PDS 456: an Extreme Accretion Rate Quasar?

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ABSTRACT

We present quasi-simultaneous ASCA and RXTE observations of the most luminous known AGN in the local (z < 0.3) universe, the recently discovered quasar PDS 456. Multiwavelength observations have been conducted which show that PDS 456 has a bolometric luminosity of ~10⁴⁷ erg s⁻¹ peaking in the UV part of the spectrum. In the X-ray band the 2-10 keV (rest-frame) luminosity is 10⁴⁵ erg s⁻¹. The broad-band X-ray spectrum obtained with ASCA and RXTE contains considerable complexity. The most striking feature observed is a very deep, ionised iron K edge, observed at 8.7 keV in the quasar rest-frame. We find that these features are consistent with reprocessing from highly ionised matter, probably the inner accretion disk. PDS 456 appeared to show a strong (factor of ~2.1) outburst in just ~17 ksec, although non-intrinsic sources cannot be completely ruled out. If confirmed, this would be an unusual event for such a high-luminosity source, with a light-crossing-time corresponding to ~2Rₜ. The implication would be that flaring occurs within the very central regions, or else that PDS 456 is a ‘super-Eddington’ or relativistically beamed system. Overall we conclude on the basis of the extreme blue/UV luminosity, the rapid X-ray variability and from the imprint of highly ionised material on the X-ray spectrum, that PDS 456 is a quasar with an unusually high accretion rate.

Key words: galaxies: active – quasars: individual: PDS 456 – X-rays: quasars

1 INTRODUCTION

Understanding the origin of the luminous, ionising continuum from Active Galactic Nuclei (AGN) is one of the prime goals of AGN research. Despite the general acceptance of the standard AGN paradigm — that the continuum (UV) emission originates in an accretion disk around a super-massive black hole — the details remain unclear. In the X-ray band, there is a hard power-law component that dominates above 2 keV in the well studied Seyfert 1 galaxies. This hard X-ray continuum may originate from a hot corona above the surface of the accretion disk, in which optical/UV photons from the disk are Comptonised to X-ray energies. These X-rays then illuminate the disk, being either ‘reflected’ towards the observer or thermalised back into optical/UV emission. In the X-ray spectral band, evidence for this disk reflection component is seen in the form of a fluorescent Fe Kα line at 6.4 keV, an iron K edge at > 7 keV and a Compton ‘hard tail’. All these features have been observed in Seyfert 1 galaxies (e.g. Pounds et al. 1990, Nandra & Pounds 1994).

The subject of this paper is the recently discovered radio-quiet quasar PDS 456 (Torres et al. 1997, Simpson et al. 1999), which is the most luminous known object in the local Universe (z < 0.3); indeed the bolometric luminosity of PDS 456 exceeds that of the well-known radio-loud quasar 3C 273. However, unlike 3C 273, PDS 456 is radio-quiet, and thus presumably not jet dominated. Therefore, PDS 456 provides a unique opportunity to study in detail the hard and soft X-ray components in a high luminosity, radio-quiet AGN, and in particular to test models of reflection expected from the putative accretion disk.

In the next section we describe the multi-wavelength properties of PDS 456. The main subject of this paper is then covered; the X-ray emission from PDS 456, using observations with ASCA and RXTE. Values of H₀ = 50 km s⁻¹ Mpc⁻¹ and q₀ = 0.5 have been assumed throughout and all fit parameters are given in the quasar rest-frame. Note that errors are in this paper are quoted at the 90% confidence level (e.g. Δχ² = 2.7 for one interesting parameter).
taken from Simpson et al. (1999). It is seen that the bolometric data are plotted; the dereddened optical/near-IR data has been ray (ROSAT, ASCA, RXTE), infra-red (ISO) and radio (VLA) luminosity of PDS 456 approaches $10^{47}$ erg s$^{-1}$.

