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Near-infrared spectroscopy of PKS 1549—79: a protoquasar revealed?

M. J. Bellamy, C. N. Tadhunter, R. Morganti, K. A. Wills, J. Holt, M. D. Taylor and C. A. Watson

Department of Physics and Astronomy, University of Sheffield, Sheffield S3 7RH
Netherlands Foundation for Research in Astronomy, Postbus 2, 7990 AA Dwingeloo, the Netherlands

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ABSTRACT

We present a near-infrared (near-IR) spectrum of the nearby radio galaxy PKS 1549—79 (z = 0.153). These data were taken with the aim of testing the idea that this object contains a quasar nucleus that is moderately extinguished, despite evidence that its radio jet points close to our line of sight. We detect broad Paα emission (FWHM 1745 ± 40 km s⁻¹), relatively bright continuum emission, and a continuum slope consistent with a reddened quasar spectrum (3.1 < A_v < 7.3), all emitted by an unresolved point source. Therefore we conclude that we have, indeed, detected a hidden quasar nucleus in PKS 1549—79. Combined with previous results, these observations are consistent with the idea that PKS 1549—79 is a young radio source in which the cocoon of debris left over from the triggering events has not yet been swept aside by circumnuclear outflows.

Key words: galaxies: active – galaxies: individual: PKS 1549—79 – quasars: emission lines – quasars: general – infrared: galaxies.

1 INTRODUCTION

In recent years, much active galactic nuclei (AGN) research has been conducted in the context of ‘unified schemes’ (e.g. Barthel 1989); i.e. that differences between certain types of active galaxy can be explained by orientation effects. A great deal of AGN research is based around refining and constraining such models. However, the simplest unified models generally describe a static and unchanging situation, a steady-state regime, and this is unlikely to be realistic. As the activity evolves it is likely to affect the distribution of the interstellar medium (ISM) surrounding the nucleus, potentially influencing the evolution of the host galaxy. To better understand these processes it is necessary to develop a more dynamic, evolutionary model for AGN, and to this end it is important to study sources at different evolutionary stages.

The existence of compact steep-spectrum (CSS) and GHz-peaked (GPS) radio sources, which are intrinsically small, illustrates the fact that there is a large range in the physical dimensions of extragalactic radio sources. The compactness of these sources must either be due to frustration, where a dense ISM is inhibiting the expansion of the radio lobes, or to youth, in which case the radio lobes simply have not yet had time to expand. Of these two possibilities youth seems the most likely (e.g. Fanti et al. 1995). Broad forbidden lines are also much more common in these compact sources, suggesting that the cores of these sources are more unsettled (Gelderman & Whittle 1994). Moreover, Baker et al. (2002) find an anti-correlation between C iv absorption – which they show to be associated with dusty regions – and radio source dimensions; the absorption becoming less pronounced with increasing size. It is therefore becoming apparent, and perhaps expectedly so, that young radio-loud AGN suffer greater dust extinction than their more evolved counterparts, with the nucleus still surrounded by a cocoon of dust and gas.

Based on its emission linewidths and kinematics, the southern radio galaxy PKS 1549—79 (z = 0.153) appears to be just such a young source. The observed properties of this unusual object are discussed in detail in Tadhunter et al. (2001) (hereafter T2001). The flat spectrum, compactness of the radio emission (∼150 mas, or ∼540 pc) and one-sided jet morphology of this source indicate that its radio axis is aligned close to our line of sight. In the standard unification model, the source would be expected to resemble a quasar at optical wavelengths, with non-stellar continuum emission and broad permitted lines. However, optical spectra of PKS 1549—79 show a predominantly stellar continuum with no good evidence for broad permitted lines, but with strong and unusually broad forbidden lines (∼1300 km s⁻¹). Amongst powerful radio galaxies such broad forbidden lines are only ever detected in sources that are intrinsically compact. The blueshift of the [O iii] λ5007, 4959 emission lines relative to low-ionization forbidden lines and the H i 21-cm absorption line suggests that the [O iii] emitting region is outflowing at 600 ± 60 km s⁻¹ (T2001, Morganti et al. 2001).

