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PKS1830−211: The strongest lensed radio source

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Abstract. The Ooty lens PKS1830−211 is a bright, variable radio source at a redshift of 2.507 consisting of a compact flat–spectrum core, associated knot and jet, which are lensed by an intervening spiral galaxy at a redshift of 0.886. It forms two images separated by $0''.98$ with a ring passing through them. Multi–epoch Very Large Array (VLA), Multi-Element Radio Linked Interferometer Network (MERLIN), Very Long Baseline Interferometer (VLBI) and Very Long Baseline Array (VLBA) observations have shown variability of the source by more than a factor of two, over time scales of less than a day to years, some of which mimic superluminality. Absorption lines of neutral hydrogen and many molecules have been observed in front of both the images. The molecular lines appear to dominate the image passing near the central part of the lens while the image farther away is dominated by HI 21 cm. Overall, the column density of various species appears to be similar to that found in the Milky Way. But isotopic ratios estimated from the line ratios of several isotopomers appear to indicate that the lens galaxy is less evolved than the Milky Way. The differential Faraday rotation between the images (upwards of 2000 rad m^{-2}) is suggestive of a large-scale magnetic field of a few microgauss in the lens galaxy. The time–delay between the images is estimated to be 26^{+4}_{-5} days. Multi–epoch VLB imaging as well as absorption line monitoring have provided rich information on the source property as well as tools for studying high-redshift objects.

Keywords : galaxies: active – quasars: individual: PKS1830−211 – radio lines: galaxies – radio continuum: galaxies – cosmological parameters

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1. Introduction

The Ooty lens PKS1830−211 is among the extensively studied gravitationally lensed systems and possibly among the very few systems to be observed from a low radio frequency of 327 MHz (cf. Rao & Subrahmanyan 1988) to X–rays (Mathur & Nair 1997). It was first reported in the 5-GHz Parkes Survey (Shimmins et al. 1969). Rao & Ananthakrishnan (1984) inferred substructures in the system during an interplanetary scintillation survey of the Galactic plane carried out using the Ooty Radio Telescope. Rao & Subrahmanyan (1988) carried out further VLA studies in 1983 and 1986, and found that the spectrum is mildly peaked at ∼1 GHz, has a flat spectrum ($\alpha \sim 0.3$, where $S_\nu \propto \nu^{-\alpha}$) above 1 GHz and an inverted spectrum below this frequency. They suggested that the unusual morphology for a flat-spectrum object is suggestive of gravitational lensing. Subrahmanyan et al. (1990) and Nair et al. (1993) studied the multifrequency VLA maps both in total flux density and polarization as well as VLB images. They modelled the system as a gravitationally-lensed radio source consisting of a core, jet and a knot. Though Swarup strongly advised to try super-resolution to extract possible extension of the images of the jet, the signal was considered to be insufficient to report the additional structures. Jauncey et al. (1991) used their MERLIN and VLA observations to detect the arcsecond–sized ring passing through the images. Wiklind & Combes (1996) reported detection of a number of molecular absorption lines and thus determined the redshift of the lens to be 0.886. van Ommen et al. (1995) reported a time delay of 44±9 days, between the compact images, from their VLA monitoring data; however, Lovell et al. (1998) used 8.6 GHz monitoring data to deduce a value of 26^{+4}_{-5} days. Wiklind & Combes (2001), from a study of correlated variability in the HCO^+ absorption lines at millimetre wavelengths, determined the time delay between the compact cores to be 26^{+5}_{-4}days. The redshift of the source remained a problem, due to the heavy obscuration towards the Galactic centre, which is close to the line of sight to the system. Lidman et al. (1999) used SOFI, a multi-purpose instrument capable of low-resolution spectroscopy, on the Very Large Telescope (VLT) to obtain a spectrum of the system between 1.51 and 2.54 μm to identify the Hα as well as possible [OIII] and Hβ lines and thus deduced the source redshift to be 2.507. Further Hubble Space Telescope (HST), Keck and Gemini observations determined the magnitudes of the images and the lens in the infra-red between I and H bands as well as gave an idea on the relative extinction between the images due to the intervening lens galaxy (cf. Courbin et al. 2002; Winn et al. 2002). Thus, over a period of 15 years of imaging, spectroscopy and numerical work, the redshift of the source and the lens, the separation and time–delay between the images and a good idea of the profile of the extended source could be determined. However, the question of how many lens galaxies are present, and how many of them matter does not appear to have a reliable answer.

