Evolution of the pc-scale structure of PKS 1934-638 revisited: first science with the ASKAP and New Zealand telescopes

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ABSTRACT

We have studied the archetypal Gigahertz Peaked Spectrum radio galaxy, PKS 1934−638, using the Australian Long Baseline Array, augmented with two new telescopes that greatly improve the angular resolution of the array. These VLBI observations represent the first scientific results from a new antenna in NZ and the first antenna of the Australian SKA Pathfinder (ASKAP). A compact double radio source, PKS 1934−638, has been monitored over a period of 40 years, and the observation described here provides the latest datum, eight years after the previous observation, to aid in the study of the long-term evolution of the source structure. We take advantage of these new long baselines to probe PKS 1934−638 at the relatively low frequency of 1.4 GHz, in order to examine the effects of optical depth on the structure of the radio source. Optical depth effects, resulting in the observation of frequency dependent structure, may have previously been interpreted in terms of an expansion of the source as a function of time. Expansion and frequency dependent effects are important to disentangle in order to estimate the age of PKS 1934−638. We show that frequency dependent structure effects are likely to be important in PKS 1934−638 and present a simple two-dimensional synchrotron source model in which opacity effects due to synchrotron self-absorption are taken into account. Evidence for expansion of the radio source over 40 years is therefore weak, with consequences for the estimated age of the radio source.

Subject headings: galaxies: individual (PKS 1934−638) — radio continuum — galaxies: structure

1. Introduction

PKS 1934−638 is the archetype of a class of radio galaxies known as GHz-Peaked Spectrum (GPS) radio galaxies. The properties of this class are well described by O'Dea (1998).

PKS 1934−638 was first noted in terms of its strongly peaked radio spectrum at 1.4 GHz by Bolton, Gardner & Mackey (1963) and Kellermann (1966), indicating the likely existence of compact structure in the radio source (Slish 1963). Subsequent interferometric observations confirmed this (Gubbay et al. 1971) and high angular resolution observations of PKS 1934−638 were made periodically over the next 20 years (Preston et al. 1989; Tzioumis et al. 1996, 2002; King 1994), at a range of frequencies. Most recently, Ojha et al. (2004) presented dual-epoch 8.4 GHz VLBI observations of PKS 1934−638 as part of a combined analysis of ∼30 years of observations.

Ojha et al. (2004) estimated an expansion rate of $23\pm10\mu$as/yr between the two compact components of radio emission that dominate the structure of PKS 1934−638, at a redshift of $z = 0.183$ (Penston & Fosbury 1978) giving an apparent separation speed of $\sim 0.2 \pm 0.1c$, an order of magnitude higher than what is generally assumed for the hot spot advance speed of Cygnus A (Readhead et al. 1996). Throughout the history of VLBI observations of PKS 1934−638 it has been clear that the structure and flux density of the object evolve slowly, if at all. This stability is consistent with the general properties of GPS radio galaxies (O'Dea 1998). The flux density stability of PKS 1934−638, in particular, has led it to be used as the primary flux density calibrator for the Australia Telescope Compact Array at centimetre wavelengths.

Because of the proposed physical nature of GPS sources, as the young progenitors of FR-I and FR-II radio galaxies (O'Dea 1998), studies of the evolution of GPS sources are very important, in order to estimate their ages via measurement of expansion of the radio structure (Polatidis & Conway 2003). Long time series observations are required because of the slow rate of evolution in GPS radio galaxies and further, optical depth effects may complicate the interpretation of multi-epoch observations made at different frequencies. Mechanisms such as free-free absorption and synchrotron self-absorption have been proposed as providing significant optical depth in GPS sources at radio wavelengths and these different mechanisms are potentially difficult to disentangle (Tingay & de Kool 2003). GPS radio spectra peak at GHz frequencies and the optical depths change rapidly over the frequency range 1 - 10 GHz. One must therefore be wary when interpreting multi-epoch data obtained at different frequencies, as is the case for the historical VLBI data for PKS 1934−638. Frequency dependent structure has been clearly seen in another GPS radio galaxy, CTD 93 (Shaffer, Kellermann & Cornwell 1999; Nagai et al. 2006).

