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ABSTRACT

We report the detection and spectrum of the distant (z=1.839), highly-polarized quasar PKS 1502+106 in the X-ray band based on data collected over the period 1990–1994 using *ROSAT* and *ASCA*. We find the source to exhibit intensity variations of a factor $\gtrsim 2$ at 1 keV on timescales of years, small compared to the variability observed historically in the radio, millimetre and optical bands. The (energy) spectral index is found in the range $0.4 \lesssim \alpha_X \lesssim 0.8$ (at 90% confidence). Its multi-waveband spectral index is broadly consistent with other Highly-Polarized Quasars (HPQ). From the application of an inhomogeneous synchrotron self-Compton (SSC) jet we find that a model similar to that proposed for 3C 279 is consistent with the multi-waveband spectrum. We suggest that a change in the energy injection and/or transport mechanisms within such a jet could easily result in PKS 1502+106 being detectable at γ-ray energies.

Subject headings: galaxies:active – galaxies: nuclei – X-rays: galaxies – quasars: individual (PKS 1502+106) – radiation mechanism:non-thermal

1. INTRODUCTION

PKS 1502+106 (4C 10.39, OR 103) is a luminous quasar (Radivich & Kraus 1971) well studied in the radio regime where it is observed to exhibit (factor ~ 3) intensity variations on timescales of weeks–months (Ghosh & Gopal-Krishna 1990; Waltman et al. 1991; Wiren et al. 1992), a high degree of polarization ($\sim 3\%$: Tabara & Inoue 1980) and a one-sided, core-dominated morphology (Browne & Perley 1986; Saikia et al. 1990; Murphy, Browne & Perley 1993). Variability is also observed at millimetre frequencies (factor ~ 5) on a timescale of months (Edelson 1987; Steppe et al. 1992). In the optical, the source exhibits variability with m_v in the range 19.5–18.6 (Peacock & Wall 1981; Hewitt & Burbidge 1989; Véron-Cetty & Véron 1991) and a high, but variable, degree of polarization ($\sim$3–19%: Impey & Tapia 1988). From the analysis of the broad emission lines in the optical the quasar has two possible redshifts $z = 0.563$ and $z = 1.839$ (Wright et al. 1979; Smith et al. 1977), with the latter the preferred value (Richstone & Schmidt 1980) and used throughout this work. There are no objects currently known with a higher degree of optical polarization at such a large redshift (Wills et al. 1992), indicating that the synchrotron emission from PKS 1502+106 is not significantly diluted by blue-bump emission up to a source-frame frequency of 2×10^{15} Hz.

To date there have been no reports of PKS 1502+106 having been detected at higher frequencies. In the X-ray band, Henriksen, Marshall & Mushotzky (1984) reported an upper limit of the flux from the source in the 0.5–4.5 keV band to be 2.5×10^{-13} erg cm^{-2} s^{-1} from observations made using the IPC on the *Einstein Observatory*, and Arnaud et al. (1985) reported an upper limit to the 0.15–2.0 keV flux of any point sources in the field of view of their target of $\sim$few $\times 10^{-13}$ erg cm^{-2} s^{-1} from the analysis of a 42 hr *EXOSAT* low energy telescope observation. At γ-ray energies, Fichtel et al. (1994) have reported a (2 sigma) upper limit of the flux from PKS 1502+106 above 100 MeV to be 7×10^{-8} photons cm^{-2} s^{-1}

from the EGRET experiment on the *Compton Gamma-Ray Observatory* (CGRO).

PKS1502+106 lies approximately 7 arcmin NE of the well known Seyfert-1 galaxy Mrk 841. Here we report the serendipitous detection and spectrum of PKS 1502+106 in the X-ray band from data collected by the *ROSAT* and *ASCA* satellites as part of an observing campaign of Mrk 841.

