The nearest GHz peaked-spectrum radio galaxy, PKS 1718–649

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ABSTRACT

In this paper wc identify PKS 1718–649, at a distance of 56 Mpc ($z=0.014; H_o=75$ km S-l Mpc^{-1}, $q_o=0$), as the nearest GHz peaked-spectrum (GPS) radio galaxy, more than four times closer than any previously known. Extensive observations at radio wavelengths with the Australia Telescope Compact Array, the Southern Hemisphere VLBI Experiment array, and the Swedish-ESO Submillimetre Telescope have allowed us to determine the properties of the radio source: PKS 171 8—649 consists of two compact sub-pc-scale components separated by approximately 2 pc, the overall radio polarization is low, and the radio spectrum is peaked near 3 GHz.

Order-of-magnitude agreement between the quantitative model for GPS sources of Bicknell, Dopita, & O'Dea (1 997) and the radio data we present, as well as data at optical wavelengths from the literature, raises the interesting possibility that PKS 171 8–649 may be frustrated in its development by the nuclear environment of its host galaxy, NGC 6328.

The model of Bicknell, Dopita, & O'Dea (1997) suggests free-free absorption as an explanation of the PKS 1718—649 radio spectrum. However, both free-free absorption and synchrotrons self-absorption mechanisms are plausible for this source and both may contribute to the overall radio spectrum.

PKS 171 8–649 provides evidence to strengthen the speculative suggestion that GPS sources arise as a consequence of galaxy merger activity.

Subject headings: Galaxies: nuclei, active, jets, individual (PKS 1718–649, NGC 6328 – Radio continuum: galaxies – Methods: polarimetric, interferometric

1. INTRODUCTION

Extragalactic radio sources which exhibit a spectral peak in the frequency range *0.4* GHz < ν < *5* GHz have become known as GHz peaked-spectrum (GPS) radio sources (e.g. O'Des, Baum, & Stanghellini 1991; hereafter OBS91) and were first noted observationally by Bolton, Gardner, & Mackey (1963) in the form of PKS 1934–638, Later, from various investigations, the overall radio wavelength properties of many GPS sources were determined (see OBS91 and references therein); in addition to peaked radio spectra near 1 GHz, the well-known and defining characteristics of GPS radio sources are low radio polarization and mostly compact morphology (OBS91).

A number of qualitative physical models have been suggested for the overall characteristics of the class of GPS radio sources. These explanations have been summarized by Stanghellini *et al.* (1993) and involve the birth, re-birth, or confinement of a normal classical double radio source, The youth or confinement of such a source would explain its compact nature. If the source is compact enough, absorption intrinsic to the source (synchrotrons self-absorption) could produce a peaked spectrum at radio wavelengths (Slysh 1963). Alternatively, absorption extrinsic to the source (free-free absorption), in a high-density confining environment could also produce the appearance of a peaked radio spectrum (van Breugel 1981). The low observed radio polarizations could be intrinsic or caused by Faraday de-polarization from a high-density environment.

The primary aim of this paper is to present new observational data which identifies PKS 1718 –649 as the nearest GPS radio galaxy (§2 and §3.1). In §3.2 we go on to summarize multi-wavelength data for this source which already exists in the literature and, in §3.3, apply the new and existing data to the model for GPS radio sources recently developed by Bicknell, Dopita, & O'Dea (1997; hereafter BD097). This model favors an extrinsic (free-free absorption) explanation for the shape of GPS radio spectra. Thus, a discussion of the PKS 1718–649 radio spectrum, considering the alternative synchrotron self-absorption interpretation, is given in §3.4. Finally, in relation to PKS 1718–649, we discuss in §3.5 the speculative suggestion that GPS radio sources arise as a consequence of galaxy merger activity.