2 MULTIWAVELENGTH PROPERTIES OF PDS 456

At $z = 0.184$, PDS 456 has a de-reddened, absolute blue magnitude $M_B \approx -27$, making it more luminous than the radio-loud quasar 3C 273 ($z = 0.158, M_B \approx -26$). The Galactic absorption column towards PDS 456 is $N_H = 2.10^{21}$ cm$^{-2}$ (Stark et al. 1999), with an extinction of $A_V = 1.4$ in the optical. We have performed a recent VLA observation; the total detected 6 cm flux of 8 mJy confirms that PDS 456 is radio-quiet ($R_L = \log[F_{6cm}/F_B] \approx -0.74$).

PDS 456 has broad Balmer and Paschen lines, strong Fe ii, a hard (de-reddened) optical continuum ($f_{\nu} \propto \nu^{-1.0 \pm 0.1}$), and one of the strongest 'big blue bumps' of any AGN (Simpson et al. 1999). PDS 456 is coincident (to $\sim 8"$) with the optical position of PDS 456 (figure 1), obtained from all our current data on this quasar (including recent VLA and ISO data, listed in table 1), giving a bolometric luminosity of $\sim 10^{47}$ erg s$^{-1}$, a value more typical of QSOs at $z \sim 3$.

3 X-RAY OBSERVATIONS AND DATA REDUCTION

3.1 ASCA observations

PDS 456 was observed by ASCA on 7–8 March 1998 with a total duration of $\sim 140$ ks. Standard screening criteria were applied to the ASCA data (e.g. see the ASCA Data Reduction Guide), giving a total 'good' exposure time of $\sim 40$ ksec per detector. Counts were extracted using a 4' circular aperture centered on the source, and the background was estimated using source-free regions at similar off-axis angles.

3.2 RXTE observations

PDS 456 was observed by RXTE on 7-10 March 1998 with a total duration of 226 ks. We extracted STANDARD-2 data from the PCU (Proportional Counter Unit) array using the RXE reduction script supplied by NASA/GSFC. Data have been extracted from Layer 1 (L1) only (the first and most sensitive layer). Poor quality data were excluded on the basis of the following selection criteria: (i) the satellite is out of the South Atlantic Anomaly (SAA); (ii) Earth elevation angle $\geq 10^\circ$; (iii) offset from the optical position of PDS 456 is $\leq 0.02^\circ$; and finally (iv) electron-0 $\leq 0.1$. This last criterion removes data with high anti-coincidence rate in the PCUs. The total 'good' exposure time selected after this screening was 92 ksec. The background was estimated using the L7-240 model. All RXTE spectral data below 2.5 keV and above 18 keV have been ignored.

| ISO Data | VLA Data |
|----------|----------|
| $\lambda(\mu m)$ | Flux(Jy) | $\nu(\text{Hz})$ | Flux(mJy) |
| 12 | 0.28 $\pm$ 0.03 | 1.4 | 30.4 |
| 25 | 0.55 $\pm$ 0.12 | 4.85 | 8.23 |
| 50 | 0.61 $\pm$ 0.11 |
| 80 | 0.51 $\pm$ 0.11 |
| 100 | 0.42 $\pm$ 0.14 |

4 SPECTRAL ANALYSIS

Initially the hard X-ray (RXTE+ASCA) data in the 2.5-18 keV range were analysed, using background subtracted spectra and by allowing the relative normalisations of all 5 instruments to vary. The pulse height spectra from each detector were binned to give at least 20 counts per spectral channel. Firstly, a power-law plus fixed Galactic absorption model fits, the overall fit remained unacceptable. A further improvement was obtained using a broad Fe line (model 3), although the fit was still inadequate as an edge was apparent in the data residuals at $\sim 7$ keV. We next tried a fit to highly ionised iron (model 4), the (narrow) line energy was fixed at 6.7 keV (corresponding to Fe xxix -- Fe xxv). Figure 3 clearly illustrates the high ionisation state of the reprocessing material. Note that we also tried fitting a smeared edge model (width 1 keV), as might be expected from the inner disk, although the fit obtained was very similar to above. Including a broad iron line in the

Table 1. ISO (ISOPHOT) and VLA fluxes.