2. OBSERVATIONS & RESULTS

A total of 11 *ROSAT* (Trümper 1983) observations of Mrk 841 were made in the soft X-ray band (0.1–2.0 keV) over the period 1990 July – 1993 February with one of the Position Sensitive Proportional Counters (PSPCs: Pfeffermann et al. 1986) in the focal plane of the X-ray Telescope (see George et al. 1994 for a detailed observing log). A source was visible at the location of PKS1502+106 in all these datasets, with a mean count rate of 1.8×10^{-2} count s^{-1} (compared to a background of 3×10^{-4} count s^{-1} in the extraction cell). The derived X-ray position of the source, from the co-addition of the PSPC images (with a combined exposure time of 4×10^4 s), is (J2000) RA = $15^h\ 04^m\ 24.70^s$, dec = $+10^\circ\ 29'\ 39.8''$, with a 90% error circle of 1.5 arcsec radius. (The position of Mrk 841 in the same co-added images agreed with the optical position of the source to within 0.5 arcsec indicating negligible boresight/aspect errors for the PSPC dataset.) This is in excellent agreement with the the radio position of PKS1502+106, (J2000) RA = $15^h\ 04^m\ 24.97972^s$, dec = $+10^\circ\ 29'\ 39.1972''$, (Walter 1989), and given the lack of suitable alternative candidates within the X-ray error circle, we assign the X-ray emission to PKS1502+106.

A soft X-ray light curve was extracted from the PSPC dataset and examined using time bins from 500–4000 s. No significant variability was detected across the 1992 January to 1993 February baseline (although the source was so faint that we cannot rule out variations up to a factor of 2.5 in 0.1–2 keV flux at 90% confidence). Thus spectra were extracted using a 2 arcmin radius cell centered on the source from each observation and coadded to construct a mean PSPC PHA spectrum. Assuming a simple power-law model ($F_E \propto E^{-\alpha_X}$ where E is in keV), corrected for the effects of low-energy absorption, we found a best fitting spectral index of $\alpha_X = 0.8^{+0.8}_{-0.6}$, with an effective hydrogen column density $N_{\rm H}$= $2.4^{+2.2}_{-1.6} \times 10^{20}$ cm^{-2} (errors are at 90% confidence throughout unless otherwise stated) and $\chi^2_\nu = 0.3$. Fixing the column density to the Galactic value, $N_{\rm HI} = 2.2 \times 10^{20}$ cm^{-2}, derived from 21 cm measurements along the line-of-sight to the nearby Mrk 841 (Elvis, Lockman & Wilkes 1989), we find a best fitting $\alpha_X = 0.7^{+0.3}_{-0.2}$ with $\chi^2_\nu = 0.3$.

PKS1502+106 was also serendipitously detected in the field-of-view of an *ASCA* AO-1 observation of Mrk 841 made on 1994 Feb 22 (George et al. 1994). As described in Inoue (1993), *ASCA* has four instruments covering the medium (approximately 0.4–10 keV) X-ray energy band: two Solid State Imaging Spectrometers (SIS) each consisting of 4 CCD chips, and two Gas Imaging Spectrometers (GIS). The observation of Mrk 841 was carried out with 2 CCD chips exposed on each SIS. A source at the position of PKS 1502+106 was observed in all four detectors. The following data-selection criteria were applied: that the spacecraft was outside of the South Atlantic Anomaly; the elevation angle above the Earth's limb was > 10°; the Bright Earth angle (elevation angle above the sun-illuminated Earth's limb) was > 20°; the magnetic cut-off rigidity was >7 GeV/c for GIS data, and >6 GeV/c for SIS data; and data taken within 200 s of the day/night transition were rejected. 'Hot' and 'flickering' pixels were removed from the SIS, and data at the start of the observation, when the satellite pointing was not yet stable, were also removed (a few hundred seconds). These selection criteria resulted in effective exposure times of 1.6–2$\times 10^4$ s in each instrument. A position of (J2000) RA = 15 04 23.3 +10 28 41.0 was derived from the SIS images with a 90% error circle of 40 arcsec radius, again consistent with the radio position of PKS 1502+106.

