PKS 1018−42: A POWERFUL, KINETICALLY DOMINATED QUASAR

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ABSTRACT

We have identified PKS 1018−42 as a radio galaxy with extraordinarily powerful jets, over twice as powerful as any 3CR source of equal or lesser redshift except one (3C 196). It is perhaps the most intrinsically powerful extragalactic radio source in the still poorly explored southern hemisphere. PKS 1018−42 belongs to the class of FR II objects that are kinetically dominated; the jet kinetic luminosity, \( Q \approx 6.5 \times 10^{46} \text{ erg s}^{-1} \) (calculated at 151 MHz), is 3.4 times larger than the total thermal luminosity (IR to X-ray) of the accretion flow, \( L_{\text{bol}} \approx 1.9 \times 10^{46} \text{ ergs s}^{-1} \). It is the fourth most kinetically dominated quasar that we could verify from existing radio data. From a review of the literature, we find that kinetically dominated quasars such as PKS 1018−42 are rare, and we list the five most kinetically dominated sources found from our review. Our results for PKS 1018−42 are based on new observations from the Australia Telescope Compact Array.

Subject headings: accretion, accretion disks — black hole physics — galaxies: active — galaxies: jets — quasars: general — quasars: individual (PKS 1018−42)

1. INTRODUCTION

The southern sky below a declination of \(-40^\circ\) is still not well explored in the radio band as compared with the northern sky, and many of the intrinsically most powerful radio sources might not have ever been imaged in detail at radio wavelengths. Suspecting this to be the case, we began to search for evidence of the most powerful southern hemisphere radio sources from archival spectral information. Two sources stood out: PKS 0743−67 (reported in Punsly & Tingay 2005) and PKS 1018−42.

In this Letter, we present the first deep radio observations of PKS 1018−42, a quasar at \( z = 1.28 \) (Hewitt & Burbidge 1993) with a 5 GHz flux density of over 1.2 Jy (Gregory et al. 1994). The steep radio spectrum of PKS 1018−42 over a frequency range of 80 MHz (Slee 1995) to 31.4 GHz (Geldzahler & Witzel 1981) suggests that the source is dominated by optically thin radio lobe emission rather than Doppler-boosted core emission. Because of its southerly declination, there are no previously published deep radio maps of this extremely powerful object; however, Ulvestad et al. (1981) obtained VLA observations that give an indication of some source structure. Basic structural information from the VLA observations was limited only to the 20 cm wave band.

We have used Australia Telescope Compact Array (ATCA) observations to separate the core and lobe emission between 2.5 and 8.6 GHz, in order to calculate the time-averaged kinetic luminosity of the jets, \( Q \approx 6.5 \times 10^{46} \text{ erg s}^{-1} \), making PKS 1018−42 one of the most kinetically dominated quasars known. In this Letter we adopt the following cosmological parameters: \( H_0 = 70 \text{ km s}^{-1} \text{ Mpc}^{-1} \), \( \Omega_m = 0.7 \), and \( \Omega_{\Lambda} = 0.3 \). We use the radio spectral index, \( \alpha \), as \( S \propto \nu^{-\alpha} \).

2. THE RADIO OBSERVATIONS

ATCA was used to obtain observations of PKS 1018−42 on 2001 December 16, in a series of 20 minute “cuts” over a 12 hr period. For half of the cuts, ATCA was configured to observe at frequencies of 1384 and 2496 MHz (1.4 and 2.5 GHz), and 4800 and 8640 MHz (4.8 and 8.6 GHz) were used for the other half. The observations took place while the array was in a 6 km baseline configuration, allowing maximum angular resolution. At all frequencies, the bandwidth was 128 MHz in each of two crossed linear polarizations.

Standard data reduction and imaging techniques were used to produce images from the data (Sault et al. 1995). Stokes \( I, Q, \text{ and } U \) images were produced from the 2.5, 4.8, and 8.6 GHz data. It was found that the 4.8 GHz data proved of insufficient angular resolution to be useful. Figure 1 shows the resulting image of PKS 1018−42 at 4.8 GHz. A core is centrally located between two powerful lobes. Estimates of component sizes and positions were made by model-fitting the \( u-v \) data with point sources, circular Gaussian, and elliptical Gaussian components in the DIFMAP package (Shepherd et al. 1994) and are summarized in Table 1.

We are confident that we have recovered the full flux density of the source at each frequency since at 8.6 GHz, our highest frequency and therefore highest angular resolution, our total measured flux density of 0.63 Jy matches the independently determined single-dish flux density at this frequency (Wright et al. 1991). We note that the 8.6 GHz image implies an axial length of 14.9′. In our adopted cosmology, this corresponds to an axial length of \( D = 140 \text{ kpc} \).

