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PKS 1830−211: A POSSIBLE COMPOUND GRAVITATIONAL LENS

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ABSTRACT

Measurements of the properties of gravitational lenses have the power to tell us what sort of universe we live in. The brightest known radio Einstein ring/gravitational lens PKS 1830−211, while obscured by our Galaxy at optical wavelengths, has recently been shown to contain absorption at the millimeter waveband at a redshift of 0.89. We report the detection of a new absorption feature, most likely due to neutral hydrogen in a second redshift system at $z = 0.19$. Follow-up VLBI observations have spatially resolved the absorption and reveal it to cover the NE compact component and part of the lower surface brightness ring. This new information, together with existing evidence of the unusual VLBI radio structure and difficulties in modeling the lensing system, points to the existence of a second lensing galaxy along our line of sight and implies that PKS 1830−211 may be a compound gravitational lens.

Subject headings: galaxies: distances and redshifts — galaxies: individual (PKS 1830−211) — gravitational lensing

1. INTRODUCTION

The strong, ~10 Jy, flat-spectrum radio source PKS 1830−211 was first suggested to be a gravitational lens by Rao & Subrahmanyan (1988). Three years later the source was identified as an Einstein ring/gravitational lens (Jauncey et al. 1991) and remains the brightest such object found in the radio sky by almost 2 orders of magnitude. While the interpretation of the source as a gravitational lens beyond the Galaxy (Subrahmanyan, Kesteven, & te Lintel Hekkert 1992) is secure, it lies in a crowded and heavily obscured field close to the Galactic Center, and so far all efforts to identify optical or infrared counterparts either for the lensing galaxy or the lensed source have been unsuccessful (Djorgovski et al. 1992; Jauncey et al. 1993). In particular, the failure of optical measurements to furnish any redshifts has driven the search for these critical parameters into the radio spectrum.

The symmetric morphology of the source, comprising two compact, flat-spectrum components of similar brightness located on opposite sides of a 1″ ring, immediately suggests a close alignment of the lensed source behind the lensing mass. Moreover, there is evidence of unusually high rotation measures in some parts of the source, which argues that the lensing galaxy is probably a gas-rich spiral (Nair, Narasimha, & Rao 1993) and suggests the possibility of detecting molecular absorption.

2. OBSERVATIONS AND INTERPRETATION

Accordingly, we undertook a survey on 1995 June 10 and 11 for redshifted H I and OH absorption with the Parkes 64 m radio telescope, as part of a cooperative observation programme with the Project Phoenix group (Tarter 1996). The Project Phoenix receiver and signal processing equipment were used to cover a frequency range of 995–1675 MHz, nicely complementing a previous absorption search over the frequency range 400–1000 MHz at Green Bank, which yielded a negative result (McMahon et al. 1993). Our observations excluded the two intervals 1535–1635 and 1165–1175 MHz because of excessive interference. Although interference of both terrestrial and satellite origin was profuse over most of the remaining band, it was generally of very narrow bandwidth and easily recognizable, and did not greatly impede the search.

We detected only a single absorption feature with two subcomponents of similar amplitude, centered at 1191.1 MHz with an overall line width of approximately 50 km s^{-1} (Fig. 1*a*). The absorption feature was detected with comparable strength on 2 consecutive days. On the second day, observations of PKS 1830−211 were bracketed with those of PKS 1921−293, a nearby source of similar flux density. No evidence of the absorption feature was seen in this comparison source.

VLBI observations were made on 1995 September 18 with four telescopes of the Australian Long Baseline Array (LBA) (Preston et al. 1993; Jauncey et al. 1994); Hobart, Coonabarabran, Parkes, and five antennas of the Australia Telescope Compact Array (ATCA) acting as a phased array. S2 recorders (Wietfeldt et al. 1991) were used, operating in dual polarization (LCP and RCP) with 4 MHz bandwidth centered on 1191.0 MHz. Correlated visibilities between all six antennas of the ATCA were also recorded to produce an improved total-power spectrum (Fig. 1*b*).

PKS 1830−211 was observed over an 8 hr period interleaved with a bandpass calibrator. The VLBI data were correlated at the ATNF VLBI correlator (Wilson, Roberts, & Davis 1996). No correlated flux was detected on the long (>4 Mλ) baselines to Hobart owing to interstellar scattering at this frequency (Jones et al. 1996).