Source spectra and light curves were extracted from the SIS and GIS datasets using cells of radius 1–2 arcmin centered on PKS 1502+106 (size and shape depended on the instrument). For the SIS, background spectra and light curves were extracted from cells in the large source–free region of the same chip; for the GIS, background cells were chosen at the same off-axis angle as PKS1502+106. No evidence for intensity variations were apparent in the *ASCA* datasets, with a mean SIS count rate of 2×10^{-2} count s^{-1}.

Simultaneous spectral analysis of the four background-subtracted *ASCA* datasets, assuming a simple power-law model with $N_{\rm H}$ fixed at $N_{\rm HI}$, gave a best fitting $\alpha_X = 0.5^{+0.3}_{-0.2}$ with $\chi^2_\nu = 1.0$ and excellent agreement between the normalizations. As the *ROSAT* and *ASCA* data in the 0.4–2.0 keV band were also in good agreement, we performed simultaneous spectral fits on the PSPC, SIS and GIS datasets, using a single power-law model but allowing the *ROSAT* and *ASCA* datasets to have independent normalizations. With $N_{\rm H}= N_{\rm HI}$, this multi-instrument fit yielded an acceptable fit with $\alpha_X = 0.6^{+0.2}_{-0.2}$, $\chi^2_\nu = 0.9$. Such an index is in excellent agreement with the mean value derived from a sample of HPQ ($\alpha_X = 0.59 \pm 0.19$; Brunner et al. 1994), but significantly flatter ($\Delta\alpha \gtrsim 0.5$) than the mean value of radio-loud quasars in general (Brinkmann, Siebert & Boller 1994). The broad–band (0.3-30 keV in the rest frame), non–thermal spectrum implied by the PSPC and ASCA observations strongly supports our identification with PKS 1502+106. We find the mean normalization for the *ASCA* dataset (7.3×10^{-8} Jy at 1 keV) a factor $\sim$ 50% higher than for the *ROSAT* dataset, and a factor ~ 2 higher than the upper limit from the *Einstein* observation carried out in 1980.

The observed frame 0.1–2.0 keV and 2–10 keV fluxes were 1.9×10^{-13} erg cm^{-2} s^{-1} and 4.9×10^{-13} erg cm^{-2} s^{-1} from the *ROSAT* and *ASCA* fits respectively. The absolute flux calibrations of both *ROSAT* and *ASCA* are considered accurate to within $\lesssim 10\%$.

3. DISCUSSION

HPQ are often grouped with BL Lac objects under the common denomination of 'blazars' (Angel & Stockman 1980). The most popular model for these classes of active galactic nuclei invokes relativistic motion of the emitting plasma at small angles (Θ) to the line-of-sight (Blandford & Rees 1978). This hypothesis, combined with the synchrotron self-Compton (SSC) or inverse Compton (IC) scattering of external photons as the underlying emission mechanisms, is able to explain most of the observational characteristics of these sources. In the comoving frame, the simplest SSC model assumes an isotropic power-law distribution of relativistic electrons embedded in a tangled magnetic field. The electrons produce a power-law synchrotron spectrum, and also scatter these photons to higher energies via the IC mechanism (Jones, O'Dell & Stein 1974a,b; Gould 1979). Within such a framework, a variety of specific models have been constructed in order to explain the multi-waveband spectra and variability of blazars. These have varied in complexity from a single homogeneous sphere moving relativistically along the line-of-sight (eg. Urry 1984 and references therein) to complex inhomogeneous relativistic jets which better explain the curved spectra and variability behaviour of blazars (eg. Königl 1981; Ghisellini, Maraschi & Treves 1985; Hutter & Mufson 1986). The recent detection of a number of blazars by EGRET with γ-ray luminosities factors of 10–100 greater than in any other waveband has revived interest in determining the radiation mechanism responsible for the emission of most of the radiative output. The observations are in general consistent with inhomogeneous jets (see e.g. Maraschi, Ghisellini & Celotti 1992, and references therein), but a number of alternatives have also been proposed involving the Comptonization of a diffuse radiation field (e.g. Dermer, Schlickeiser & Mastichiadis 1992; Sikora, Begelman & Rees 1994). Unfortunately, the lack of high quality/simultaneous data, and especially of γ–ray emission, in PKS1502+106 does not allow us to discriminate among these.