*E-mail: m.bellamy@sheffield.ac.uk

1 We assume cosmological parameters of H₀ = 50 km s⁻¹ Mpc⁻¹ and q₀ = 0 throughout.
Overall, observations suggest that there is significant dust obscuration in this object even though our line of sight is close to the radio axis. This is entirely consistent with PKS 1549–79 being a young radio source in which the obscuring material around the nucleus has not yet been swept aside (T2001). If this model is correct, near-infrared (near-IR) observations—being subject to only ~10 per cent of the visual extinction—should show a bright, non-stellar continuum and broad permitted lines as the quasar shines through the ISM. This is the prediction we test in this paper.

2 DATA COLLECTION AND REDUCTION

The $K$-band IR spectra were taken in shared risks service mode on 2002 July 26 using the IRIS2 instrument on the Anglo-Australian Telescope (AAT). The Sapphire 240 grism was used with a 1-arcsec slit oriented north-south on the sky. The seeing was reported to be 1.1 arcsec throughout the observations; analysis of stars in the 10-s exposure acquisition image is in good agreement with this (see Section 3.1). 22 exposures of 300 s were obtained for PKS 1549–79; the galaxy was ‘nodded’ between two positions on the slit in an ABBA pattern with 11 exposures at each position. Four exposures of 80 s were taken of the AO star HIP 77712 at a similar airmass for calibration purposes.

Each set of 11 galaxy exposures was co-added in the IRAF package using median filtering to remove cosmic rays; the median ‘B’ image was then subtracted from the median ‘A’ image to remove the night sky lines. The standard star frames were combined in a similar way. The resulting galaxy and star frames were then flat-fielded using a dark-subtracted flat-field taken with the same instrumental set-up.

A xenon arc frame was used to make a two-dimensional wavelength calibration which was then applied to the data frames. The original spectra cover the range 20 109–24 640 Å but the useful data presented here cover the range 20 500–23 000 Å. Analysis of the night sky lines shows the uncertainty in the wavelength calibration to be $\pm 0.65$ Å ($\pm 9$ km s$^{-1}$) and the systematic errors are estimated to be $\pm 1$ Å ($\pm 14$ km s$^{-1}$). Fits to the night sky lines show the spectral resolution to be 10.1 $\pm$ 0.4 Å; the pixel scale of 4.43 Å pixel$^{-1}$ is adequate to sample this. The spatial pixel scale of the acquisition image is 0.446 arcsec pixel$^{-1}$. One-dimensional spectra were extracted from the two-dimensional frames, using 11 pixel-wide extraction apertures to aid accurate flux calibration.

The exposures of HIP 77712 were used to flux-calibrate the data, with the assumption that the intrinsic spectral energy distribution (SED) of the star is that of a perfect blackbody at $T = 9480$ K. The magnitude-to-flux conversion was performed with reference to Bessell, Castelli & Plez (1998).

During data reduction it became apparent that there was a problem with the IRIS2 instrument in spectroscopy mode at the time of the observations. All the spectra we had obtained, including arc calibration frames, showed a splitting of spectral features in the wavelength direction. After consulting with the AAT team we were informed that the manufacturers had mounted the Sapphire grisms at right-angles to their intended orientation and that a birefringence effect was leading to the observed doubling. The spectra we obtained are composites of the actual spectrum and a copy of this spectrum, blueshifted by around 50 pixels (~230 Å in the case of these data) relative to the original and at a slightly lower intensity. However, the splitting caused by the birefringence is large enough that useful kinematic information can be extracted for individual lines in the spectra. The final, reduced $K$-band spectrum of PKS 1549–79 is shown in Fig. 1. The Starlink FIGARO and DIPSO packages were used to analyse the data.

3 RESULTS

3.1 Paschen alpha

A single Gaussian provides an adequate fit to each of the two components of the split line. The best fit to the Pa$\alpha$ line(s) is shown in Fig. 2, with the redder peak at the correct wavelength. A constraint was applied that the two Gaussians should have the same width. The results of the fitting are summarized in Table 1.

The fit gives a full width at half maximum (FWHM) of 126 $\pm$ 3 Å ($1745 \pm 40$ km s$^{-1}$ in the rest frame). This value is consistent with the widths of permitted lines in broad line radio galaxies (BLRG) and quasars (Hill, Goodrich & DePoy 1996; Marziani et al. 2001), although it is at the lower end of the range. The relatively small broad linewidths are also consistent with the radio jet being oriented close to our line of sight (Wills & Browne 1986).