2. Radio observations

The radio source PKS1830−211 has a 35-year history of radio astronomical observations covering various methods, wavelengths and resolutions. The Parkes 5-GHz survey (Shimmins et al. 1969) and the Molonglo 408 MHz survey (Large et al. 1981) have catalogued the source. The Ooty scintillation survey (Rao & Ananthakrishnan 1984) detected a scintillating flux density and thus clearly demonstrated that the source has compact components. Subsequent VLA observa-

Table 1. Basic data for the system PKS1830−211

Co-ordinates: R.A= 18h 33m 39.94s Dec= −21° 03′ 39.7″ (J2000)
Source redshift: 2.507 Lens redshift: 0.886
Image separation: 0″.980±0″.004

Radio flux density (Jy)			Optical magnitudes (HST)			
Frequency GHz	NE Image	SW Image	Band	NE Image	SW Image	lens Galaxy
22.5	3	2.1	K=F205W	15.4	19.4	17.4
14.94	4.3	2.8				
8.4	2.8	2.3	H=F160W	16.9	22.4	18.6
4.86	4.6	5.1				
1.49	5.3	6.4	I=F814W	22.3	-	21.4
0.83	total:	13.7				
0.408	total:	11.5	V=555W	25.6	-	-
0.327	total:	9.1				

Source is variable (cf. Rao & Subrahmanyan 1988, Table 1).
Optical magnitudes: Winn et al. (2002); Courbin et al. (2002).

tions (Rao & Subrahmanyan 1988) carried out in 1983 and 1986, covering frequency range of 1.69 GHz to 14.95 GHz showed (a) a two-component, flat-spectrum source with further structures like the extended jet, (b) variability of each component and (c) frequency-dependent flux density ratio between the two compact components. Subrahmanyan et al. (1990) carried out further VLA observations to get some idea of the extended image profile as well as polarization maps to construct a model of the lens. Nair et al. (1993) used both VLA and VLBI data to get the substructures of the lens system and schematically produced a frequency dependent core-jet model for the source. They argued, from the Faraday rotation estimates, that the lensing galaxy is likely to be a spiral. Jauncey et al. (1991) used the VLA and MERLIN observations to detect an elliptical ring-like structure connecting the two compact images and thus interpreted it as the Einstein ring.

There have been extensive interferometric observations from cm to mm wavelengths to monitor the source and analyse the substructures (cf. Jones et al. 1996). Jin et al. (2003) used eight epoches of 43 GHz VLBA observations to find that the distance between the two compact cores as well as their brightness has been changing. They interpreted this apparent superluminality as a manifestation of the shift in the centroid of the individual images due to variability of some of the substructures. Thus, the source is a multicomponent one, possibly even at sub-milliarcseconds, and these sub-components appear to vary in brightness (and position) at different rates.

3. Numerical modelling

PKS1830−211 has produced interesting new ideas in modelling of lenses. Kochanek & Narayan (1992) introduced the LensClean algorithm to match the observed flux density distribution with model predictions. This is a beautiful piece of work which goes well with the observations, and helps in discriminating between good and bad lens models. Since then, the method has been used extensively to model many other systems. Subrahmanyan et al. (1990) and Nair et al. (1993) used the profile of extended images and a set of constraints based on multifrequency VLA and VLBI data to model the system. In this way Nair et al. (1993) produced the model profile of the jet as a function of frequency. Extending the concept further, they and Nair (1994) introduced the 'Q' and 'R parameter' representing the time variable core as well as total magnification ratios, characterising chromatism of the magnification based on the spectral indices of the multicomponent source. Since the source is polarized, mapping of the polarization vector provides an important tool to study the mapping of the various regions of the source between the multiple images, including the possible four or five images of part of the jet that can be roughly identified in PKS1830−211. The main advantages of the method are as follows.

1. It incorporates multi-frequency information of extended structures through a small number of parameters.
2. Typically, the depolarization effects are least near the caustics, and visually, this kind of information can be examined and used in the models.
3. For monotonous variation of flux density along a structure like the jet, and smooth density variation in the lens at scales larger than the source size, the flux contours of extended images show a minimum at the caustics.