Our VLBI image in Figure 2 is similar to an earlier 2.3 GHz VLBI image (Jauncey et al. 1991) and shows the two compact components of PKS 1830−211, but little of the low brightness ring that is heavily resolved at this resolution. Figure 2 also shows the absorption spectrum of each component, clearly demonstrating that the two velocity components of the absorption system obscure different parts of the source. The low

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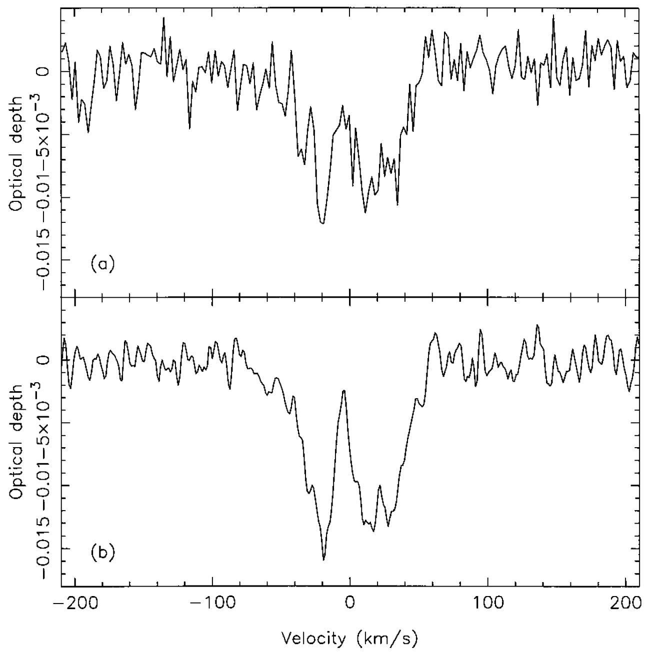

FIG. 1.—(*a*) Discovery spectrum taken at Parkes with the Project Phoenix SETI Receiver. (*b*) Confirmation spectrum taken with the ATCA during our VLBI observations. The velocity scale on the horizontal axis assumes H I as the molecular species.

velocity component is also heavily resolved and therefore must be obscuring only the extended ring while the high-velocity component is resolved only partially and covers the NE component but is weak or absent in the SW component. This, together with a comparison of the relative optical depths in Figures 1 and 2, also allows us to infer that the angular size of the absorbing features must be greater than a few tenths of an arcsecond.

A molecular absorption system at a redshift of 0.88582 has already been found in this source (Wiklind & Combes 1996a), and is argued to arise in an intervening galaxy rather than in the lensed object. This has been confirmed by observations with the BIMA array which have spatially resolved the $z = 0.89$ absorption (Frye, Welch, & Broadhurst 1997). We believe that our detection constitutes a second absorption system in PKS 1830−211 and is probably H I absorption in an intervening galaxy at a redshift of 0.1926 ± 0.0001. In support of this we note that there are no cataloged lines near 2246 MHz, the rest frequency of our observed absorption if it belongs to the $z = 0.89$ system. Further, we observed the bright Galactic sources Sgr B2, Ori KL, and IRC 10216 with the 26 m telescope at Hobart to search for a possible unlisted transition at this frequency, and detected nothing above an rms noise level of ~0.1% of the continuum. Moreover, our detection appears to lie mainly in front of the NE component whilst the $z = 0.89$ absorption is confined to the SW component (Wiklind & Combes 1996a; Frye et al. 1997). Our absorption feature also displays velocity structure not seen in the $z = 0.89$ absorption profiles.

The interpretation of the feature in Figure 1 as OH is unlikely for two reasons. First, the spectra show none of the "satellite" profiles typical of OH absorption and second, we see no evidence of absorption at 1016 MHz corresponding to H I at the same redshift, which we would expect to be clearly visible. Neither can this be a hydrogen recombination line as we would have detected many such lines across the band and did not.

Wiklind & Combes (1996b) report no evidence of molecular absorption in PKS 1830−211 at $z = 0.19$ in their SEST observations. However, this is not totally unexpected, since the total solid angle subtended by the source at these high frequencies is small (~1 mas^2) and hence the probability of intersecting a dense molecular cloud along the line of sight is presumably small.