The redshift of the Pa$\alpha$ line is found to be $z = 0.15266 \pm 0.00007$. This is consistent with the [O $\it{i}$] redshift of $z = 0.1526 \pm 0.0002$ but inconsistent with the [O $\it{iii}$] (outflow) redshift of $z = 0.1501 \pm 0.0002$ (T2001). This indicates that the Pa$\alpha$ emission originates in a broad line region (BLR) at the systemic redshift. The Pa$\alpha$...
wavelengths corresponding to the [O iii] and [O ii] redshifts are marked on Fig. 2 for comparison.

The K-band continuum flux level is \(\sim 4 \times 10^{-9}\) erg cm\(^{-2}\) s\(^{-1}\) that measured in the optical spectrum of T2001, despite the fact that the optical spectrum was obtained using a larger aperture (4.3 by 5 arcsec). This is inconsistent with the SED of an unreddened stellar population, particularly a young population, but is consistent with that of a moderately obscured quasar source shining through the intervening ISM. A power-law was fitted to the continuum to aid comparisons with quasar continua (see Section 4). The spectral index of this power law is \(\alpha = 2.3 \pm 0.1 (F_\nu \propto \nu^{-\alpha}, F_\lambda \propto \lambda^{\alpha+2})\). This index is significantly larger than that measured for the 16 unreddened sources in the Simpson & Rawlings (2000) sample of radio-loud quasars (\(\sim 1 \times \alpha < 1.6\)), but similar to the two reddened quasars in that sample. If the intrinsic spectrum of PKS 1549–79 is quasar-like then this indicates significant reddening.

The combined flux of both Pa\(\alpha\) components is \((3.16 \pm 0.08) \times 10^{-18}\) erg cm\(^{-2}\) s\(^{-1}\). This flux gives a rest-frame equivalent width of 69 ± 3 \(\AA\) for an assumed continuum flux of \((4.0 \pm 0.1) \times 10^{-16}\) erg cm\(^{-2}\) s\(^{-1}\) \(\AA^{-1}\) in the observed frame. For comparison, the rest-frame Pa\(\alpha\) equivalent widths measured in the low-redshift quasars 3C 273 and PDS 456 are 167 ± 16 \(\AA\) and 120 ± 8 \(\AA\), respectively (Hill et al. 1996; Simpson et al. 1999). Both of these quasar values are significantly larger than that measured in PKS 1549–79. This could indicate the presence of a beamed, non-thermal continuum component in PKS 1549–79, which would further support the theory that the radio jet is oriented towards our line of sight.

If there is a quasar nucleus shining through at near-IR wavelengths then the emission from the galaxy should be dominated by a central, unresolved source. To test this, the spatial intensity profile of PKS 1549–79 was compared with those of four bright stars in the acquisition image. The mean FWHM of the stellar 2D Gaussian measures 1.13 ± 0.06 arcsec in the \(x\)-direction by 1.23 ± 0.06 arcsec in the \(y\)-direction. In comparison, the profile of PKS 1549–79 measures 1.13 ± 0.17 arcsec by 1.43 ± 0.15 arcsec. Therefore PKS 1549–79 appears quasar-like at near-IR wavelengths.

3.2 Other features

Apart from the Pa\(\alpha\) line, the only other feature in the spectrum is a second line visible at \(\sim 22.550\) \(\AA\), subject to the same splitting as the rest of the spectrum. As the line appears faint, the spectrum was re-binned to one-quarter resolution over this region to improve the signal-to-noise ratio (S/N). The line is broad enough for this to be acceptable. The blueshifted split component is too noisy for an adequate fit to be made and so only the redmost component was fitted in Pa\(\alpha\). The fit is shown in Fig. 3 and the results of the fitting are given in Table 1.

The FWHM of this line is 83 ± 14 \(\AA\) (1100 ± 180 km s\(^{-1}\) in the rest frame). Correcting for the fact that only one component was fitted, the total flux of the line is \((3.5 \pm 1.0) \times 10^{-15}\) erg cm\(^{-2}\) s\(^{-1}\). This corresponds to an isotropic luminosity of \((4.1 \pm 1.2) \times 10^{21}\) erg s\(^{-1}\).