Ojha et al. (2004), in their analysis of historical PKS 1934−638 VLBI data, raise the possibility that frequency dependent structure effects complicate their analysis. In this paper we further examine the possibility of frequency dependent structure in PKS 1934−638 and find evidence that the apparent expansion of the source noted by Ojha et al. (2004) can be explained as a consequence of these frequency dependent effects. In section 2 we describe new VLBI observations at 1.4 GHz that use the Australian Long Baseline Array (LBA) augmented by two new radio telescopes. In section 3 we discuss our new results within the context of the historical results (both those presented by Ojha et al. and other data we have extracted from the literature), in particular the possibility of frequency dependent structure in PKS 1934−638 and the impact on historical measurements of the expansion rate of PKS 1934−638.

2. New VLBI observations and results

VLBI observations of PKS 1934−638 were undertaken on 2010 April 29, using the array of radio telescopes listed in Table 1 and shown in Figure 1. Two of these telescopes were used for the first time for scientific observations, the first ASKAP (Australian SKA Pathfinder) antenna in Western Australia (Johnston et al. 2007), and Warkworth, a new facility of the Auckland University of Technology in New Zealand (Gulyaev & Natusch 2009). The addition of ASKAP and Warkworth greatly increase the angular resolution (factor of ∼4) and (u, v) coverage for observations of radio sources by the Australian Long Baseline Array (LBA). This is particularly useful at relatively low frequencies, where long baselines are required to obtain high angular resolution.

The VLBI observations were made by recording right and left circularly polarised signals at each antenna in the frequency range 1368 − 1432 MHz (a 64 MHz bandwidth). Data at the ATCA, Parkes, Mopra and Hobart antennas were recorded with the standard LBA systems (Phillips et al. 2009). The observation occurred over a period of six hours.

The data from the ASKAP and Warkworth antennas were obtained from a custom-made single-pixel feed and receiver system that delivered the band limited signals (downconverted to the frequency range 256 − 320 MHz) at both polarisations to a custom-made digital system. The digital system utilises a commodity Signatec sampler/digitiser PCI-based card (Signatec PX14400) to sample the band limited analog signals at the Nyquist-Shannon rate (Shannon 1949) and digitise the signals with 14-bit precision. These 14-bit samples are then recorded to a 32 TB RAID disk. The Signatec card and RAID are hosted in a server class PC. After recording, the 14-bit samples are converted to 2-bit precision, to decrease data storage and transport requirements, and to be more compatible with the 2-bit samples recorded with the standard LBA system. A full description of the digital system will appear in Stansby (2010). A hydrogen maser clock was available at Warkworth and a