The absorption feature seen in Figure 1 is very similar in both width and column density to that found in the lens system

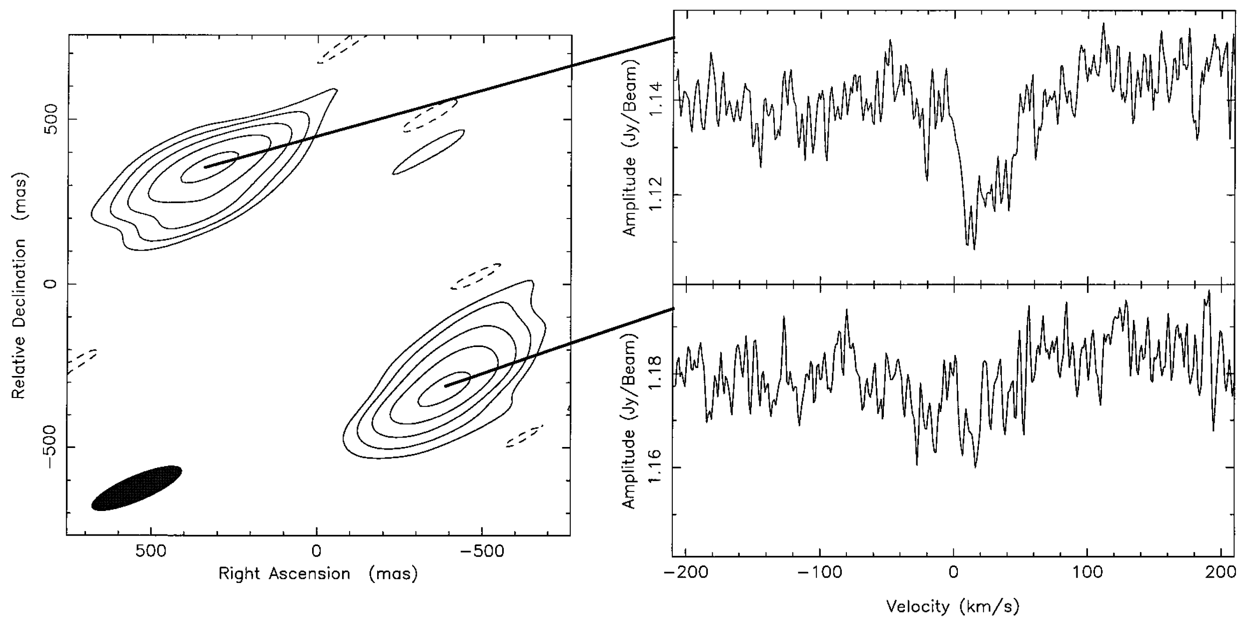

FIG. 2.—Our VLBI continuum map of PKS 1830−211 (*left*). The restoring beam is 294 by 75.2 mas and the contours are at −5%, 5%, 10%, 20%, 40%, and 80% of the map peak, which is 1.27 Jy per beam. Also shown here are the spectra at the positions of the two continuum components (*right*).

0218+357 (Carilli, Rupen, & Yanny 1993), which is convincingly argued to arise from H I absorption in the lensing galaxy, probably a spiral galaxy seen nearly edge-on. We favor a similar interpretation for the absorption in PKS 1830−211, with the line of sight intercepting several H I clouds in a gas-rich galaxy at $z = 0.19$. The two features seen in the absorption profile may well correspond to two spiral arms of ∼kpc scale seen nearly superposed, both of which partially obscure the ring and one of which obscures the NE compact component. Such a picture is entirely consistent with the properties of H I clouds and galaxy dynamics observed within our own Galaxy.

Independent evidence for a considerable amount of material along the line of sight is suggested by the unusually high rotation measure seen in the NE component (Nair et al. 1993; Subrahmanyan et al. 1990). Furthermore, the observed downturn in total flux density of PKS 1830−211 below 1 GHz (Rao & Subrahmanyan 1988) implies significant free-free absorbing material obscuring the noncompact structure, which has a steep spectrum and cannot be synchrotron self-absorbed.

3. PKS 1830−211 AS A COMPOUND GRAVITATIONAL LENS

While the H I absorption toward PKS 1830−211 indicates the presence of a galaxy at $z = 0.19$, this does not infallibly imply a priori that gravitational lensing is taking place at this redshift, any more than it does for the $z = 0.89$ system. That lensing of some kind is taking place is beyond dispute given, for example, the near-simultaneous variation seen in the flux density variations of the two compact components (van Ommen et al. 1995), apparently separated by more than ∼10 kpc: a most improbable effect in any nonlensed interpretation. It seems almost certain, therefore, that at least one of the two redshift systems at $z = 0.19$ and $z = 0.89$ is partaking in the lensing, and there is further evidence that both systems may be involved.