3. ESTIMATING THE JET KINETIC LUMINOSITY

We estimate the jet kinetic luminosity from the isotropic extended emission, applying a method that allows one to convert 151 MHz flux densities, \( F_v \) (measured in janskys), into estimates of kinetic luminosity, \( Q \) (measured in ergs per sec-
(Large et al. 1981) and 25.5 Jy (Slee 1995), respectively. Thus, the 408 and 160 MHz flux density of 0.016 Jy. The core spectrum therefore appears to represent pure accretion luminosity. The piecewise collection of thermal emission from the accretion flow, including any radiation in broad emission lines from photoionized gas or as IR reprocessed by molecular gas. In order to estimate $L_{\text{bol}}$, we construct a composite spectral energy distribution (SED) of a quasar accretion flow (Punsly & Tingay 2005). In order to separate the accretion flow thermal luminosity from IR and optical contamination from the jet, a SED for radio-quiet quasars (normalized to $M_v = -25$) was chosen, since this represents pure accretion luminosity. The piecewise collection of power laws in Table 2 is used to approximate the individual bands in the SED. The second and third columns are the start and stop frequencies for each local power law. The fourth and fifth columns are the log of the frequency and the peak fractional polarization.

### Table 1: ATCA Radio Data for Core and Lobes of PKS 1018–42

<table>
<thead>
<tr>
<th>Frequency (MHz)</th>
<th>Beam (arcsec)</th>
<th>Component</th>
<th>Flux (Jy)</th>
<th>FWHM (arcsec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1384 . . .</td>
<td>7.4 × 8.7</td>
<td>North</td>
<td>1.07</td>
<td>3.4 × 1.5</td>
</tr>
<tr>
<td>2496 . . .</td>
<td>4.2 × 3.5</td>
<td>North</td>
<td>0.51</td>
<td>1.7 × 1.4</td>
</tr>
<tr>
<td>4800 . . .</td>
<td>2.3 × 1.9</td>
<td>Core</td>
<td>0.12</td>
<td>5.7 × 1.3</td>
</tr>
<tr>
<td>8640 . . .</td>
<td>1.3 × 1.1</td>
<td>South</td>
<td>0.06</td>
<td>1.9 × 0.0</td>
</tr>
<tr>
<td>151</td>
<td></td>
<td>Total</td>
<td>1.77</td>
<td>1.2 × 0.7</td>
</tr>
<tr>
<td>25</td>
<td></td>
<td>Total</td>
<td>2.40</td>
<td>2.0 × 0.0</td>
</tr>
<tr>
<td>1.4 GHz</td>
<td></td>
<td>Total</td>
<td>0.96</td>
<td>1.3 × 0.7</td>
</tr>
<tr>
<td>4800</td>
<td></td>
<td>Total</td>
<td>1.26</td>
<td>1.0 × 0.0</td>
</tr>
<tr>
<td>4.8 GHz</td>
<td></td>
<td>Total</td>
<td>0.49</td>
<td>0.63</td>
</tr>
</tbody>
</table>

- Core not detected/resolved at 1384 MHz.
- Core detected but appears highly extended in the direction of the lobes. Lobe emission is probably contaminating the estimate of core flux and size.
- Core unresolved in direction perpendicular to the lobe direction.
- South lobe resolved into four subcomponents, between 0.01 and 0.20 Jy in flux and 0.05 and 1.70 in size. The flux given is the sum of the subcomponent fluxes.

### Table 2: Composite SED of a Radio-quiet Quasar ($M_v = -25$)

<table>
<thead>
<tr>
<th>Band</th>
<th>Start</th>
<th>End</th>
<th>Start</th>
<th>End</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mid-IR</td>
<td>12.5</td>
<td>13.35</td>
<td>44.65</td>
<td>45.3</td>
<td>1</td>
</tr>
<tr>
<td>Near-IR</td>
<td>13.35</td>
<td>14.4</td>
<td>45.3</td>
<td>44.95</td>
<td>1</td>
</tr>
<tr>
<td>Optical</td>
<td>14.4</td>
<td>15.0</td>
<td>44.95</td>
<td>45.45</td>
<td>1</td>
</tr>
<tr>
<td>UV</td>
<td>15.0</td>
<td>15.4</td>
<td>45.45</td>
<td>45.6</td>
<td>2</td>
</tr>
<tr>
<td>EUV/soft X-ray</td>
<td>15.4</td>
<td>17.25</td>
<td>45.6</td>
<td>44.3</td>
<td>2, 3, 4</td>
</tr>
<tr>
<td>X-ray</td>
<td>17.25</td>
<td>19.4</td>
<td>44.3</td>
<td>44.3</td>
<td>4</td>
</tr>
</tbody>
</table>

**References:**
particularly useful, since it allows knowledge of IR, UV, or particularly in order to compute actual spectra (referenced in the last column of Table 3) of cross-correlated with archival VLA and MERLIN radio maps, from Archibald et al. (2001) and IR data for $z \approx 100$ one can only use the reprocessed IR dust emission, which peaks around 100 GHz estimate of $Q$ and $R = 5$ for the 4.8 GHz estimate of $Q$.