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The line equivalent width is a disk surface temperature of 10\(^{30}\) in XSPEC was used (Magdziarz & Zdziarski 1995), assuming surface layers of an ionised accretion disk. The reprocessing features in terms of reflection of X-rays off the highly ionised matter, we then attempted to model these that the detection of the ionised iron edge is robust, even with the model (in addition to the edge, model 5) lead to a further improvement in the spectral fit (\(\Delta \chi^2 \sim 11\)), at a significance level of \(\sim 90\%\) confidence (F-test, 2 additional parameters). The line equivalent width is \(\sim 350\) eV; the line is broad (\(\sigma \sim 1\) keV) and possibly redshifted (\(E \sim 6\) keV). We note that the detection of the ionised iron edge is robust, even after the inclusion of a broad line in the model fit.

Having established the presence of reprocessing by highly ionised matter, we then attempted to model these reprocessing features in terms of reflection of X-rays off the surface layers of an ionised accretion disk. The PEXRIV model in XSPEC was used (Magdziarz & Zdziarski 1995), assuming a disk surface temperature of \(10^6\) K (e.g. Zycki et al. 1994; Ross, Fabian & Young 1999) and a disk inclination angle of 30\(^\circ\). The disk ionisation parameter (\(\xi\)) and the strength of the reflection component \(R (=\Omega/2\pi)\) were both left as free parameters in the fit. (Note that \(\xi = L/\sigma n^2\), where \(n\) is the number density of the material at a distance \(r\) from an ionising source of luminosity \(L\), where \(L\) is defined from 5 eV to 20 keV.) An ionised reflector provides a good fit to the hard X-ray spectrum and the iron K edge (model 6, \(\chi^2 \approx 1\)), giving a value of \(R\) close to 1 and a high ionisation (\(\xi \approx 6400\) erg cm s\(^{-1}\)). Although a narrow iron K line is not required in this fit, the presence of a broad line was not ruled out (EW \(\lesssim 250\) eV).

We also attempt to model the hard X-ray spectrum of PDS 456 with a power-law modified by a warm line-of-sight absorber (model 7), using the ABSORI routine in XSPEC (note we assume a temperature of \(T = 3 \times 10^5\) K). This model provides a good alternative description of the X-ray data, modelling both the ionised edge and providing a good overall fit (\(\chi^2 \sim 1\)). However both a large column of material (\(N_H \approx 4.7 \times 10^{23}\) cm\(^{-2}\)) and a very high degree of ionisation (\(\xi \approx 1.5 \times 10^4\) erg cm s\(^{-1}\)) are required to reproduce the energy and depth of the edge feature.

Extrapolation of the preferred hard X-ray spectral model to lower energies (0.7 keV) does not provide an adequate description of the broad-band data. There remains a significant deficit of counts present below \(\sim 2\) keV (see figure 4, panel 1), indicating that significant intrinsic absorption (in excess of Galactic) is present. A neutral absorber (\(N_H \approx 10^{22}\) cm\(^{-2}\)) gave a poor fit; the spectrum is poorly modelled and an excess of counts is present below 1 keV in the ASCA data. However an ionised absorber provides a good fit (figure 4, panel 2), with \(N_H \approx 5 \pm 1.5 \times 10^{22}\) cm\(^{-2}\) and \(\xi \sim 350\pm 100\) (again assuming \(T = 3 \times 10^5\) K). Note that this material is not sufficiently ionised to reproduce the deep, ionised, iron K edge seen in the hard X-ray spectrum; the absorber effectively contributes a negligible amount (\(\tau < 0.1\)).

Table 2. Results of simultaneous spectral fits to the ASCA and RXTE data in the 2.5–18 keV range. Column 1 gives the models as defined in the text. Columns 2–7 give the fit parameters: column 2 gives the power law photon index; column 3 the iron K edge energy (keV) or ionization parameter (\(\xi\)); column 4 gives the edge depth (\(\tau\)), reflection strength (\(R=\Omega/2\pi\)) or \(N_H\) (units 10\(^{21}\) cm\(^{-2}\)). Columns 5, 6 and 7 give the iron K line energy (keV), the intrinsic width \(\sigma\) (in keV) and equivalent width (in eV) respectively. Column 8 gives the best-fit \(\chi^2\) over number of degrees of freedom. \(f\) indicates the parameter is fixed.