First, the lens evinces a quite paradoxical appearance at high resolution. VLBI images made over a 3 year period (Jones et al. 1993; Garrett et al. 1996) show the SW component to be unresolved at ∼milliarcsecond resolution, while the NE component shows a well-resolved linear structure. This difference in morphology of the two components is too long-lived to be due to the difference in propagation times to the two components, estimated to be no more than a few tens of days (Nair et al. 1993; van Ommen et al. 1995). The results presented here suggest that the second absorption system at $z = 0.19$ may be responsible for this striking disparity in the two images by causing additional lensing distortion of the NE image, thus forming a compound gravitational lens. The alternative explanation that scattering by a high gas concentration in front of the NE component is causing the additional linear structure is ruled out as there is no λ^2-dependence on the length of this feature in the 5 and 15 GHz images (Jones et al. 1993 and Garrett et al. 1996, respectively). Second, attempts to model PKS 1830−211 with a single, simple gravitational potential have achieved only modest success, and have produced markedly different models. The models developed by Nair et al. (1993) and by Kochanek & Narayan (1992), for example, differ in a number of material respects, not least in the time delay between the two compact components, which has the opposite sign in the Nair et al. model to that inferred from the Kochanek et al. model.

The presence of a second lensing galaxy in this system adds an extra layer of complexity to any lensing model. This galaxy is likely to influence the light travel time through the NE component and so must be considered before H_0 can be determined from the time delay. It is important therefore to estimate the mass and position of the $z = 0.19$ system. We are unable to obtain this information from our data. However, polarization images of PKS 1830−211 at two or more frequencies to map rotation measure would help delineate the intervening material.

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REFERENCES

Carilli, C., Rupen, M., & Yanny, B. 1993, ApJ, 412, L59
Djorgovski, S., et al. 1992, MNRAS, 257, 240
Frye, B, W. J., Welch, W. J., & Broadhurst, T. 1997, ApJ, submitted
Garrett, M., Nair, S., Porcas, R., & Patnaik, A. 1996, in IAU Colloq. 173, Astrophysical Applications of Gravitational Lensing, ed. C. Kochanek & J. Hewitt (Dordrecht: Kluwer), 189
Jauncey, D., et al. 1991, Nature, 352, 132
———. 1993, in Sub-Arcsecond Radio Astronomy, ed. R. Davis & R. Booth (Cambridge: Cambridge Univ. Press), 134
———. 1994, in Very High Angular Resolution Imaging, ed. J. Robertson & W. Tango (Dordrecht: Kluwer), 131
Jones, D., et al. 1993, in Sub-Arcsecond Radio Astronomy, ed. R. Davis & R. Booth (Cambridge: Cambridge Univ. Press), 150
Jones, D., Preston, R., Murphy, D., Meier, D. L., Jauncey, D. L., Reynolds, J. E., & Tzioumis, A. K. 1996, in IAU Colloq. 173, Astrophysical Applications of Gravitational Lensing, ed. C. Kochanek & J. Hewitt (Dordrecht: Kluwer), 345
Kochanek, C., & Narayan, R. 1992, ApJ, 401, 461
McMahon, P., Moore, C., Hewitt, J., Rupen, M., & Carilli, C. 1993, BAAS, 25, 1307
Nair, S., Narasimha, D., & Rao, A. 1993, ApJ, 407, 46
Preston, R., et al. 1993, in Sub-Arcsecond Radio Astronomy, ed. R. Davis & R. Booth (Cambridge: Cambridge Univ. Press), 428
Rao, A. & Subrahmanyan, R. 1988, MNRAS, 231, 229
Subrahmanyan, R., Kesteven, M., & te Lintel Hekkert, P. 1992, MNRAS, 259, 63
Subrahmanyan, R., Narasimha, D., Rao, A., & Swarup, G. 1990, MNRAS, 246, 263
Tarter, J. 1996, in Proc. SPIE, Optical SETI Meeting, in press
van Ommen, T., Jones, D., Preston, R., & Jauncey, D. 1995, ApJ, 444, 561
Wietfeldt, R., Newby, P., Baer, D., Cannon, W., Feil, G., Jakovina, R., Leone, P., & Tan, H. 1991, in Frontiers of VLBI, ed. H. Hirabayashi, M. Inoue, & H. Kobayashi (Tokyo: Universal Academy Press), 177
Wiklind, T., & Combes, F. 1996a, Nature, 379, 139
Wiklind, T., & Combes, F. 1996b, private communication
Wilson, W., Roberts, P., & Davis, E. 1996, in Proc. 1995 Aisia Pacific Telescope Workshop, ed. E. King & D. Jauncey, in press