Optical and infrared observations of the luminous quasar PDS 456: a radio-quiet analogue of 3C 273?

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ABSTRACT
We present infrared photometry and optical and infrared spectroscopy of the recently discovered, extremely luminous nearby quasar PDS 456. A number of broad emission features are seen in the near-infrared, which we are unable to identify. We measure a more accurate redshift from a narrow forbidden emission line and compare the optical–infrared spectrum to that of 3C 273. The close similarity suggests that PDS 456 is a radio-quiet analogue of 3C 273, although radio observations do not support this idea.

Key words: galaxies: active – galaxies: distances and redshifts – galaxies: photometry – quasars: emission lines – quasars: individual: PDS 456 – radio continuum: galaxies.

1 INTRODUCTION
Torres et al. (1997; hereafter T97) reported the discovery of a new bright \( V = 14.0 \) quasar at relatively low redshift \( z = 0.184 \). This object, called PDS 456, was discovered in the Pico dos Dias survey for young stellar objects, which uses optical magnitude and IRAS colours as selection criteria. Although somewhat fainter than 3C 273, PDS 456 lies close to the Galactic Centre and is seen through \( A_v \approx 1.5 \) mag of extinction (T97), and it is therefore intrinsically more luminous. It is, however, radio-quiet, with \( S_{408} < 42 \) mJy (Griffith et al. 1994) and \( S_{14} = 22.7 \) mJy (PDS 456 can be identified with NVSS J172819–141555; Condon et al. 1998), where \( S \) is the flux density at \( 408 \) MHz.

In this paper we present optical and infrared observations of PDS 456. We confirm the redshift found by T97, and make a more accurate determination based on the unblended narrow emission line of [Fe II] \( \lambda 1.6435 \mu m \). We also confirm the existence of significant Galactic reddening. We compare the properties of PDS 456 with those of 3C 273, with which it has a number of similarities, and investigate the possibility that it is a radio-quiet analogue of the latter source.

We adopt \( H_0 = 50 \text{ km s}^{-1} \text{ Mpc}^{-1} \) and \( q_0 = 0.1 \). With this cosmology and our improved redshift determination, the proper distance to PDS 456 is 1.01 Gpc.

2 OBSERVATIONS AND REDUCTION

2.1 Infrared imaging
\( JHKLM \) images of PDS 456 were obtained using IRCAM3 on the United Kingdom Infrared Telescope (UKIRT) on UT 1997 August 24. Standard near-infrared jittering techniques were used to allow flat-fielding without the need to observe blank regions of sky. The dark-subtracted images were scaled to the same median pixel value and median-filtered to produce a flat-field image, which was divided into the individual frames. These frames were then registered using the centroid of the quasar and averaged with bad pixel masking. Total integration times were 50 s at \( JHK \), 270 s at \( L' \), and 72 s at \( M \). Conditions were photometric and flux calibration was performed using a solution derived from observations of a number of standard stars during the course of the night. Similar observations were also performed with the same instrument on UT 1997 September 16.

2.2 Infrared spectroscopy
Near-infrared spectra of PDS 456 in the \( J \) and \( K \) windows were taken using UKIRT/CGS4 on UT 1997 August 12 and 10, respectively. Conditions were photometric throughout and both spectra have a resolution \( R \approx 900 \) and total integration times of 640 s. Bad pixel masking and interleaving of the separate integrations was performed with the Starlink CGS4DR software, and the remaining reduction was undertaken with the IRAF data reduction package. The spectra were taken through a 1.2-arcsec slit and extracted along a single 1.2-arcsec pixel. The \( J \) spectrum was corrected for atmospheric absorption and flux calibrated using the A2 star HD 161903. The \( K \) spectrum used the F0 star SAO 121857 as an atmospheric dividing standard and was flux calibrated using HD 225023. The spectra were wavelength calibrated using krypton \( (J\text{-band}) \) and argon \( (K\text{-band}) \) arc lamps and the rms deviation from the adopted fit was \( \lesssim 1 \AA \).

An 8–13 \( \mu m \) spectrum of the source was taken with UKIRT/ CGS3 on UT 1997 August 30 as a service observation. A 5.5-arcsec aperture was used with the low-resolution grating, which gives a resolution \( R \approx 50 \). Triple sampling was employed and the total
integration time was 3600 s. A spectrum was taken of $\alpha$ Aql (Altair) at similar airmass, which was used for flux calibration using its ratio with the spectrum of $\alpha$ Lyr (Vega, assumed to be a 9400-K blackbody) from Cohen & Davies (1995).