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| Model                  | \(\Gamma\) | \(E_{\text{edge}}\) or \(\xi\) | \(\tau\), \(R\) or \(N_H\) | \(E_{\text{line}}\) | \(\sigma\) | \(\text{EW}\) |
|------------------------|------------|-------------------------------|-----------------------------|----------------------|------------|-------------|
| 1. PL                   | 2.38±0.03  | –                             | –                           | 6.4\(^f\)            | 0.03\(^f\) | –           |
| 2. PL+LINE              | 2.42±0.04  | 7.1\(^f\)                     | \(<0.10\)                   | 6.7\(^f\)            | 0.01\(^f\) | 178±49      |
| 3. PL+BROAD-LINE        | 2.44±0.05  | –                             | –                           | 5.6\(^f\)          | 0.14\(^f\) | 900±200     |
| 4. PL+EDGE+LINE        | 2.12±0.04  | 8.70±0.15                     | 0.76±0.12                   | 6.7\(^f\)            | 0.01\(^f\) | <77         |
| 5. PL+EDGE+B-LINE      | 2.22±0.08  | 8.7±0.3                       | 0.53±0.18                   | 6.1±0.5             | 0.03      | 340±100     |
| 6. PL+PEXRIV+LINE      | 2.54±0.07  | 6400+3000                    | 23000                      | 6.7\(^f\)            | 0.01\(^f\) | <30         |
| 7. PL+ABSORI+LINE      | 2.39±0.08  | 1.5±0.4 \times 10^4          | 47±11                      | 6.7\(^f\)            | 0.01\(^f\) | <35         |
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Figure 2. The data/model ratio residuals from a simple power-law fit (model 1) to the RXTE data of PDS 456. The effect of the deep, ionised iron K edge is clearly seen in the residuals.

Figure 3. Confidence contours of Fe K edge energy against depth, for the RXTE and ASCA spectrum of PDS 456. The contours represent the 68\%, 90\%, 99\%, 99.9\% significance levels respectively.
to the iron K edge. The absence of any appreciable optical absorption (aside from Galactic) may also imply either a low intrinsic dust-to-gas ratio, or that most of the dust close to the central engine has sublimated.

5 TEMPORAL ANALYSIS

Light curves were constructed by binning the data into 96 min orbital bins, for the background-subtracted RXTE (2–10 keV) and ASCA (2–10 and 0.5–2 keV) data. The results are plotted in Figure 5. The RXTE light curve shows an increase by a factor of ∼2.1 in 3 orbits (17 ksec). Note that the time-averaged RXTE flux in the 2-10 keV band is 8.5 × 10^{-12} erg cm^{-2} s^{-1}, and if this flare is real, it would be the most rapid variation ever seen in a radio-quiet quasar. Unfortunately the (lower signal/noise) ASCA observation had ended before the flare began, so independent confirmation is not possible. In order to assess the reality of this event, we consider two possibilities that arise because RXTE was observing in the central engine has sublimated. The background model was determined in the same fashion as with the flare, but instead look like errors in modelling the source should not contribute significantly to the 2–10 keV count rates, these residuals can be used to assess the quality of the background subtraction.

The background model was determined in the same fashion for all three light curves. As X-rays from this rather weak source should not contribute significantly to the 2–10 keV L2 and 20–40 keV L1 count rates, these residuals can be used to assess the quality of the background subtraction. The 2–10 keV L2 data are well-behaved, consistent with the estimated 0.15 ct/s systematic error, but the 20–40 keV L1 show apparently small periodic daily excursions on the ∼0.5 ct/s level. These latter excursions are not correlated with the flare, but instead look like errors in modelling the daily effect of SAA passage. Thus, we consider it unlikely that the observed flare could be due entirely to poor background subtraction.

Figure 4. Data-ratio residuals for the broadband 0.7-18 keV ASCA and RXTE spectrum of PDS 456. The first panel shows the hard X-ray spectrum extrapolated down to lower energies. The deficit of counts below 2 keV indicates the presence of substantial soft X-ray absorption. The lower panel shows the data residuals, after including a warm absorber of column ∼5 × 10^{22} cm^{-2}.