Nair et al. (1993) used these considerations to get some idea of the source as well as construct simple model of the lens. They also suggested a new method to estimate time delay between images by correlating the position angle of the polarization between the images as a function of time. These efforts provided a working model for many observations, in the absence of optical data or redshift information and the models allowed a one parameter conversion between time delay and the effective distance scale to the lens system. Using these numerical models, the Hubble constant was estimated by various groups, when the time delay and redshifts to the lens and source became available. For example, Wiklind & Combes (2001) obtained H_o=69^{+12}_{11} km s^{-1} Mpc^{-1} for a q_o=0.5 model, while Lidman et al. (1999) estimated the value to be 65^{+15}_{-9} km s^{-1} Mpc^{-1} for the same cosmology and 76^{+18}_{-10} km s^{-1} Mpc^{-1} for $_m$=0.3 flat cosmological model.

The optical observations were hampered by the proximity to the Galactic centre, of the line of sight to the source. Courbin et al. (1998) were able to locate the lens galaxy and get its redshift, from observations at sub-arcsecond seeing taken at Keck and ESO/MPI telescopes in the near infrared regions, along with powerful deconvolution techniques. The ability to identify possibly three galaxies, two stars and two AGN images within an arcsecond radius of the lens centre is as much a credit to the deconvolution techniques as to the powerful space- and ground-based telescopes.

4. Spectral studies

The redshift of the lens (z=0.88582) was measured from 12 molecular absorption lines appearing in front of one of the images (SW), observed using the Swedish-ESO Submillimetre Telescope (Wiklind & Combes 1996). Since then a number of molecular lines as well as 21 cm HI absorption has been detected towards the system (cf. Menten et al. 1999, Chengalur et al. 1999), mainly at a redshift of 0.886, but some due to the absorber at the redshift of 0.19 (Lovell et al. 1996), and variability of the lines has been monitored. Study of absorption lines, specially in radio and millimetre wavelengths have great advantages in this system due to the following two reasons.

1. The crowding towards the Galactic centre does not affect these lines, since their observed frequencies would be different from those expected for Galactic absorbers.
2. In general, when the source is strong, specially in the low-frequency regime, and the size of the compact core of the background source is comparable to the typical size of absorbers, the lines can be detected and studied with high spectral resolution as well as good sensitivity. The distance to the absorber does not affect the quality of the data.

Consequently, the system, with $\sim$ 10 Jy flux density has provided an opportunity for abundance analysis, monitoring for variability, Doppler velocity studies as well as some novel cosmological applications.

Chengalur et al. (1999) tried to decompose their HI and OH spectra into a shallow but wide component due to the ring (which is bright at subGHz frequencies) and two narrower lines due to the compact images. A possible value for the line of sight rotation velocity of the lens of $\sim$165 km s^{-1} could be estimated by this method, fairly independent of the detailed lens models and could be checked for the consistency of models. They also noticed that the equivalent width of the OH doublets is almost in the ratio of 9:5 and there is very little flux density in the other two lines. Hence, the inference is that the OH environment in the lens galaxy appears to be in thermal equilibrium, mainly due to collisions between particles as against radiative pumping in the infrared and de-excitation to various lower levels. However, unlike the molecular lines which appear to originate from the cold matter (typical rotation temperature for molecular rotational lines $\sim$ 4 K), the HI line appears to be more due to the NE image, away from the expected lens centre. It is interesting that though the HI regions contributing to absorption lines consist of both cold and warm components of interstellar medium, the estimated spin temperature is a few hundred K.

Wiklind (2001) noticed that the HCO$^+$ line, though saturated along one of the images, does not reduce the flux density to zero and hence could conclude that the size of the absorber is likely to be less than the size of the compact core of the source. Since VLBA gives some idea of the image size, a reasonable limit on the size of the absorber could be arrived at. Indeed, Carilli et

Table 2. Peak Optical depth of some of the observed lines towards 1830−211

Absorption line	Optical depth SW image	towards NE image	Absorption line	Optical depth SW image	towards NE image
HCO^+ (J:2-1)	0.34	0.21	HCN (J:2-1)	0.42	0.18
$HC^{17}O^+$ (J:2-1)	0.004	-	$HC^{15}N$ (J:2-1)	0.02	-
$HC^{18}O^+$ (J:2-1)	0.04	-	HC_3N(J:5-4)	0.08	0.05
$H^{13}CO^+$ (J:2-1)	0.10	-	HCN (J:3-2)	0.42	-
HCO^+ (J:3-2)	0.3	0.08	HNC(J:2-1)	0.4	-
N_2H^+(2-1)	0.25	(0.05)	HNC(J:3-2)	0.2	-
N_2H^+(3-2)	0.06	-	CS(J:3-2)	0.3	-
OH(1667)	0.006	-	CS(J:4-3)	0.15	-
OH(1665)	0.004	-	HI	(0.03)	0.05