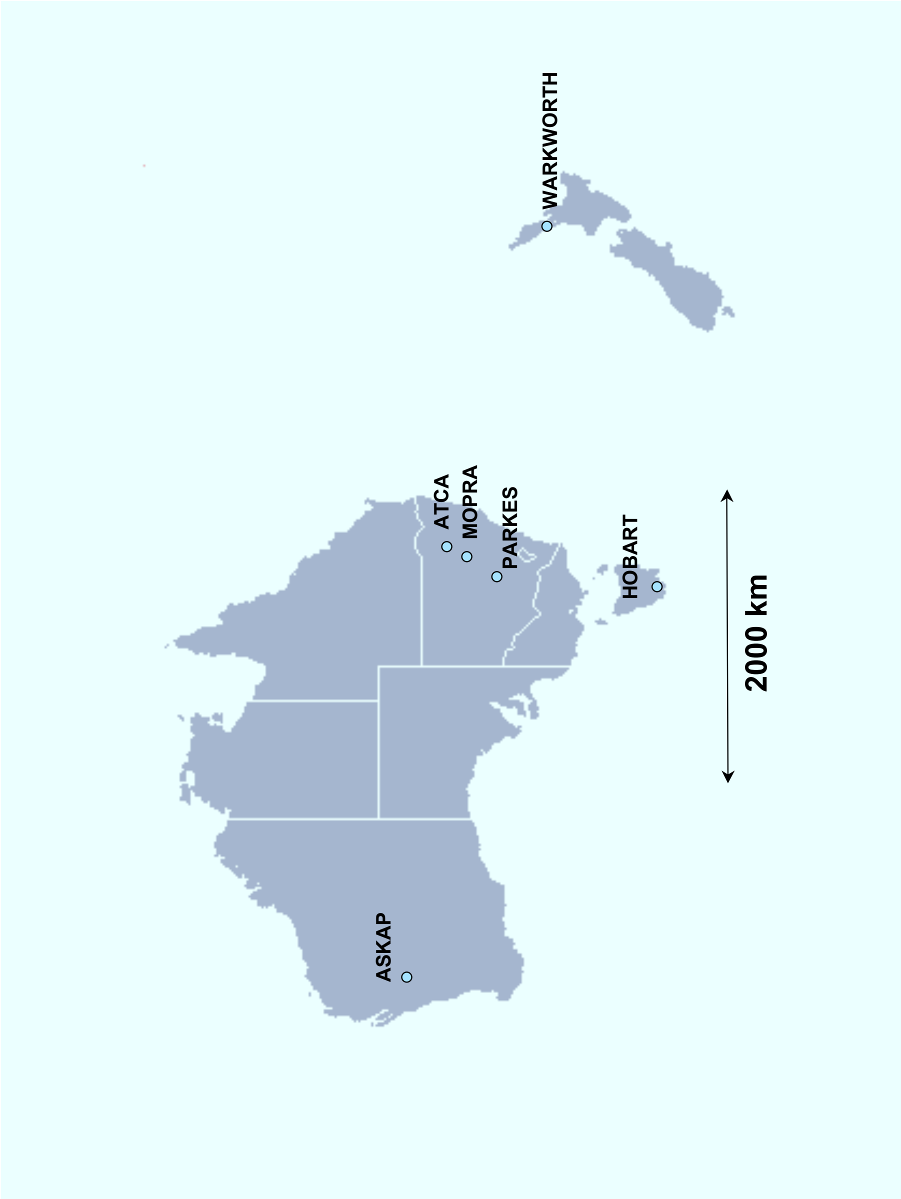

Fig. 1.— Schematic geographical distribution of antennas used in the VLBI observations of PKS 1934−638

rubidium clock was used at ASKAP, to drive frequency synthesisers for the local oscillator and the digital system sample clock. Global Positioning System receivers at Warkworth and ASKAP were used to determine (x, y, z) positions for the antennas and generate 1PPS signals for the digital system.

Following the observations, data from most telescopes were transferred via fast network connections to Curtin University of Technology in Western Australia to be correlated using the DiFX software correlator (Deller et al. 2007). The data from the ASKAP telescope were transported to Perth by car, as fast network connections are still under construction. The data were correlated using an integration period of 2 seconds and 32 frequency channels per 64 MHz band. All Stokes parameters were correlated. PKS 1934−638 was detected with high signal to noise on all baselines in the array. The resultant (u, v) coverage for the observation is shown in Figure 2. All baselines above $6M\lambda$ are due to the new antennas at ASKAP and Warkworth, increasing the maximum baseline to $24M\lambda$ and thus the array resolution by a factor of 4.

The correlated data were imported into AIPS for initial processing using standard techniques such as fringe-fitting. The data were also amplitude calibrated using system temperature and gain values. For the new antennas at ASKAP and Warkworth these calibration parameters were measured at the telescopes by performing on-off pointings toward strong radio sources of known strength. Once fringe-fitted and amplitude calibrated, the data were exported to DIFMAP (Shepherd, Pearson & Taylor 1994) for excision of bad data, imaging and model-fitting.

Figure 3 shows the best representation of the Stokes I data in the image plane, obtained by model-fitting the visibility data, using the model specified in Table 2, determined using the modelfit task in DIFMAP. A uniform weighting of the (u, v) data was used in the transformation to the image plane. Phase self-calibration was used in early iterations of

Table 1. List of radio telescopes used in the VLBI observations. ASKAP = Australian Square Kilometre Array Pathfinder; ATCA = Australia Telescope Compact Array. Longitudes are listed as east of Greenwich. SEFD = System Equivalent Flux Density.

Telescope	Long. (deg)	Lat. (deg)	Diameter (m)	SEFD (Jy)
ASKAP	116.64	−26.69	12	6000
Hobart	147.44	−42.80	26	600
Parkes	148.26	−33.00	64	25
Mopra	149.07	−31.30	22	350
ATCA	149.57	−30.31	5 × 22	70
Warkworth	174.66	−36.43	12	8000