It is interesting to ask how rare it is to find a kinetically dominated quasar, $R > 1$. The natural place to find $R > 1$ sources is among the highest-redshift sources in a low radio frequency–UV quasar luminosity is reprocessed in the broad-line region. Combining this with the continuum luminosity yields $L_{\text{bol}} = 1.35 \times 10^{46} \text{ ergs s}^{-1}$. Now if one assumes that the shape of the SED is unchanged with the magnitude of $L_{\text{bol}}$, then Table 2 is particularly useful, since it allows knowledge of IR, UV, or X-ray flux to estimate $L_{\text{bol}}$. Namely, $L_{\text{bol}}(1.35 \times 10^{46} \text{ ergs s}^{-1})$ scales with the value of the measured $\nu F_\nu$ divided by the value of $\nu F_\nu$ in the composite of Table 2 at the selected frequency of observation. With this assumption, the UV continuum flux density at the rest-frame frequency of $1.37 \times 10^{15} \text{ Hz}$ in the spectrum of PKS 1018–42 from Stickel et al. (1993) applied to the composite in Table 2 yields $L_{\text{bol}} = 1.9 \times 10^{46} \text{ ergs s}^{-1}$. Thus, $R = 3.4$ for the 151 MHz estimate of $Q$ and $R = 5$ for the 4.8 GHz estimate of $Q$.

To determine the rate of occurrence of kinetically dominated quasars, the UV data from Véron-Cetty & Véron (2001) were cross-correlated with archival VLA and MERLIN radio maps, in order to single out possible large-$R$ quasar candidates. The actual spectra (referenced in the last column of Table 3) of sources that looked promising were subsequently studied explicitly in order to compute $L_{\text{bol}}$. Similarly, submillimeter data for high-redshift, $z > 3.0$, sources (redshifted dust emission) from Archibald et al. (2001) and IR data for $z < 1.5$ sources from Meisenheimer et al. (2001) and Haas et al. (2004) were used to estimate $L_{\text{bol}}$ for obscured quasars with powerful radio emission. An exhaustive search of the literature revealed very few sources with $R$ larger than that of PKS 1018–42. We found deep radio observations of more than 800 radio-loud quasars, primarily in the references Akujor et al. (1991), Akujor & Garrington (1995), Antonucci & Ulvestad (1985), Bogers et al. (1994), Hintzen et al. (1983), Hutchings et al. (1988), Liu et al. (1992), Lonsdale et al. (1993), Mantovani et al. (1992), Murphy et al. (1993), Neff et al. (1989), Neff & Hutchings (1990), Punsly (1995), and Reid et al. (1999), with $M_{\text{t}}$ tabulated in Véron-Cetty & Véron (2001). In addition, there were another ~100 powerful FR II radio galaxies with IR data from Archibald et al. (2001), Meisenheimer et al. (2001), or Haas et al. (2004) and deep radio observations. The large-$R$ sources are tabulated in Table 3. The first two columns are the source and its redshift, followed by $Q$ and $R$ computed with equation (1a). The fifth column is the frequency in which a rest-frame flux density was used to estimate $L_{\text{bol}}$ from Table 2. The sixth column is the UV spectral index, when it was available. Despite this search, two of the four highest-$R$ sources in Table 3, 3C 82 and PKS 1018–42, had no previously published radio maps and were found by looking for high-redshift sources in Véron-Cetty & Véron (1991) with the largest low-frequency flux densities and steep spectral indices. These were the most promising candidates out of the 6225 quasars. This initiated follow-up observations, reported here and in Semenov et al. (2004).