2.3 Optical spectroscopy

Optical spectra were taken with the Intermediate Dispersion Spectrograph (IDS) on the 2.5-m Isaac Newton Telescope (INT) as service observations on the night of UT 1997 August 22. Four grating settings were used to cover the entire optical spectrum from 3320–9150 Å at a dispersion of $\sim$1.6 Å pixel$^{-1}$. A 1.5-arcsec slit was used, and the seeing was reported to be 1.0 arcsec. The total integration time at each position was 500 s, split into three separate exposures to facilitate cosmic ray removal. Wavelength calibration was achieved through the use of argon and neon lamps, and the rms deviation from the adopted fit was $\lesssim$0.1 Å for all wavelength regions except in the range 5800 Å $\leq$ $\lambda$ $\leq$ 6100 Å, where the arc lines were saturated, and the deviations became as large as 1.5 Å. We determined the flux-scale using Bohlin’s (1996) spectrum of BD +33°2642 (which was also observed with the same instrumental setup), available from the Space Telescope Science Institute. The three exposures at each grating position were averaged together after masking out cosmic ray hits, and the spectra merged by using the regions of overlap to compute necessary greyshifts between the different grating positions. Shifts of up to 8 per cent were needed to match up the flux-scales, and it was noted that the fluxes in the different exposures taken at a single grating position differed by as much as 25 per cent. This strongly suggests the presence of clouds or significant slit losses, and as such the flux-scale must be considered approximate.

3 RESULTS AND ANALYSIS

3.1 Photometry

The results of our aperture photometry are presented in Table 1. The flux calibration solutions for the night of 1997 September 16 were slightly more uncertain than for the night of 1997 August 24, but we find no evidence for variability in any of the five filters at greater than 2$\sigma$ significance. This supports the lack of variability observed by T97 at optical wavelengths over a period of three weeks.

A power-law fit to the observed $H - K$ colour (and $K$-band continuum from our spectrum) gives $\alpha = 2.4 \pm 0.1$ ($S \propto \nu^{-\alpha}$). This is very steep for quasars, which have typical spectral indices $\alpha = 1.4 \pm 0.3$ (Neugebauer et al. 1987), and suggests significant reddening is present. The near-infrared colours imply $A_V = 1.5 \pm 1.0$, in line with the estimate of T97.

3.2 Spectroscopy

We present our near-infrared spectra in Figs 1 and 2. We confirm the redshift found by T97 on the basis of the [Fe ii] $\lambda$1.6435 μm emission line, the only unblended forbidden line in the entire spectrum. The sharpness of this line (FWHM $\approx 1000$ km s$^{-1}$)
allows a more accurate redshift determination than from the broad lines, and we measure \( z = 0.18375 \pm 0.00030 \). The optical spectrum is shown in Fig. 3.

There are a number of emission features in our near-infrared spectra which we are unable to identify. Their rest wavelengths (assuming they are at the redshift of PDS 456) do not correspond to lines seen in the spectra of other quasars or Seyfert galaxies (e.g. Hill, Goodrich & DePoy 1996; Thompson 1995). However, they also do not correspond to features in the dividing standards, the spectra of which we also show in Figs 1 and 2. The emission features observed at 1.185 and 1.245 \( \mu \text{m} \) are the most clearly real, since the emission feature observed at 1.095 \( \mu \text{m} \) may be composed partly of Pa\( \gamma \) from the dividing standard and Pa\( \alpha \) from the quasar. However, the former line is in a fairly clean part of the atmosphere and was readily removed, and Pa\( \gamma \) should be weaker than Pa\( \alpha \). It therefore appears that there may be another unidentified emission line at this wavelength. The weak broad feature near 2 \( \mu \text{m} \) is at the wrong wavelength to be caused by imperfectly subtracted atmospheric CO\(_2\) absorption, and again we suspect it is a real emission feature in the quasar spectrum. We have re-reduced the \( J \)-band spectrum with a dividing standard of completely different spectral type (K0III), and we also re-observed PDS 456 in the \( J \) window with a different camera/grating combination of CGS4 on UT 1998 August 26. In both cases the final spectrum was indistinguishable from Fig. 2. The wavelengths of the lines are inconsistent with their being lines from higher orders (e.g. H\( \alpha \)), and their relative wavelengths do not correspond to any pair of strong lines, so we can rule out their being from a single system at a different redshift (either lower or higher). We obviously cannot conclusively rule out their being more than one additional system along the line of sight.

**Figure 2.** Observed \( K \)-band spectrum of PDS 456. The top trace shows the normalized spectrum of SAO 121857. Note how the weak broad feature near 2 \( \mu \text{m} \) is at the wrong wavelength to be imperfectly removed CO\(_2\) absorption.