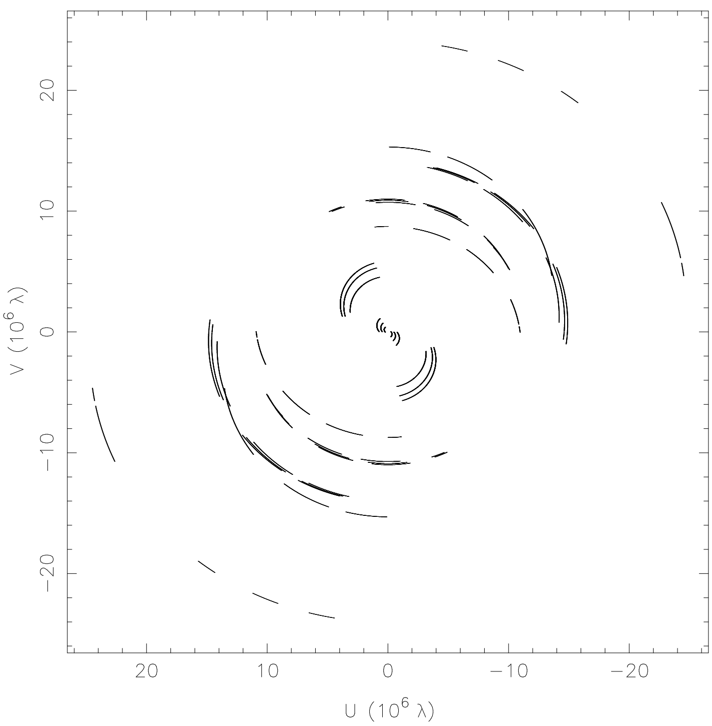

Fig. 2.— (u, v) coverage of the VLBI observation of PKS 1934−638. All baselines larger than $6M\lambda$ are contributed by the new antennas at ASKAP and Warkworth.

model-fitting, with amplitude self-calibration used in the final iterations of model-fitting. Amplitude self-calibration led to changes in individual antenna gains of the order 15%, relative to the *a priori* amplitude calibration.

The structure seen in Figure 3 agrees very well with all previous published images of PKS 1934−638 in this angular resolution regime with synthesised beams of ≈ 5-10 mas (Tzioumis et al. 1989; King 1994; Tzioumis et al. 1996, 2002; Ojha et al. 2004; Lovell et al. 2010). The two components have been interpreted as the terminal hot spots from oppositely directed jets emerging from a black hole accretion disk system, a smaller and younger version of an FR-I or FR-II type radio galaxy, into which GPS radio galaxies are postulated to evolve. This is the general interpretation of these double component structures, which are typical of GPS radio galaxies (O'Dea 1998).

We derived errors on the main parameter of interest in this analysis, the separation between the two components in the image, in order to compare our results to historical results. We did this by keeping one model component fixed at the phase centre of the image and forcing variation of the position of the second component, then assessing the degradation of the fit of data to model as a function of this variation. This technique for estimating errors has been used extensively previously (Tingay et al. 1998). In the case of PKS 1934−648, which is an almost equal strength double at this angular resolution, the visibility amplitudes and phases vary strongly, allowing this technique to tightly constrain the error bars on the separation, especially using the long and sensitive baselines from the east coast Australian antennas to ASKAP and Warkworth. We estimated that the separation of the two components at 1.4 GHz is 41.0 mas ± 0.6 mas (3σ).

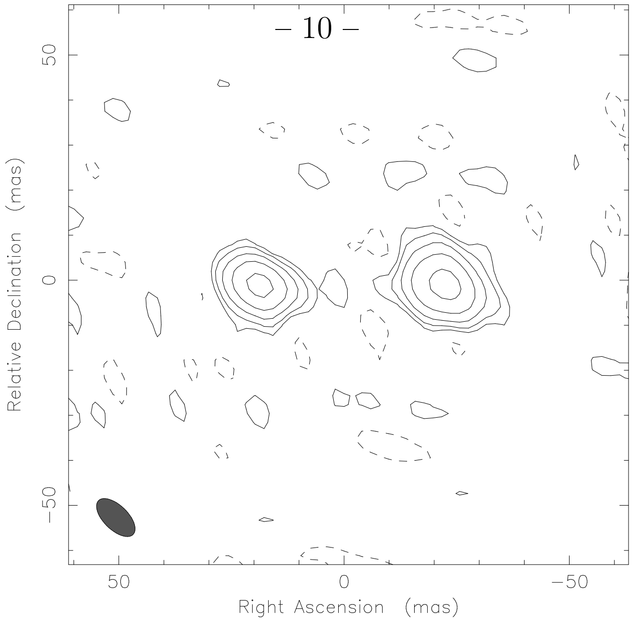

Fig. 3.— Stokes I VLBI image of PKS 1934−638 at 1.4 GHz. Contour levels are −4 ,4, 8, 16, 32 and 64% of the peak surface brightness of 2.4 Jy/beam. The restoring beam is 10.8 × 5.4 mas at a position angle of 45.7°. Note, the phase centre of the image has been shifted relative to the positions of the components indicated in Table 2 by (-20 mas, 0 mas), for convenience of display.