Data from Wiklind & Combes (1996), Chengalur et al. (1999), Carilli et al. (1998) and Muller et al. (2004). SW image corresponds to a redshift of z_{helio}=0.88582 and NE image is shifted by ∼ −147 km s^{-1}. (-) indicates that either the line cannot be decomposed or no line has been detected above the noise level. The peak optical depth should be taken with caution because various instruments had different spectral and spatial resolution. From the available £gures, it is not possible to get uniform velocity integrated optical depth.

al. (1998) suggest that the upper limit on the absorbing cloud size is 2.5 mas, comparing the optical depth of HC_3N(J:5−4) line with an image resolution of 1 and 2.5 mas. Also, at millimetre wavelengths, only the compact core is expected to contribute to the absorption lines. Accordingly, variation in the line strength introduced due to source variability is a good way to determine the time delay between the images, without appreciable contamination from the extended ring component. Wiklind (2001) obtained a value of 26^{+4}_{-5} days for the time delay between the images, from a three-year monitoring of the HCO^+ absorption line.

PKS1830−211 is a strong source and the molecular lines have been used for a variety of astrophyiscal applications, such as the ones listed below.

1. Menten et al. (1999) observed that HC_3N rotational line (J:5−4) has an optical depth of ∼0.08. Arguing that it should be radiatively excited by CMBR, they estimated the CMBR temperature at the lens redshift of 0.886 to be $T_{ex}=4.5^{+1.5}_{-0.6}$ consistent with the expected value of 5.14K.

2. Menten et al. (1999) and Muller et al. (2004) observed the isotopomers of several species and from their relative line strengths, argued that N^{15} is typically enhanced with respect to N^{14}, and S^{34} with respect to S^{32} by a factor of ∼2 in the intervening matter compared to the local ISM as well as solar atmosphere. Similarly, O^{18} is enhanced with respect to both O^{16} and O^{17}. The interpretation is that the lens galaxy in PKS1830−211, though has column density of elements similar to the Milky Way, the isotopic differences appear to imply that it is less evolved compared with even the solar nebula. This is not a surprising

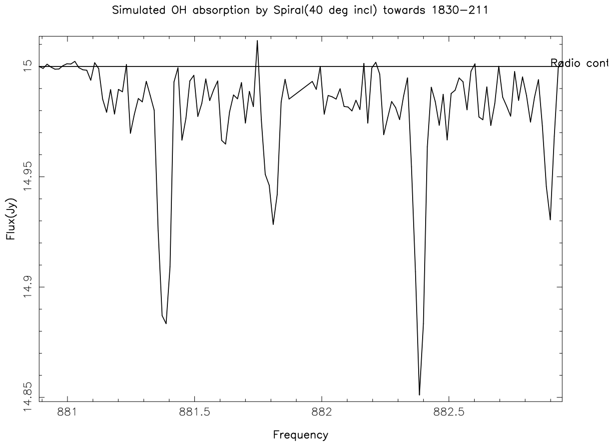

Figure 1. Simulated OH absorption doublet profile due to possible single main lens spiral galaxy inclined at ~ 40° to the plane of the sky, located near the position predicted by Nair et al. (1993).

result, considering that we are seeing a galaxy when the Universe was only about 5 billion years old, which is well before the solar system formed.

5. Additional lens or low H_o?

PKS1830−211 is located almost along the line of sight to the Galactic Centre. Consequently, in addition to heavy obscuration, contamination by Galactic stars and an additional possible HI absorber at redshift of 0.19 have only added to the confusion. But there have been remarkable efforts to map the region and get accurate positions to the various objects nearby.