The multi-waveband spectrum of PKS 1502+106, compiled from our observations together with data from the literature, is shown in Fig 1. The variability in the radio and optical bands is apparent and it should be stressed that none of the observations shown in these bands were simultaneous with any of the X-ray observations. The broad-band spectrum of PKS 1502+106 is typical of core-dominated quasars. Using the fluxes at 5 GHz, 550 nm & 2 keV, we find broad-band power-law spectral indices ($\alpha_{ab} = -[\log F_\nu(\nu_b) - \log F_\nu(\nu_a)]/[\log \nu_b - \log \nu_a]$) of $\alpha_{rx} \sim 0.9$ and $\alpha_{ox} \sim 1.2$, compared to $\alpha_{rx} \sim 0.88 \pm 0.02$ and $\alpha_{ox} \sim 1.41 \pm 0.09$ found for a sample of similar sources (Brunner et al. 1994). It can be seen that the global energy distribution of PKS 1502+106 consists of a broad peak in the sub-millimetre – infrared band, and potentially a second peak of similar magnitude in the hard X-ray – γ-ray band. Under the SSC paradigm, the former is related to the synchrotron component, whilst the latter assigned to IC emission (e.g. Maraschi et al. 1992). Unfortunately the lack of data in these bands do not allow us to determine which of these two processes dominates the energy output in this source (i.e. the ratio of magnetic to radiation energy densities). The lack of detection of γ–ray emission also prevents limits on the amount of beaming or the size of the X- and γ–ray emitting region being derived using arguments based on the opacity to electron–positron ($e^{\pm}$) pair production. In SSC models, where the γ–ray emission is the high energy extrapolation of the X-ray IC component, a lack of γ-rays either implies a high energy cutoff in the relativistic electron distribution, or is the signature of $e^{\pm}$ pair absorption. The (flat) X-ray spectrum of PKS 1502+106 is similar to other HPQ both with and without significant γ-ray luminosities. If the lack of γ–rays were attributable to $e^{\pm}$ pair reprocessing then we would expect to see a correlation of γ-ray luminosity and X-ray spectral slope (where the effects of $e^{\pm}$ reprocessing should be observed) in HPQ. Thus we consider it unlikely that $e^{\pm}$ pair reprocessing is significant in PKS 1502+106.

VLBI imaging of PKS 1502+106 at 5 GHz reveals a core of angular size $\theta_d \simeq 0.8$ milliarcsec containing a flux density $\sim$ 1.5 Jy (Zensus, Porcas & Pauliny-Toth 1984). Considering the region of the source dominating the emission (ie. which becomes synchrotron self-absorbed) at this frequency. From the application of standard SSC theory for a homogeneous sphere (eg. Urry 1984), and assuming an optically thin synchrotron spectral index, $\alpha = 0.5$, we find that the observed radio emission from PKS 1502+106 must be relativistically beamed with a kinematic Doppler factor δ ($= [\Gamma_b - (\Gamma_b^2 - 1)^{1/2} \cos \Theta]^{-1}$, where Γ_b is the bulk Lorentz factor) of $\gtrsim 5$ in order that the predicted IC flux does not exceed the observed flux at 1 keV. This limit is fairly typical of those obtained from a similar treatment of many HPQ (eg Madau, Ghisellini & Persic 1987). The value of θ_d used above corresponds to a region of size ~ 5 pc, consistent with the scale over which relativistic expansion of radio knots is seen in such sources. The radio variability timescale of weeks – months can further constrain the size of the emission region and hence confirms the requirement for beaming in PKS 1502+106, yielding $\delta > 60 t_{var}^{-0.62}$ (in this simplistic SSC model) where t_{var} is in months.

