22, 5, and 1.7 GHz were determined with the AIPS program IMFIT, using only the upper 50% of the brightness range in order to avoid bias by any extended low-level structure. The size at 2.3 GHz is taken from King (1995). A least-squares linear fit to the data points is shown; this line has a slope of 1.96 ± 0.14.

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[5] The Astronomical Image Processing System was developed by the National Radio Astronomy Observatory, which is operated by Associated Universities, Inc., under a cooperative agreement with the National Science Foundation.

1995), 4.9 GHz (Jones 1994), and 22 GHz (this paper). Deconvolved sizes are used to remove (or at least reduce) the bias in observed angular sizes that is introduced by the limited range of baseline lengths in each VLBI array. We compare the minor-axis sizes because intrinsic source structure is more likely to contribute to the major-axis size. The slope of the line fit to the angular size measurements in Figure 3 is 1.96 ± 0.14, consistent with the λ^2 dependence expected for scattering. This suggests that angular size measurements made by VLBI at frequencies ≤22 GHz are indeed affected by angular broadening due to ISS.

At 22 GHz, the deconvolved size of the SW component core is less than 0.6 × 0.2 mas and $T_b \geq 10^{11}$ K. This is much more typical of the brightness temperatures seen in other extragalactic compact radio sources.

4. DISCUSSION

The amount of ISS expected for a line of sight passing close to the center of our Galaxy can be estimated from the measured angular broadening of isolated H_2O maser features in W49N and Sgr B2. Gwinn, Moran, & Reid (1988) found minimum angular sizes of 0.2 mas in W49 and 0.3 mas in Sgr B2. This is consistent with our measured angular size of the SW component core in PKS 1830−211 at 22 GHz. Gwinn et al. (1988) also found that OH masers in W49 and Sgr B2 had angular sizes consistent with $\Theta \propto \lambda^2$ when compared with $H_2 0$ maser sizes in those objects.

It is interesting to compare our measurements with those predicted by the Blandford & Narayan (1985) formula for ISS:

$$\Theta_{\rm ISS} \sim 2(C_n^2)^{3/5}\lambda^{11/5}D^{3/5} \text{ arcsec},$$

where λ is the wavelength in meters and D is the path length through the ISM in kiloparsecs. C_n^2 gives the strength of electron density fluctuations in the ISM. Anantharamaiah & Narayan (1988) find $C_n^2 \approx 1.5$ for low Galactic latitudes and $|l| \leq 30°$; we use a value of 1 since the Galactic latitude of PKS 1830−211 ($-5\overset{\circ}{.}7$) is not very small. Setting $\lambda = 0.013$ m and $D \approx 5$ kpc (the path length for $|b| = 5\overset{\circ}{.}7$ through a plane parallel ISM with a height of 500 pc) gives us $\Theta_{\rm ISS} \approx 0.4$ mas. This is also consistent with our angular size determination for PKS 1830−211.

Future work may allow this analysis to be extended to the core of the NE component. This will be more difficult because of the higher level of extended emission associated with the NE component, particularly very close to the brightest peak. If we can determine the degree of angular broadening of the NE component core due to ISS, we will have an opportunity to study differences in the scattering properties of our Galaxy's ISM at multiple frequencies along two lines of sight 1″ apart. The results presented here also suggest that still higher frequency VLBI observations of PKS 1830−211 will be useful, since the intrinsic angular size of the radio source core is still not causing a significant deviation from the $\theta \propto \lambda^2$ relation at 22 GHz.

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