The most likely candidate for this emission is the H\(\beta\) \(v = 1\)–0 S(3) line. Our identification is based on redshift arguments, the H\(\beta\) \(v = 1\)–0 line would lie at the same redshift as the Pa\(\alpha\) line, whereas other lines imply large inflow or outflow velocities. However, [Si vi] is also a possibility as the implied outflow velocity and width are broadly consistent with the [O iii] outflow parameters (T2001). The possibility that this feature is a blend of both lines cannot be discounted. However, the low S/N of the data – coupled with the uncertainties introduced by the splitting of the spectrum – means that no definite conclusions can be drawn.

If the feature is indeed H\(\beta\) \(v = 1\)–0 S(3), then PKS 1549–79 is one of the most luminous molecular hydrogen emitters in the local universe, surpassing the H\(\beta\) luminosity of Cygnus A by almost an order of magnitude (Ward et al. 1991; Thornton, Stockton & Ridgway 1999).

Unfortunately no other molecular hydrogen lines are visible in the spectrum with which to compare this result. This is to be expected however, as the H\(\beta\) \(v = 1\)–0 S(3)/[Si vi] feature is only weakly detected and the only molecular line expected to be comparable in luminosity \(\{H\beta\} v = 1\)–0 S(1)) is redshifted out of the useful range of our data.

4 DISCUSSION

Our observations provide clear evidence that emission from the central regions of PKS 1549–79 is significantly affected by dust obscuration. In this section we attempt to estimate the degree of
Table 2. Resulting Paα emission parameters corresponding to the different degrees of reddening as discussed in the text.

| Reddening degree → | Minimum | Average | Maximum |
|--------------------|---------|---------|---------|
| Spectral index α   | 1.62    | 0.90    | −0.67   |
| E_V(σ)             | 0.60    | 1.23    | 2.62    |
| A_V (total)        | 1.8     | 3.8     | 8.0     |
| A_V (intrinsic)    | 1.2     | 3.1     | 7.3     |
| Paα flux (10^{-14} erg s^{-1} Å^{-1}) | 3.95 ± 0.10 | 5.02 ± 0.13 | 8.50 ± 0.22 |
| Paα luminosity (10^{41} erg s^{-1}) | 46.4 ± 1.2 | 59.0 ± 1.5 | 99.8 ± 2.5 |

Notes. a) Assuming Galactic extinction A_V = 0.68 (Schlegel et al. 1998).

reddenings and correct for it in order to obtain a more realistic estimate of the intrinsic Paα luminosity. For comparison, T2001 derive a visual extinction in the range 0.23 < A_V < 18 mag, based on Hα 21-cm absorption characteristics.

First, we try to determine the reddening directly using atomic hydrogen line ratios, these being relatively insensitive to variations in the physical conditions of the emitting medium. With reference to Tadhunter et al. (1993), the Paα/Hβ line ratio is found to be 25 ± 1. Assuming case B recombination, a temperature of 10000 K and an electron density of 10^4 electron cm^{-3}, this line ratio gives E_V(σ) = 1.29 ± 0.01 (Seaton 1979; Osterbrock 1989), corresponding to a visual extinction of A_V = 4.00 ± 0.13 mag (A_V = R × E_V(σ), assuming R = 3.1 ± 0.1). However, there is considerable uncertainty associated with this value because the Hβ emission is likely to be dominated by a narrow line region (NLR) component. The BLR emission from within the obscuring region may then contribute only a fraction, if any, of the total Hβ flux, and therefore the derived extinction is likely to be an underestimate. Recently obtained high-resolution spectra of PKS 1549−79 include Hα emission; however, the Hα line is contaminated with bright [N II] forbidden lines and an atmospheric absorption line. These features will significantly reduce the accuracy of line fittings to the Hα line, and for this reason the line has not been used in this analysis.