2. OBSERVATIONS AND RESULTS

Total flux-density measurements of PKS 1718 –649 made between 843 MHz and 230 GHz are listed in 5 and plotted in Figure 1. The 843 MHz datum was obtained from the Molonglo Observatory Synthesis Telescope (MOST) on 1 994 July 15. The 1.4, 2.3, 4.8, and 8.4 GHz data were obtained from coeval observations with the Australia Telescope Compact Array (ATCA) on 1993 November 9. The 22 GHz datum was obtained from the 70 m Deep Space Network telescope at Tidbinbilla on 1995 December 22. Finally, the 90 and 230 GHz data were obtained from the Swedish-ESO Submillimetre Telescope (SEST) on 1996 February 26. The datum at 408 MHz was taken from the literature (Large *et al.* *1981*). Figure 1 shows that the radio spectrum of PKS 1718–649 is peaked near 3 GHz with a low-frequency spectral index of α = 0.36 and a high-frequency spectral index of α = –0.65 ($S_\nu \propto \nu^\alpha$). Flux-density monitoring observations with MOST (843 MHz) and the University of Tasmania's 26 m telescope (8.4 GHz) over a 12 month period have not shown any significant variations in the source strength at these frequencies. However, there is some evidence suggesting a slow variation. Bolton & Butler (1975) give the flux density of PKS 1718–649 at 5.0 GHz as 4.00 Jy in 1972. From the 1993 ATCA data the 4.8 GHz flux density was 4.7 Jy, giving a 17% change over a 21 yr period.

Separate observations of PKS 1718–649 were made with the ATCA on 1993 September 5, at a frequency of 2.37 GHz. A full polarimetric calibration of the data was made in multifrequency synthesis mode with the MIRIAD imaging software. The 6 km ATCA configuration, southerly declination of the source, and 12 h synthesis gave a nearly circular 3".8 FWHM beam. The resulting image revealed a completely unresolved component of 4.6 Jy, coincident with the optical nucleus of its host galaxy, with no extended structure at a dynamic range of 1000:1. The fractional polarization of the E vector was 0.35% and the polarization position angle was –6°.

Higher angular resolution imaging observations of PKS 171 8–649 were obtained using the Southern Hemisphere VLBI Experiment (SHEVE) array (Preston *et al.* 1989; Preston *et al. 1992;* Jauncey *et al.* 1994) at the frequencies of 2.3, 4,8, and 8.4 GHz on 1994 February 23, 1993 May 14, and 1993 July 4, respectively. Table 5 lists the observing epochs, frequencies, and participating telescopes. All data were recorded with the Mark 11 VLBI setup and correlated at the JPL/Caltech Block 11 processor, Correlated data were fringe-fitted using the AIPS[4] task FRING. Standard calibration and imaging routines in the Caltech VLBI reduction package (Pearson 1991; Shepherd, Pearson, & Taylor 1994) were used to reduce the data. The total VLBI flux densities were $4.7\pm0.5, 4.3\pm0.4$, and 3.4 ± 0.3 Jy at 2.3, 4.8, and 8.4 GHz, respectively, comparable to the total flux densities as shown in Figure 1. Figure 2 shows the highest resolution image obtained, from the 4.8 GHz data, showing that the unresolved component seen with the ATCA is resolved into two components separated by 6.8 mas along a position angle of -45°. The two components were de-convolved from the beam, using the AIPS task JMFIT, to obtain measures of the component sizes, orientations and flux densities shown in Table 5. Figure 3 shows the 8.4 GHz image of PKS 1718–649, The component flux densities were also found from this image, giving the estimates of spectral index in Table 5.

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

The VLBI data collected on baselines from the Australian stations to the Hartebeesthoek station (South Africa) contributed little to the *u-v* coverage and the calibration on these baselines was more uncertain than the 10% for the internal Australian baselines. These data were therefore excluded from the imaging process, but they yielded valuable information on the very high resolution structure of the source, At both 4.8 GHz (angular resolution of ~ 1.3 mas $\equiv$ 0.3 pc) and 8.4 GHz (~ 0.8 mas $\equiv 0.2$ pc) both components seen in Figure 2 were detected. The total flux density of the two components at 1.3 mas resolution at 4.8 GHz was ~ 0.5 Jy.