Table 2. Model for the structure of PKS 1934−638 at 1.4 GHz. S = flux density of model component; R = distance of model component from phase centre of image; θ = position angle of model component centroid from the phase centre of image; a = major axis length of model component; r = minor axis to major axis ratio; ϕ = position angle of model component major axis

S (Jy)	R (mas)	θ (deg)	a (mas)	r	ϕ (deg)
5.6	0.0	0.0	8.7	0.9	6.4
3.7	41.0	−90.7	8.2	0.0	−62.5

3. Discussion

To place our new measurement of the separation between the two compact components in PKS 1934−638 within the context of the historical measurements, we reproduce in Table 3 the data compiled by Ojha et al. (2004), with the addition of our new datum at 1.4 GHz. Also listed in Table 3 are the results of other historical observations that were not included in the analysis of Ojha et al. (2004), namely a 5 GHz observation from the Southern Hemisphere VLBI Experiment (a precursor of the Australian LBA) (Tzioumis et al. 1996) and a 1.6 GHz observation from the VLBI Space Observatory Programme (Lovell et al. 2010). In addition, the parameter measurements for the images of 1998 and 1991 (King 1994; Tzioumis et al. 1996, 2002) have been repeated using the original published images, and new estimates of separation and position angle are reported, together with conservative error estimates. Table 3 now includes all historical VLBI observations of PKS 1934−638, with all parameters reported in a consistent way.

We reproduce Figure 2 of Ojha et al. (2004) below in Figure 4, including the new datum and the additional historical data. Also plotted are lines showing the expansion rate of 23±10μas/yr between the two compact components of radio emission in PKS 1934−638, as estimated in Ojha et al. (2004). As can be seen from Table 3 and Figure 4, the new measurement of separation at 1.4 GHz lies significantly below the extrapolation of the previously measured values of separation at 2.3 and 8.4 GHz. The same can be said of the 1.6 GHz VSOP datum. However, if the separations are plotted as a function of observing frequency, as shown in Figure 5, a consistent trend of separation with frequency is revealed, with larger separations measured at higher frequencies and smaller separations measured at lower frequencies.

We suggest that this is a signature of frequency dependent structure in PKS 1934−638 and is caused by optical depth effects. To investigate the origin of the apparent increase of

Table 3. Measured component separations in PKS 1934−638. References are: 1=Gubbay et al. (1971); 2=Tzioumis et al. (1989); 3=King (1994); 4=Tzioumis et al. (2002); 5=Tzioumis et al. (1996); 6=Lovell et al. (2010); 7=Ojha et al. (2004); 8=This work.

Epoch	Separation	Position Angle	Freq (GHz)	references
1970.8	41.9±0.2	−90±0.1	2.3	1
1982.3	42.0±0.2	−90.5±0.1	2.3	2
1988.9	41.4±0.5	−92±0.5	2.3	3,4,5
1991.9	42.2±0.5	−92±0.5	8.4	3,4,5
1992.9	41.9±0.5	−92±0.5	4.85	5
1999.3	41.4±0.5	−92±0.5	1.65	6
2002.5	42.7±0.4	−92±0.5	8.4	7
2002.9	42.6±0.3	−92±0.4	8.4	7
2010.3	41.0±0.6	−91±1.0	1.4	8

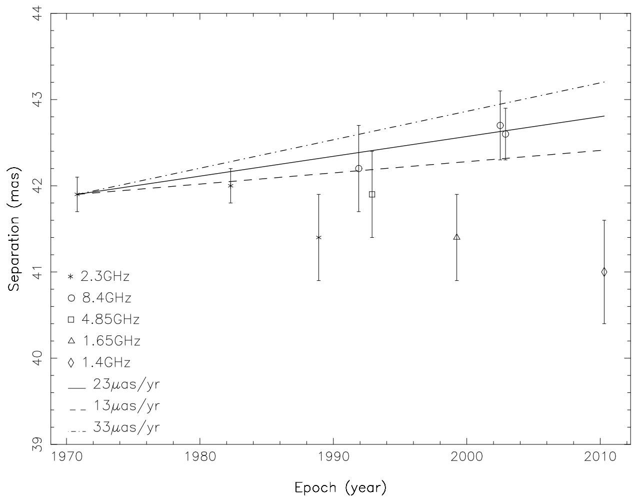

Fig. 4.— Separation between the two components in PKS 1934−638, as a function of time. The solid lines show the predictions of the expansion rate estimated in Ojha et al. (2004).