Given the similarity of Fig. 1 to the low and medium state multi-waveband spectra of the blazar 3C 279 we have applied the inhomogeneous relativistic jet model proposed by Maraschi, Ghisellini & Celotti (1992) to PKS 1502+106. The Ghisellini & Maraschi (1989) model assumes a parabolic jet emitting in the infrared – γ-ray part of the spectrum. Power-law functions of distance, R, along the jet are assumed for the magnetic field density ($B = B_0(r/r_0)^{-m}$), the density of relativistic electrons ($K = K_0(r/r_0)^{-n}$), and the maximum Lorentz factor of the comoving synchrotron-emitting electron distribution ($\gamma_{max} = \gamma_0(r/r_0)^{-g}$), where r is the cross-sectional radius ($r = R_0(R/R_0)^{1/2}$). Bulk acceleration is also allowed with $\Gamma_b = \Gamma_0(R/R_0)^a$. The predicted spectrum from the entire jet is then obtained by simply integrating the local SSC spectra and transforming to the observers frame. Such a model has a large number of free parameters, and a full and meaningful exploration of parameter space requires high quality, simultaneous monitoring in all wavebands.

Given the lack of such data currently available for PKS 1502+106, we simply assume a similar jet structure and dynamics for PKS 1502+106 to that found for 3C 279 by Maraschi et al. (1992), namely of the same extent $R_c = 4 \times 10^{18}$ cm, with the same gradients which determine the inhomogeneity $n = 1.5$, and $m = 1.0$, and the same bulk velocity behaviour, $\Gamma_0 = 5.5$, $a = 0.2$. Interestingly, we find the model adequately fits the multi-waveband spectrum of PKS 1502+106 (Fig. 1), assuming an optically thin synchrotron spectral index $\alpha = 0.6$, $R_0 = 1 \times 10^{15}$ cm, $B_0 = 22$ G, $\Theta = 4°$, and $\gamma_0 = 6 \times 10^3$. The Thomson optical depth at the base of the jet is $\tau = \sigma_T K_0 R_0 = 10^{-3}$. Besides some minor geometrical differences, the only major difference between these results and those derived by Maraschi et al. for for 3C 279 ($\alpha = 0.5$, $R_0 = 2 \times 10^{15}$ cm, $B_0 = 8$ G, $\Theta = 3°$, and $\gamma_0 = 2 \times 10^4$) is that in the case of 3C 279, the synchrotron-emitting electron population extends to higher energies, γ_{max}. Thus the maximum frequencies of the synchrotron ($\propto \gamma^2_{max}$) and IC ($\propto \gamma^4_{max}$) spectral components are also higher in 3C 279. As pointed out by Maraschi et al., the value of γ_{max} in these model is related to the electron (re-)acceleration process, and most likely varies in a given source as a result of fluctuations in the energy injection and/or transport mechanisms. Thus we conclude that a relatively small increase in γ_{max} in the jet of PKS 1502+106 could easily result in this source being detectable at γ-ray energies.

In summary we have serendipitously observed PKS 1502+106 and found that ~10 billion years ago it possessed a flat 0.1-10 keV band spectrum ($0.5 \lesssim \alpha_X \lesssim 0.8$). The multi-waveband spectral indices α_{rx} and α_{ox} are consistent with those observed in other HPQ, with the bulk of the luminosity emitted in the infrared and/or γ-ray regimes. Application of the inhomogeneous relativistic SSC jet model suggests that PKS 1502+106 may be similar in nature to 3C279. Further multi-waveband observations, especially in the X- and γ-ray bands, are required in order to derive more robust constraints on physical models for this and other such sources.

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Fig. 1.— A composite multi-waveband spectrum of PKS 1502+106 showing the 90% confidence regions of X-ray spectra reported here (corrected for the effects of Galactic absorption), along with observations from other wavebands compiled from the literature. The datasets included are those listed in Section 1, plus Owen et al. (1978), Gregorini et al. (1984), and Neugebauer et al. (1986), Also shown is the the SSC spectrum derived using the inhomogeneous jet model discussed in Section 3, with the solid curve showing the synchrotron and IC spectra from the inner, parabolic section of the jet, and the dotted curve showing the assumed synchrotron spectrum from an outer, conical jet.

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Fig 1