Previously, the only multibaseline VLBI observations of PKS 1718–649 available were obtained as part of the first SHEVE experiment in 1982 (Preston *et al.* 1989). The model for PKS 1718–649 shown in Preston *et al.* (1989) is significantly different from the images shown in Figures 2 and 3. The discrepancies can be readily explained by the sparseness of the data obtained in 1982 and consequently the difficulties in constraining a model.

Thus the images in Figures 2 and 3 present the first reliable investigation of the VLBI structure of PKS 1718–649.

3. DISCUSSION

3.1. PKS 1718–649 as a GPS source

Criteria for the selection of samples of GPS radio sources have been established previously, based on the properties of radio source spectra (Stanghellini *et al.* 1990), namely 0.4 GHz < $\nu_{turnover} < 5.0$ GHz and $\alpha < -0.5$ ($\nu > \nu_{turnover}$). Figure 1 shows that PKS 171 8–649 clearly meets these spectral criteria.

As well as the radio spectral properties, GPS sources have other well-defined characteristics. First, a large fraction of the total radio power from a given GPS source originates in a compact component coincident with the galaxy nucleus (OBS91). Second, the fractional polarization of GPS radio sources is consistently low, with a median value of 0.2% (OBS91). Our polarimetric imaging observations with the ATCA show that PKS 1718–649 displays these characteristics and the comparison of the VLBI flux densities with the total flux densities at 2.3, 4.8, and 8,4 GHz in Figure 1 reinforces the statement that the source is compact; the combined flux density of the two milliarcsecond-scale components accounts for the total flux density of the source, Furthermore, the double component morphology of PKS 171 8–649 is typical for GPS sources which have been found to be associated with galaxies (cf. PKS 1934–638, Tzioumis *et al. 1989;* OQ208, Stanghellini *et al.*, in preparation). The absence of radio variability in PKS 1718–649 on a time scale of 12 months is also consistent with the known properties of GPS sources (King 1994).

Thus, on the grounds of the radio spectrum, the fractional polarization, and the source morphology, the classification of PKS 171 8–649 as a GPS radio source is secure, It has been identified with NGC 6328 (Savage 1976), at a redshift of z=0.014 (Fosbury *et al.* 1977), making it the nearest GPS source now known, by a factor of more than 4 (cf. 1144+352, z=0.06, Snellen *et al.* 1995; 0Q208, z=0.077, OBS91).

3.2. Data from the literature

Being a relatively nearby galaxy, NGC 6328 has already been studied quite extensively at optical and other wavelengths, more so than is typical for GPS radio source host galaxies.

Fosbury *et al.* (1977) observed strong optical emission lines from the galaxy nucleus and also found that approximately 6% of the galaxy mass is in the form of neutral hydrogen gas, Carswell *et al.* (1984) studied the nuclear emission line region but could not distinguish between photoionization and shocks as the excitation mechanism for the emission line gas. Filippenko (1985) obtained high-quality optical spectra of NGC 6328, concluding that photoionization is the dominant excitation mechanism and that the electron density of clouds in the nucleus is very high, of the order 10^6 - 10^7 cm^{-3} within $\sim$ 500 pc of the radio source,

Using the ATCA, Véron-Cetty *et al.* (1995) imaged the neutral hydrogen content of NGC 6328 and found it to be distributed in an incomplete ring centered on the galaxy nucleus, 37 kpc in diameter, with a fainter envelope which extends over 180 kpc. Véron-Cetty *et al. (1995)* also obtained broadband CCD imaging of NGC 6328 which revealed faint extended spiral-like arms and a bright elliptical-like nuclear region.

Keel & Windhorst (1991) obtained a narrow-band H_α+ N[II] image of NGC 6328 showing the bright nuclear emission region to be a bar-like structure 10” x 20” in extent, oriented approximately north-south, and coincident with the compact radio source.