The two estimates for both 3C 82 (the highest-redshift 3C quasar known) and 3C 9 (the highest-redshift 3CR quasar) in the IR and UV are in close agreement, verifying the validity of the composite in Table 2. Both 3C 405 and 3C 190 were added to the list of the five largest-$R$ sources for comparison purposes. The source 3C 405 (Cygnus A) is the best-studied example of a very high $Q$ radio galaxy, and the close agreement between the X-ray and IR estimates for 3C 405 are also affirmation of the application of Table 2. Note the difference in the estimates for 3C 190. The IR and the continuum UV estimate at $1.34 \times 10^{15} \text{ Hz}$ disagree tremendously. This is because 3C 190 is an obscured quasar with a red spectrum, indicated by the steep UV spectral index of 3. Thus, a third estimate for 3C 190 is given, $L_{\text{bol}} = 1.07 \times 10^{45} \text{ Hz}$, from the Mg II broad emission line. According to Wang et al. (2004), $L_{\text{bol}} = 165L_{\text{Mg II}}$, where $L_{\text{Mg II}}$ is the line luminosity. This 3C 190 line estimate agrees with the IR estimate, consistent with an attenuated line of sight toward the accretion disk but not toward the low-ionization broad-line region. The main reason for including 3C 190 is the rather steep UV spectral index of PKS 1018–42. This might raise some concerns about a heavily obscured accretion flow that is skewing the estimate of $R$. We note that the Mg II line estimator agrees with the UV continuum estimate.

### Table 3: The Most Kinetically Dominated Quasars

<table>
<thead>
<tr>
<th>Source</th>
<th>$z$</th>
<th>$Q$ ($10^{46}$ ergs s$^{-1}$)</th>
<th>$R$ ($10^{15}$ Hz)</th>
<th>$\alpha$</th>
<th>Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>3C 82</td>
<td>2.878</td>
<td>155.4</td>
<td>10.7</td>
<td>0.7</td>
<td>1</td>
</tr>
<tr>
<td>3C 9</td>
<td>2.009</td>
<td>148.3</td>
<td>6.22</td>
<td>1.67</td>
<td>1</td>
</tr>
<tr>
<td>4C 45.21</td>
<td>2.686</td>
<td>59.3</td>
<td>5.93</td>
<td>1.67</td>
<td>3</td>
</tr>
<tr>
<td>PKS 1018–42</td>
<td>1.28</td>
<td>65.2</td>
<td>5.11</td>
<td>1.14</td>
<td>2</td>
</tr>
<tr>
<td>3C 190</td>
<td>1.195</td>
<td>42.63</td>
<td>13.1</td>
<td>1.34</td>
<td>5</td>
</tr>
<tr>
<td>TXS 1243+036</td>
<td>3.57</td>
<td>114.8</td>
<td>2.71</td>
<td>0.0016</td>
<td>7</td>
</tr>
<tr>
<td>3C 405</td>
<td>0.056</td>
<td>23.2</td>
<td>0.75</td>
<td>0.005</td>
<td>8</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>0.93</td>
<td>100</td>
<td>9</td>
</tr>
</tbody>
</table>

5. CONCLUSION

In this Letter, we have investigated radio images of a very powerful quasar, PKS 1018–42, that is not well known as a consequence of its southerly declination. However, PKS 1018–42 is extraordinarily powerful, with jets over twice as powerful as any 3CR source of equal or lesser redshift except for one (3C 196), and is certainly worthy of more detailed study. We found that it is kinetically dominated, with $R \sim 3–5$. It is the fourth most kinetically dominated quasar that we could verify from existing radio maps.

We showed in Table 3 that kinetic dominance is a particularly rare circumstance for quasars. This is consistent with the study of 7C sources by Willott et al. (1999), which was based on estimating $L_{\rm bol}$ from O II narrow line emission. The O II narrow lines are very distant from the central quasar, and it is not clear how much jet propagation excites narrow line emission (see Veilleux & Bland-Hawthorn [1997] for one of many examples of narrow line emission that is stimulated by jet propagation).

Using the UV luminosity from the central quasar directly as a measure of the long-term activity of the radio source over $\sim 10^7$ years and so is not contemporaneous with the thermal emission from the accretion flow (Punsly 2005). The timescale for the extended emission is so long that it would seem there must be sources in which the accretion engine has long since shut off despite powerful radio lobe emission 100 kpc away. Where are the “fossil” sources with $Q \approx 5 \times 10^{45}$ erg s$^{-1}$ and the accretion flow almost shut off, $L_{\rm bol} \approx 10^{46}$ erg s$^{-1}$? Perhaps some can be found as distant, $z > 1.5$, 3C narrow-line galaxies with improved IR sensitivity. The Spitzer IR telescope is ideal for looking for such hidden kinetically dominated quasars. PKS 1018–42 would be an interesting source for the Spitzer telescope, in order to verify its standing in Table 3. However, Spitzer observations to date have not added any new sources to Table 3 (Haas et al. 2005). Alternatively, the absence of such sources might tell us something about the fundamental nature of the quasar jet central engine.

REFERENCES

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