**Figure 3.** Optical spectrum of PDS 456. The Balmer lines are marked, and atmospheric absorption features are indicated by a circled cross symbol. The dashed line is the same spectrum after removal of the optical Fe\( \text{II} \) emission (see text for details), and shifted downwards for clarity.
although this is very unlikely, especially given our small spectroscopic aperture. The H\textsc{i} lines have such broad wings (FWZI \( \gtrsim 30\,000\,\text{km}\,\text{s}^{-1} \)) that fluxes are difficult to measure reliably. In addition, many of the lines are blended, further hampering measurements of their fluxes. We have opted to use the Pa\textsc{\textalpha} line as a template for measuring the fluxes of the blended H\textsc{i} lines. We first subtract a low-order cubic spline from our K-band spectrum, masking out regions contaminated by emission lines, and interpolating across the Br\textsc{\textdelta} line. We then progressively subtract a scaled version of the Pa\textsc{\textalpha} line from the locations of the other emission lines until the resultant spectrum shows no evidence of line emission. We determine the strength of the other line in the blend by measuring the flux above an adopted continuum level in the spectrum with the hydrogen line subtracted. In the case of He\textsc{i} \( \lambda 5876\,\mu\text{m} \) (blended with Pa\textsc{\textgamma}), this results in a very broad line (FWHM \( \approx 7000\,\text{km}\,\text{s}^{-1} \), compared to FWHM \( \approx 3500\,\text{km}\,\text{s}^{-1} \) for the H\textsc{i} lines) with a pronounced blue wing, as can be anticipated from Fig. 2. While no strong emission lines have been observed in this wavelength region in other objects, we cannot rule out the possibility that the He\textsc{i} line is further blended because of the presence of the unidentified emission lines in our spectrum. We note, however, that Netzer (1976) suggests that the He\textsc{i} lines should be broader than those of H\textsc{i}.

A determination of the H\textbeta{} flux is further complicated by the strong Fe\textsc{\textii} emission which produces a 'pseudo-continuum' on both sides of the emission line. We removed the Fe\textsc{\textii} emission from the spectrum by first performing a fit (by eye) to the emission lines so that the continuum was approximately linear over short wavelength intervals. A Gaussian fit to the isolated 4177 and 5534 \( \AA \) lines was used to model the profiles of the lines. We then took each individual line in turn and determined the flux which produced the minimum sum-of-squares residual about a continuum level, which was linearly interpolated between points either side of the line. A new spectrum was constructed using these line fluxes and the process repeated until the result converged. The Fe\textsc{\textii}-subtracted spectrum is shown in Fig. 3.

From this analysis, we measure the flux of the Fe\textsc{\textii} multiplets at \( F(\lambda 4570) = (5.1 \pm 0.7) \times 10^{-18}\,\text{W}\,\text{m}^{-2} \) and of the H\textbeta{} line at \( F(H\beta) = (1.1 \pm 0.2) \times 10^{-15}\,\text{W}\,\text{m}^{-2} \), three times larger than that determined by T97. We believe this discrepancy is the result of an incorrect placement of the continuum level by T97 when performing their simple flux determination. The value we obtain from our more detailed method is likely to be far more accurate. The line fluxes are listed in Table 2. Note that for this Table and future discussions, we have brightened our K-band spectrum by 25 per cent to match our photometry, suspecting poor seeing and slit losses for the difference; no such shift was needed for the J-band spectrum. The equivalent width of H\textbeta{} is fairly typical of nearby luminous quasars (Miller et al. 1992) and the ratio Fe\textsc{\textii} \( \lambda 4570/\lambda H\beta = 0.5 \) is not unusually strong.

We also have reason to suspect T97’s [O \textsc{iii}] \( \lambda 5007 \) flux, which is blended with the \( \lambda 5018 \) line of Fe\textsc{\textii} multiplet 42, and which we fail to detect in our spectrum after removing the Fe\textsc{\textii} and H\textbeta{} emission as described above. T97 deblend these two lines and obtain Gaussians of similar, narrow (FWHM \( \approx 700\,\text{km}\,\text{s}^{-1} \)), widths whose wavelengths are significantly different from those expected. The mean wavelength of T97’s two deblended components is very close to the wavelength expected for the \( \lambda 5018 \) line alone (our revised redshift improves the agreement), and their combined flux is in excellent agreement with the flux we determine for this line alone. The Fe\textsc{\textii} lines are also known to be broad (we measure FWHM \( \approx 1500\,\text{km}\,\text{s}^{-1} \)), casting doubt on the narrow line produced by T97’s deblending. We also fail to detect [O \textsc{iii}] \( \lambda 4959 \) at its expected flux level. We place an upper limit of \( F([\text{O}\text{iii}]\lambda 5007) < 2 \times 10^{-17}\,\text{W}\,\text{m}^{-2} \), corresponding to a rest-frame equivalent width of \( < 2 \,\text{\AA} \).