3.3. Application of data to the BDO97 model

One of the qualitative physical models which has been proposed to explain the overall characteristics of GPS sources involves a radio source which attempts to expand out of the dense nuclear environment of its host galaxy (e.g. OBS91; Stanghellini *et al. 1993).* Recent VLBI observations which have revealed some GPS radio sources to be “miniature radio galaxies” with compact cores, oppositely directed jets, and lobes on milliarcsecond-scales (Taylor, Read head, & Pearson 1996) are suggestive of this interpretation.

BDO97 have developed a detailed model which quantifies this idea and attempts to unify the radio and optical properties of peaked spectrum radio sources, The model is based upon the idea of a relativistic jet from the nucleus which impinges upon and attempts to expand into a clumpy, high-density gaseous medium, producing a small-scale radio lobe; the peaked radio spectrum is the result of extrinsic free-free absorption caused by ionized gas in the environment of the radio source, not synchrotrons self-absorption processes internal to the radio source. Shocks form at the interface of the radio jet and the gaseous medium, producing strong emission lines at optical wavelengths from both the shocked region and a much larger photoionized precursor region. Thus, constraints on the model come not only from VLBI observations of the radio sources but also from optical spectroscopy of the nuclear regions of the host galaxies.

The model evaluates the jet energy flux into the radio lobe, F_E, and the hydrogen number density around the radio lobes, ρ, using observational estimates of the radio lobe pressure, P_{lobe}, and the distance of the radio lobe from the source of the relativistic jet, d_{lobe}. For PKS 171 8–649, from Figure 2, values for these quantities are $P_{lobe} > 10^{-5}$ dyn cm-z and $d_{lobe} \sim$ 1 pc (ignoring projection effects), respectively. Equipartion methods (Bicknell 1994) have been used here to estimate the minimum radio lobe pressure (caused by both electrons and magnetic fields), hence the lower limit. Thus, from BD097 F_E > 1039t;l erg S-l and p > 3 x $10^8 t_6^2$ cm^{-3}, where t_6 is the age of the source in megayears. BDO97 argue that the typical age of GPS sources is a few times 10^5 yr. For PKS 1718–649, if we adopt t_6 = 0.1, then $F_E > 10^{40}$ erg s^{-1} and the density, $p > 3 \times 10^6$ cm-s, agrees well with the range of 10^6 - 107 cm^{-3} inferred from the optical observations of Filippenko (1 985). A young age for PKS 171 8–649 is also consistent with its being the GPS radio source with the smallest linear size, by at least an order of magnitude (cf. 13 DO97).

Further, based upon the model, predictions for the luminosities of the H_β, [0111], and $H_\alpha + [NII]$ emission from the shocked and precursor regions surrounding the expanding radio source in PKS 1718–649 are 6 x 10^{40}, 8 x 10^{39}, and 6 x 10^{41} erg s^{-1}, respectively, In comparison, Filippenko's observations give (assuming isotropic emission) 1 x 10^{40}, 2 x 10^{40}, and 6 x 10^{40} erg s^{-1}, respectively, providing order-of-magnitude agreement with the model (cf. figs 4 & 5, BD097). However, the 2" x 4" aperture used by Filippenko in measuring emission-line luminosities corresponds to 0.6 x 1.2 kpc at the source, whereas BD097 predict that the optical emission lines originate within 0.1 kpc of the radio source. Agreement with the model can only be reached if higher resolution optical observations (i.e. with the HST) reveal that most of the emission-line flux seen by Filippenko occurs within 0.1 kpc of the radio source.

BDO97 also develop an analytical expression for GPS radio spectra, based on the free-free absorption of radio photons by electrons in the shocked and precursor regions. Figure 1 shows that the form of the PKS 1718–649 radio spectrum can be reproduced with this expression, although the fit of the the four free parameters of the spectral model to nine data points is not a conclusive demonstration of the model's validity.

Finally, with the combination of an *average* spectral model, derived from a large sample of GPS spectra, and their dynamical model for the interaction between radio source and environment, BD097 derive the relationship between turnover frequency and source size for GPS sources. If the relationship is calculated for a jet energy flux representative of PKS 171 8–649, 1040 1041 erg s^{-1}, the model predictions agree reasonably well with the observed PKS 1718–649 source size and t u mover frequency, the predicted values being a factor of 2- 5 larger than the observed values.