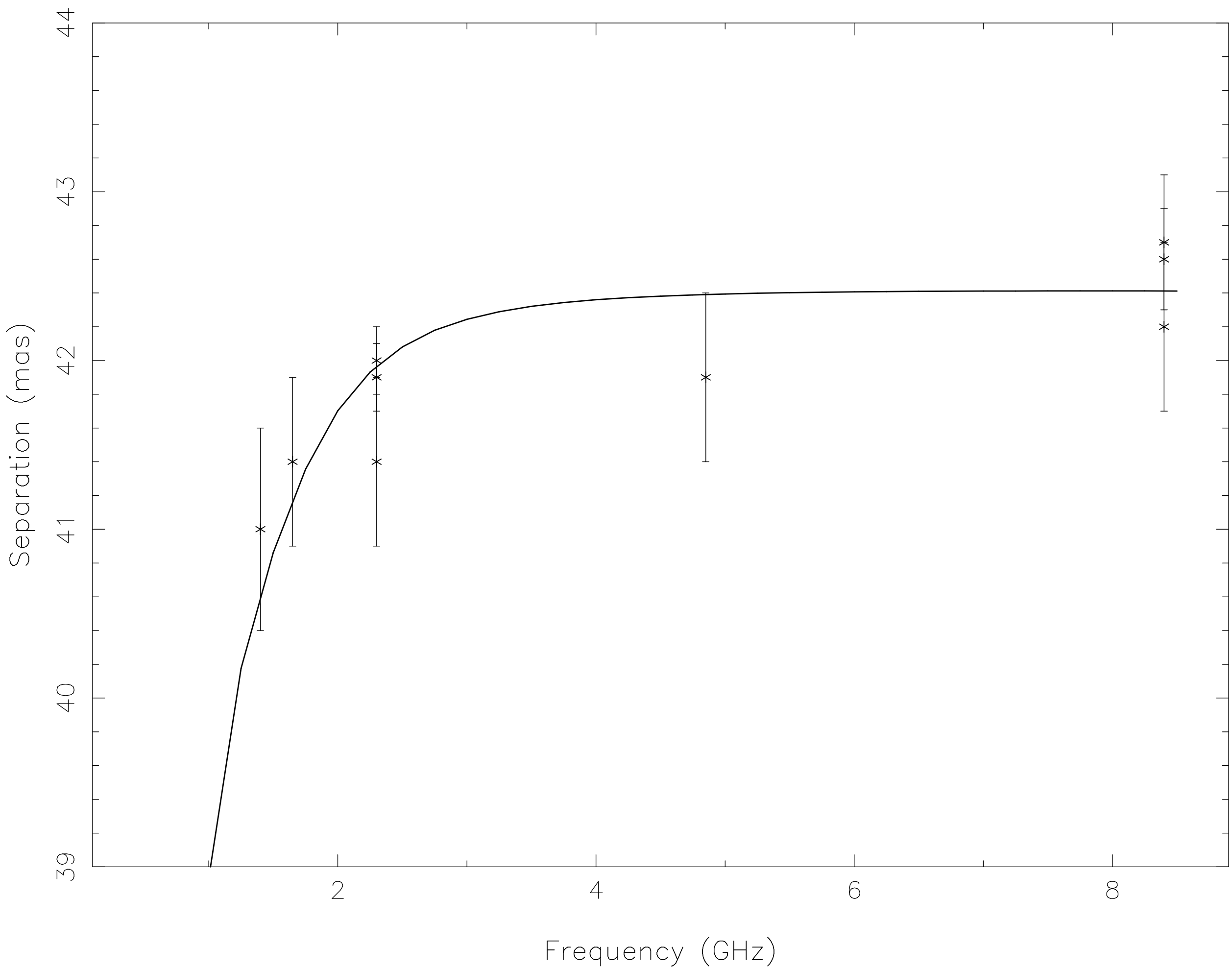

Fig. 5.— Separation between the two components in PKS 1934−638, as a function of observing frequency. The results of the model described in the text is plotted for a viewing angle $\theta = 0$ (solid line), to explain the variation in separation as a function of frequency.