### 3.3 Reddening

Whilst the H\textsc{i} line ratios can be used to estimate the reddening, they are too uncertain to provide an accurate value, although they are broadly consistent with the \( A_V = 1.5\,\text{mag} \) determined by T97 from the equivalent width of the Na D 1 line, and the extinction maps of Burstine & Heiles (1982). We make an additional estimate of the extinction by comparing the optical spectrum of PDS 456 to that of the quasar 3C 273. As Fig. 4 shows, there is excellent agreement (at least blueward of H\textsc{\textalpha}; we discuss the disagreement at longer wavelengths in the next section) when PDS 456 is dereddened by \( A_V = 1.4\,\text{mag} \). Since 3C 273 is itself reddened by \( A_V = 0.1\,\text{mag} \) (Burstine & Heiles 1982), we infer a total Galactic extinction of 1.5 mag towards PDS 456, and adopt this value in our later analysis.

![Figure 4. Comparison of the rest-frame optical spectra of PDS 456 (dereddened by \( A_V = 1.4\,\text{mag}, \) dashed line) and 3C 273 (solid line). The spectrum of 3C 273 has been taken from Morris & Ward (1988) and the flux has been multiplied by a factor 1.77 to match the flux of PDS 456 at \( \lambda = 6000\,\text{\AA} \).](image-url)

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4 DISCUSSION

In the previous section, we noted the similarity between the optical spectra of PDS 456 and 3C 273. In Fig. 5, we present the dereddened optical–infrared spectral energy distributions of the two quasars. We use the data of Rieke & Lebofsky (1985) to correct the data at \( \lambda > 3.5 \mu m \), which is beyond the range of Cardelli, Clayton & Mathis (1993) extinction law. The similarity is once again striking, with the exception of the 10-\( \mu m \) flux, which is nearly a factor of two higher in PDS 456 than 3C 273, relative to the optical–near-infrared data. Note that although these data are measured through different apertures, the quasar is more than 300 times brighter than an L* galaxy in the \( K \)-band (Gardner et al. 1997), and so the stellar contribution will be negligible.

There is clearly a problem with the continuum level redward of \( H\alpha \), since it does not match the interpolation between the rest of the optical spectrum and the \( J \)-band spectrum. This is not a simple flux calibration error affecting the reddest of the four INT subspectra which can be corrected with a constant shift, since the match is excellent in the region of overlap with the adjoining subspectrum.

The dereddened optical continuum is well-described by a power law with spectral index \( \alpha = -0.11 \pm 0.11 \). This is bluer than the mean optical spectral index for quasars, but still within the observed range (Neugebauer et al. 1987). The inflexion at \( \lambda_{rest} \sim 1.2 \mu m \) is a ubiquitous feature of quasar SEDs (Neugebauer et al. 1987; Elvis et al. 1994). However, the near-infrared bump usually extends to longer wavelengths, a power law often being able to fit the SED throughout the range 1–10 \( \mu m \) (see Neugebauer et al. 1987).

Given the similarities between the optical and infrared properties of PDS 456 and 3C 273, it is natural to ask the question: is PDS 456 a radio-quiet analogue of 3C 273? Certainly the low equivalent widths of the optical forbidden lines and blue optical continuum suggest blazar-like properties. A blazar nature should also be apparent at radio wavelengths, since the core emission should be strongly boosted by Doppler beaming (Falcke, Sherwood & Patnaik 1996), resulting in a flat radio spectrum that is more luminous than the general radio-quiet quasar population. To investigate this possibility, we have obtained VLA A-array data at 1.4 and 4.85 GHz. A detailed discussion of the data will be presented in a future paper, but they confirm the NVSS identification and flux, and reveal a steep radio spectrum. By extrapolating this spectrum to 8.4 GHz, we predict a flux of 4.6 mJy, which would cause PDS 456 to lie on the optical–radio luminosity relation for RQQs of Kukula et al. (1998).

The high optical luminosity and low forbidden-line equivalent widths of PDS 456 are characteristic of the ‘Baldwin effect’ (Baldwin 1977). Although several explanations for this effect have been advanced, including Doppler-boosting (Browne & Murphy 1987), radiation from an accretion disc (Netzer 1987) and reddening (Baker 1997), these all incorporate an orientation dependence such that very luminous, very low equivalent width sources like PDS 456 should be seen nearly pole-on. The lack of a dominant, boosted radio core is therefore something of a mystery.

5 SUMMARY

We have presented optical and infrared spectra of the nearby luminous quasar PDS 456. We measure a redshift \( z = 0.18375 \pm 0.00030 \) based on the forbidden line of [Fe II] \( \lambda 1.6435 \mu m \), but do not detect any other forbidden emission lines. We detect at least three emission lines in the near-infrared that we are unable to identify. The dereddened optical continuum is rather
blue and very similar to that of 3C 273. Despite the similarities at optical wavelengths, observations reveal that PDS 456 does not possess a strongly Doppler-boosted radio core. We defer detailed discussion of the radio observations to a later paper, wherein we will also present and discuss an X-ray spectrum of PDS 456.

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