Winn et al. (2002) analysed HST/WFPC2 data taken with F814W filter (I band) on September 25, 2000 (4800 s integration time) and F555W filter (V) on July 11, 2001 (2000 s integration time) by the CASTLE programme. They deduced that the lens is a face-on spiral with certain compact source as the bulge of the galaxy and hence it is the lens centre. Thus, they argued that the lens is centred away from the position suggested in the models of Nair et al. (1993) which had been the basis for many interpretations of data as well as estimates of Hubble constant. They find from their analyses the value of Hubble constant to be 44±9 km s^{-1} Mpc^{-1} for an $_m$=0.3 flat cosmological model. However, Courbin et al. (2002) analysed the same data along with new Gemini-North K-band image and estimated the barycentre of the spiral arms. From these analyses, they argued that there are indeed two galaxies and that the bulge suggested by Winn et al. (2002) is likely to be an unidentified foreground object. Using a two-lens model, they arrive at a value of ~65 km s^{-1} Mpc^{-1} for the same cosmological model. Our HI and OH data (Chengalur et al. 1999) could, in principle, indirectly clarify the lens scenario; however, the shallow absorption profile due to the ring and the sharp lines due to the images could not be resolved reliably, due to poor spectral resolution of ~ 31 km s^{-1}. GMRT could solve the problem, e.g. by comparing the simulated absorption profiles for the various scenarios (cf. Fig.1), specially if a narrow but weaker absoprtion line due to the supposed central image is identified. However, this requires the GMRT L-band to have sensitivity down to 850 MHz. As a specific example, let there be one main lens galaxy located near the position predicted by Nair et al. (1993) which is inclined at approximately 40° to the plane of the sky and produces the absorption lines. The feature due to the central image, almost at the middle of the shallow absorption trough to the ring, should be noticeable next to the absorption line due to the SW image. On the other hand, if the lens is face on and is away from the position of Nair et al. then the absorption trough will be narrower and the central component can be hardly identifiable among the fluctuations. For a two-lens scenario, we are unlikely to get a noticeable shallow absorption trough; instead we might just expect two separate absorption lines in front of the two compact cores and some small features around them. Thus, I would believe that an absorption spectrum like what is shown in Fig. 1 is a vindication of the models of Nair et al. (1993). Such a test is important for understanding structure formation. For instance, suppose the IR images confirm two sub-arcsecond objects, both at a redshift of ~0.886 and the radio spectra support a single lens scenario. Then, this is probably a strong support for hierarchical merging, where, the numerical simulations of CDM models indicate the formation of distinct two or three blobs of optical radiation by a redshift of 2 which evolve into the normal galaxy by a redshift of 1 or so.

6. Concluding remarks

An attempt has been made here, to give some historical glimpses and memories of more than a decade, as well as present some science relating to the gravitational lens system PKS1830−211. It is evident that the system has provided a wealth of information which could be used to experiment with new techniques, both observational and numerical. But the subject is not closed, and lots of uncertainties and controversies still remain. GMRT, when the capabilities are slightly enhanced, could further help to clarify some of these problems. Some directions where the system could be a good cosmological probe, such as for instance studying monolithic versus merger scenario of structure formation, CMBR temperature at higher redshifts using molecular absorption line strengths, and CNO nucelosynthesis from isotopic ratios have been briefly alluded to. On the whole the Ooty lens has given us rich astronomy and physics and we have reason to hope for more.

Acknowledgements

Govind Swarup's contributions in bringing PKS1830−211 to the limelight cannot be underestimated; equally, he showed to his colleagues what the joy of working with an exciting new system is. He brought together the observers and model builders in 1987, allowed them to shout and fight with one another, then sat with each one to see what can be extracted with the available data using his variety of weapons. This allowed us to visualise the super-resolved image, gave an idea of what the lens system is like and how further observations could be carried out. His enthusiasm was a motivation and good example for the younger generation. Using the lengthy discussions and many hand-written notes, he wrote a proposal for VLA observing time while on a flight and posted it while waiting in the airport to change the plane. He was eager to try a spectrum of the system using the incomplete GMRT way back in 1994; he was a bundle of enthusiasm when the HI and OH absorption lines were shown. Naturally, it was due to his ambition to build an instrument to probe the structures in formation at high redshifts that GMRT could produce a very fine OH absorption spectrum at 1 mJy sensitivity and 2.4 km/sec spectral resolution for another somewhat similar gravitational lens system B0218+357 (Narasimha et al. 2002; Kanekar et al. 2003). I thank Govind Swarup for the many discussions and arguments, which have enlightened me. He has been a source of inspiration. I am grateful to Japan Society for the Promotion of Science for an Invitation Fellowship.

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