lobe separation with frequency, we explored a two-dimensional synchrotron source model which takes into account opacity effects associated with synchrotron self-absorption. We modelled the electron density profiles of the two lobes in terms of a "cut-off" gaussian profile as a means of representing the discontinuity associated with the shock front at the jet working surface and the corresponding backflow from the shock region. In the plane of the jet axis the lobe edges are located at $\pm x_0$, measured relative to the core at $x = 0$, so that the electron density profiles of the two lobes are:

$$\rho(x,z) = \begin{cases} \rho_0 \exp\left[-\frac{(|x|-x_0)^2+z^2}{r_0^2}\right], & |x| < x_0, \\ 0, & \text{otherwise}, \end{cases} \tag{1}$$

A constant magnetic field was assumed, and a spectral index of -3.7 for the electron energy distribution was chosen to match that implied by the $\nu^{-1.35}$ spectrum of the optically thin regime at frequencies above 2 GHz. The spectral index was assumed constant across the extent of the source; the model does not take into account any spectral steepening due to synchrotron cooling in the regions removed from the shock front. Correction for an arbitrary viewing angle, θ, was made by effecting a rotation of the co-ordinate axes $(x', z') \rightarrow (x\cos\theta + z\sin\theta, -x\sin\theta + z\cos\theta)$, and integrating along the z' axis the equations of radiative transfer (Sazonov 1969):

$$\frac{d}{dz'}\begin{pmatrix} I \\ Q \\ U \end{pmatrix} = \begin{pmatrix} \alpha_I \\ \alpha_Q \\ 0 \end{pmatrix} + \begin{pmatrix} -\mu_I & -\mu_Q & 0 \\ -\mu_Q & -\mu_I & -\rho_V \\ 0 & \rho_V & -\mu_I \end{pmatrix}\begin{pmatrix} I \\ Q \\ U \end{pmatrix}. \tag{2}$$

Here, the emission and absorption coefficients are $\alpha_{I,Q}$ and $\mu_{I,Q}$ respectively (Melrose & McPhedran 1991). We neglect the contribution of Faraday rotation associated with any ambient thermal plasma and set $\rho_V = 0$.

The lobe separation was computed by calculating the separation between the intensity-weighted means of the emission around each peak in the emission profile. The value of x_0 was fixed by requiring that, for a given viewing angle, the radiative transfer code reproduced the observed separation between the lobes at high frequency, where the lobe separation asymptotes to the true lobe separation.

This simple model explains the data to the satisfaction of the error bars.We find that models within $\sim 20^\circ$ of the plane of the sky account well for the observed frequency dependence of the lobe separation. Thus, we can demonstrate that our suggestion of frequency-dependent structure has a reasonable basis in physics. A corollary of this suggestion is that the expansion rate calculated by Ojha et al. (2004) should be viewed with considerable caution, until more VLBI measurements can be made at a single frequency, to minimise frequency dependent structure effects. We note that the sequence of 2.3 GHz observations listed in Table 3, and shown in Figure 4, by themselves do not constitute evidence for a significant expansion rate. Likewise, the sequence of 8.4 GHz observations, taken by themselves, do not show evidence for significant expansion. Given the evidence for frequency dependent source structure, we consider the evidence for source expansion to be weak. A further consequence of the frequency dependent source structure is that estimates of the radio source age derived from the apparent expansion must also be considered with caution.

4. Conclusions

We have obtained new high angular resolution observations of the archetype GPS radio galaxy, PKS 1934−638, by using the Australian Long Baseline Array enhanced with two new radio telescopes, the first antenna of the Australian SKA Pathfinder in Western Australia and a new 12 m antenna at Warkworth, New Zealand. The addition of these two new antennas have greatly improved the angular resolution obtainable at the low frequency end of the the LBA's operating range, 1.4 GHz. These new capabilities have been used to examine the frequency dependent structure of PKS 1934−638 on the parsec scale, within the context of historical VLBI observations of the source at various frequencies. We show that frequency dependent structure effects are important in PKS 1934−638 and present a simple two-dimensional synchrotron source model in which opacity effects due to synchrotron self-absorption are taken into account. We find that previous estimates of the expansion rate of the radio source must be viewed with caution, and therefore that calculations of the source age and limits of the onset of jet production must also be considered with care.

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