3.4. The synchrotrons self-absorption interpretation

Since some aspects of the BDO97 model rely heavily on free-free absorption, it is important to contrast this interpretation for PKS 1718–649 with the alternative interpretation, synch rot ron self-absorption (SSA).

An ideal SSA radio spectrum (with no contribution from free-free absorption) will have $\alpha = -(\gamma - 1)/2$ for $\nu > \nu_s$ and $\alpha = 2.5$ for $\nu < \nu_s$, where α is the radio spectral index, γ is the index of the power-law, electron-energy distribution, and ν_s is the critical frequency for SSA (Slysh 1963). Figure 1 shows that this ideal case is not relevant to PKS 171 8–649 since the low-frequency spectrum is much flatter than $\alpha = 2.5$. A partial explanation for this, in the SSA scheme, may be that PKS 171 8–649 consists of two components which almost certainly peak at different wavelengths, given the information on the component spectral indices in Table 5. From the overall spectrum, at least one of the components must have a shallow spectral index at low frequencies. Both components, on the other hand, must become optically thin at high frequencies because the overall spectrum is steep in that regime. Inhomogeneities in the compact components could prod uce such a shallow low-frequency spectrum (Condon & Dressel 1973).

Also, although the components in Figure 2 are resolved, the substantial detection of the two components on intercontinental VLBI baselines indicates highly compact internal structure which is more likely to be affected by synchrotrons self-absorption than the lower resolution structures seen in Figure 2.

We feel that the most easily supported conclusion from these data is that the highly compact cores of the two com ponents cent ribute to the overall spectrum via SSA, but that the dense, ionized gaseous environment of the radio source also contributes to the overall spectrum via free-free absorption. At present it is not possible to determine observationally which of the two mechanisms is dominant, although both appear to be plausible. Future VLBI observations which resolve the source at frequencies other than 4.8 and 8.4 GHz will help us to further investigate SSA models.

3.5. GPS sources from mergers?

It has been speculated that GPS sources may be produced as a consequence of the merging of galaxies, the infall of gas into the center of the merger product fueling, and then smothering, the nuclear radio source (OBS91; Stanghellini *et al.* 1993; O'Dea *et al.* 1996). A CCD imaging survey of GPS radio source host galaxies shows that most have irregular isophotes and/or evidence for multiple nuclei and/or close companion galaxies (Stanghellini *et al.* 1993).

We note that PKS 171 8–649 is an excellent candidate merger system. Optical images show extended spiral-like structure reminiscent of the tidal tails seen in numerical simulations of mergers, and a companion galaxy only 45 kpc to the north (Véron-Cetty *et al. 1995).* What is more suggestive, however, is that the distribution and kinematics of HI in the host galaxy prompted Véron-Cetty *et al.* to conclude that NGC 6328 was formed by the merger of two galaxies, including at least one gas-rich spiral.

Interestingly, recent simulations by Barnes & Hernquist (1996), which track the. evolution of both gas and stars in the merger of two disk galaxies, show that, in the final state of such a merger, 60'%0 of the gas is driven into the inner part of the galaxy, within 100 pc of the nucleus. This nuclear gas assumes a bar-like morphology very similar to that observed by Keel & Windhorst (1991) in PKS 1718–649. Consequently the gas density in the simulations is high, with 66% of the total gas content at densities greater than 10^4 c m^{-3} and a maximum density of $\sim 10^6$ cm^{-3}, agreeing well with the optical observations of Filippenko (I 985) and the results of the BD097 model.

The existence of PKS 1718–649 perpetuates and therefore strengthens the suggestion that there is a link between GPS radio sources and galaxy mergers.