Figure 5. RXTE and ASCA light curves for PDS 456. The ASCA data were shifted upwards in this logarithmic plot by an arbitrary amount and the errors on the RXTE data were increased by 0.15 ct/s in quadrature to account for systematic errors. The source appears to flare by a factor of ∼2.1 in 17 ksec, corresponding to a light-crossing size of ∼2R_s.

6 DISCUSSION

No contaminating sources of sufficient brightness were seen in the ASCA image, but that covered only ∼20% of the ∼1° RXTE field-of-view. The RASSBSC (Voges et al. 1996) was searched and no sources were found within 1° of PDS 456. Ginga background fluctuation data (Butcher et al. 1997), which do cover a similar energy band, suggest a ≤2% probability of a contaminating source at the 2 ct/s level; a similar probability of 2.5% is found from the distribution of Piccinotti et al. (1982). However, there is no assurance that the RXTE field-of-view does not contain a highly variable contaminating source at a lower flux level. For instance, the Butcher et al. data suggest that a few sources could be expected with mean RXTE count rates of 0.2–0.4 ct/s. If one of these is a narrow-line Seyfert 1 galaxy (NLS1s can show factor of ≥5 in a few hours; e.g., Boller, Brandt & Fink 1996), or even a BL-Lac object, this could produce a spurious flare identical to the one seen. This is unlikely but cannot be ruled out. Thus the most likely interpretation of the data is that the flare is intrinsic to PDS 456, but other possibilities cannot be completely excluded. The discussion below assumes that the flare is intrinsic to the QSO.
is possible that such a high ionisation absorber may not be thermally stable (see Reynolds & Fabian 1995).

Overall an ionised reflector appears a more physically appealing description of the hard X-ray data. Indeed strong, highly ionised, iron-K edge features are predicted by disc photoionisation models (e.g. Ross, Fabian & Young 1999) and are also thought to be observed in some high-state Galactic black-hole candidates (e.g. Zycki, Done & Smith 1997). The iron line and edge produced in such highly ionised disks can be significantly broadened through multiple Compton scatterings (e.g. Ross et al. 1999). However we were unable to differentiate here between a smeared and a sharp iron edge, given the limited signal to noise of our observations.

The high ionisation of the reflector could imply a high accretion rate in PDS 456 (relative to the Eddington limit), this implies that the X-ray flare occurs for the varying region. For a black hole of mass $10^{9}\, M_{\odot}$, with $L_{\text{bol}} = 10^{77}\, \text{erg s}^{-1}$, at the Eddington limit, this implies that the X-ray flare occurs within a region of less than 2 Schwarzschild radii (2$R_S$). (A more conservative $H_0$ of 75 km s$^{-1}$ Mpc$^{-1}$ gives a region of $< 5R_S$, which is still tightly constrained). A smaller mass black hole would loosen this requirement somewhat, but would then imply a super-Eddington accretion rate. Therefore one possible implication of the rapid variability is accretion near to or greater than $L_{\text{Edd}}$. The variability also implies a (non-beamed) efficiency of converting matter to energy of $\sim 5\%$, close to the limit for a Schwarzschild black hole (see Fabian 1979). Some Seyfert 1s (such as MCG-6-30-15, Reynolds et al. 1995) can also exhibit rapid variability, limiting the X-ray emission to a few $R_S$. Rapid flux changes have also been reported in 2 narrow-line QSOs; in PKS 0558-504, a 70% increase is observed in 3 minutes (Remillard et al. 1991) and PHL 1092 shows a reported increase by a factor of 3.8, using the ROSAT HRI, in less than 5000 sec (Brandt et al. 1999). In any event, the flare in PDS 456 must come from a very compact region (for instance, a small hot spot on the disk), presumably very close to the "central engine" in which the luminosity is actually generated.

In conclusion PDS 456 is a remarkable object, showing clear features of a high ionisation reprocessor, one possible interpretation of which is through reflection off a highly ionised accretion disk. Both the high ionisation spectral features and the extreme rapid variability suggest that the super-massive black hole in PDS 456 could be running at an unusually high accretion rate.

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