Another approach is to fit a power-law to the near-IR continuum and then calculate the de-reddening necessary to make the slope consistent with a quasar spectrum. As stated in Section 3.1., the spectral index of the power-law fit to our data is α = 2.3 ± 0.1. Typical unreddened quasar spectral indices lie in the range −0.67 < α < 1.62 and average α = 0.90 (Simpson & Rawlings 2000). Clearly the spectrum for PKS 1549−79 is considerably redder than even the upper limit. De-reddening of the spectrum to match the quasar range of values requires a visual extinction in the range 1.8 < A_V < 8.0 with A_V = 3.8 for the average case. The full de-reddening results are given in Table 2. If the spectrum is contaminated by a beam, non-thermal component then the intrinsic continuum shape may not resemble a quasar; in the extreme case it may more closely resemble a BL Lac. The six BL Lacs in the Massaro et al. (1995) sample show a tighter range of spectral indices (0.86 < α < 1.19) with an average that is redder than that of the quasar sample. However, as the full range of BL Lac spectral indices lies within the broader range of quasar spectral indices, this result has no significant effect on our conclusions.

To investigate the contribution such reddened power-law continua would make at optical wavelengths, curves were generated for the derived power-laws and then re-reddened by the corresponding amount. Fig. 4 shows the results of this for the maximum, average and minimum extinctions/power-laws derived above. Certainly, the minimum reddening case is ruled out on the basis that the quasar alone would contribute more flux at 8−6000 Å than is detected (T2001). The average reddened power-law — corresponding to that derived from the Paα/Hβ ratio — would also be contributing around 20−50 per cent of the observed flux in the optical region but modelling shows no evidence for such a red power law in this region (Tadhunter et al. 2002). This implies that the actual reddening is closer to the upper limit than to the average, regardless of whether the intrinsic continuum slope more closely resembles a quasar or BL Lac. It seems safe to conclude that the total visual extinction lies in the range 3.8 < A_V < 8.0 mag. This corresponds to an intrinsic extinction in the host galaxy of 3.1 < A_V < 7.3, having corrected for the Galactic extinction of A_V = 0.68 (Schlegel, Finkbeiner & Davis 1998).

The de-reddened Paα fluxes for the three cases are given in Table 2, along with the corresponding isotropic luminosities. Comparison with similarly derived luminosities for quasars and BLRGs (Rudy & Tokunaga 1982; Hill et al. 1996; Simpson et al. 1999) shows that the luminosity corresponding to the average reddening [69.0 ± 1.5] × 10^{41} erg s^{-1}] is more than an order of magnitude less than that measured in the low-z quasars, and at the upper end of the range measured in the BLRGs. These results are consistent with PKS 1549−79 being a low-luminosity quasar.

5 CONCLUSIONS AND FURTHER WORK

The detection of a broad Paα line and a bright, reddened IR continuum indicates that we have, indeed, uncovered an obscured BLR and quasar nucleus in PKS 1549−79. The calculated intrinsic luminosity and equivalent width of the Paα emission, and the star-like profile of the near-IR nucleus, further support this conclusion. Although such findings are unprecedented (Djorgovsk et al. 1991; Hill et al. 1996), PKS 1549−79 is a special case because the observed radio properties lead us to believe that its AGN is viewed from a direction close to that of the radio axis and should therefore

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2 We assume the standard interstellar extinction law of Whitford (1958).

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exhibit the optical/IR properties of radio-loud quasars; i.e. no significant obscuration of the BLR and nucleus. The fact that significant obscuration is seen suggests that PKS 1549−79 is a fundamentally different type of object that does not fit neatly into standard unified schemes.

It is our suggestion that PKS 1549−79 is an AGN in the early stages of evolution; a protoquasar. The high obscuration is a transitory phase that will pass as the gas and dust is dissipated or blown out of the ionization cones by the circumnuclear outflows detected at optical wavelengths (T2001). These IR data support this model and tie in well with expectations.

As a key assumption of the model is that the radio jet is oriented towards us, it is important to validate this assumption. The fact that the PAz equivalent width is significantly smaller than that for a typical quasar is consistent with the presence of a beamed continuum component and may therefore support this assumption. However, this is not sufficient evidence in itself. Multi-epoch very long baseline interferometry (VLBI) imaging of the radio emission could provide incontrovertible evidence that the radio axis is oriented towards us by revealing superluminal motion in the jet.

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