4. CONCLUSIONS

In conclusion, new radio data presented here identifies PKS 1718–649 (NGC 6328) as the nearest GPS radio source, more than four times closer than any GPS source previously known. As a consequence of its proximity and prominence, this is now one of the best studied GPS sources,

The frustrated radio source model, as developed by BDO97, has been applied to the available radio and optical data and can reproduce the radio spectrum of PKS 171 8–649. It is also in order-of-magnitude agreement with observational estimates of the density around the radio source, the radio spectrum turnover frequency, and radio source size, if an age of 105 yr is assumed,

The overall success of the BDO97 model raises the interesting possibility that PKS 171 8–649 is a young radio source which may be frustrated in its development by the dense nuclear environment of its host galaxy, A critical test of this model will come from high-resolution optical observations of the region of the nucleus within 0.1 kpc of the radio source. Future VLBI observations of this source will also be of interest, in an attempt to detect the expansion of the source into its surrounding medium.

We have not tried to constrain SSA models with our data because it is not possible to determine the radio spectra of the individual components in the source accurately. However, it is clear that the two components have significantly different spectra, the south-east component probably having a broader peaked spectrum than the north-west component. And the two components have highly compact radio structures within them, Thus, it is plausible that SSA may make some contribution to the shape of the PKS 171 8–649 radio spectrum, although a contribution from free-free absorption also appears plausible,

Finally, the speculation that GPS sources are formed in merger products is qualitatively supported by the optical morphology and HI kinematics of NGC 6328 and a very general comparison with the results of numerical simulations of galaxy mergers involving gas.

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Frequency	Total Flux Density (Jy)	VLBI Frequency	VLB1 Flux Density (Jy)
408 MHz	2.47	–	–
843 MHz	3.30	–	–
1.4 GHz	3.77	–	–
2.4 GHz	4.70	2,3 GHz	4.6±0.5
4.8 GHz	4.73	4.8 GHz	4.3±0.4
8.6 GHz	3.22	8.4 GHz	3.4±0.3
22.2 GHz	1.75	–	–
90 GHz	0.73	–	–
230 GHz	0.26	–	

Table 1: Flux densities measured at arcsecond resolution (left) and at milliarcsecond resolution (right).

Epoch	Freq. (G H z)	Telescopes
1993 May 14	4.851	Pk,Hb,Na, Mr,Pr27,Ht
1993 July 4	8.418	Ds45,Pk,Hb, Na,Mr,Ht
1994 Feb. 23	2.290	Pk,Hb,Na,Mr

Table 2: Log of the VLBI observations: Pk = Parkes (64 m, ATNF), Hb = Hobart (26 m, Uni. Tas.), Na = Narrabri (22 m, ATNF), Mr = Mopra (22 m, ATNF), Pr27 = Perth (27 m, Telstra), Ht = Hartebeesthoek (26 m, HRAO), Ds45 = Tidbinbilla (34 m, DSN).

Property	NW Comp.	SE Comp.
Size (mas)	2,3 X 1.2	2.4 X 1.5
Maj. axis PA (^{0})	6	55
Flux density (Jy)	3.0	1.3
Brightness temp. (K)	5×10^{10}	2×10^{10}
Luminosity (W/Hz)	1.0 X1024	4,3 X1023
$\alpha_{4.8}^{8.4}$ (s" $\propto \nu^{\alpha}$)	–0.8	–0.3

Table 3: VLBI radio properties of the two compact components in PKS 171 8–649 at the frequency of 4.8 GHz, including the 4.8 to 8.4 GHz spectral indices.

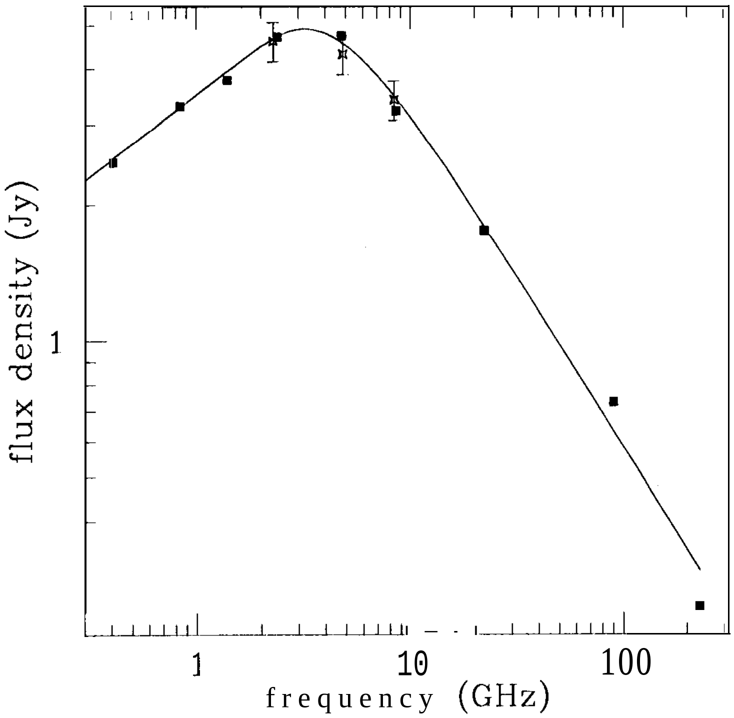

Fig. 1.— Radio spectrum of PKS 1718–649. Total flux densities from single-dish or synthesis (MOST or ATCA) observations are shown as filled squares between 408 MHz and 230 GHz. VLB1 flux densities from SHEVE observations are shown as open stars with errorbars between 2.3 and 8.4 GHz. Finally, the solid line fitted to the total flux densities is from the free-free absorption model of BDO97, using the following free parameter values (described in BDO97): $A = 6.5$, $\nu_0 = 4.0$, $\alpha = 0.65$, and $P = -0.47$.

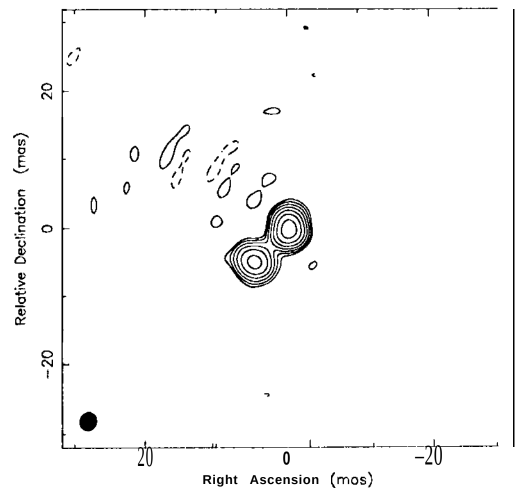

Fig. 2.— 4.8 GHz SHEVE VLBI image of PKS 1718–649. The contour levels shown are -1, 1, 2, 4, 8, 16, 32, and 64% of the peak flux density of 2.0 Jy beam^{-1}. The restoring beam FWHM dimensions are 2.6 x 2.3 mas and its major axis position angle is -29.5°.

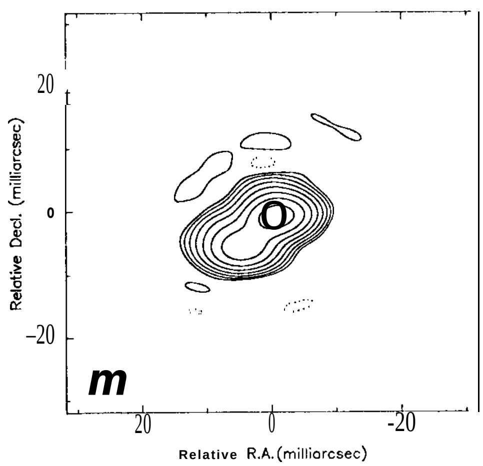

Fig. 3,— 8.4 GHz SHEVE VLB1 image of PKS 1718–649. The contour levels shown are -0.5, 0.5, I, 2, 4, 8, 16, 32, and 64% of the peak flux density of 1.8 Jy beam-l. The restoring beam FWHM dimensions are 6.4 x 3.8 mas and its major axis position angle is -83.2°.