A PANCHROMATIC VIEW OF PKS 0558–504: AN IDEAL LABORATORY TO STUDY THE DISK–JET LINK

M. Gliozzi1, I. E. Papadakis2,3, D. Grupe4, W. P. Brinkmann5, C. Raeth4, and L. Kedziora-Chudczer6,7

1 George Mason University, 4400 University Drive, Fairfax, VA 22030, USA
2 Physics Department, University of Crete, 710 03 Heraklion, Crete, Greece
3 Foundation for Research and Technology-Hellas, IESL, Voutes, 71110 Heraklion, Crete, Greece
4 Department of Astronomy and Astrophysics, Pennsylvania State University, 525 Davey Lab, University Park, PA 16802, USA
5 Max-Planck-Institut für Extraterrestrische Physik, Postfach 1312, D-85741 Garching, Germany
6 Australia Telescope National Facility, CSIRO, P.O. Box 76, Epping, NSW 1710, Australia

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ABSTRACT

PKS 0558–504 is the brightest radio-loud Narrow-line Seyfert 1 galaxy (NLS1) at X-ray energies. Here we present results from the radio, optical, UV, and X-ray bands obtained with Swift, XMM-Newton, and the Australia Telescope Compact Array (ATCA) during a ten-day monitoring campaign in 2008 September. The simultaneous coverage at several wavelengths makes it possible to investigate in detail the broadband spectral energy distribution (SED) and the energetics of this source. The main results can be summarized as follows. The ATCA reveals the presence of an extended radio emission in PKS 0558–504 with two lobe-like structures ~7′ from the bright central source. The extended radio structure and the low value of the radio loudness similar to radio-quiet Seyfert galaxies coupled with constraints from higher energy bands argue against a jet-dominated emission in PKS 0558–504. The study of the SED, which is dominated by a nearly constant optical–UV emission, supports the conclusion that PKS 0558–504 is accreting at a super-Eddington rate. This conclusion was reached by assuming $M_{BH} = 2.5 \times 10^8 M_\odot$, which was obtained with a new scaling method based on X-ray spectral variability results. A comparison between the accretion luminosity and the kinetic power associated with the jet suggests that in this source, the accretion power dominates in agreement with the results obtained from radiation–magneto-hydrodynamic simulations of Galactic black holes (GBHs) accreting at the Eddington rate. The combined findings from this panchromatic investigation strongly suggest that PKS 0558–504 is a large-scale analog of GBHs in their highly accreting intermediate state. More importantly, PKS 0558–504 may also be the prototype of the parent population of the very radio-loud NLS1s recently detected at $\gamma$-ray energies.

Key words: galaxies: active – galaxies: jets – galaxies: nuclei – X-rays: galaxies

Online-only material: color figures

1. INTRODUCTION

Bipolar relativistic jets are common features in a variety of astrophysical objects, most notably in Galactic black holes (GBHs) and active galactic nuclei (AGNs). Accretion of gas onto black holes (BHs) is thought to power these collimated outflows. However, the details of the jet formation as well as the nature of the coupling between accreting matter and outflows are still among the outstanding open questions in high-energy astrophysics.

Because of their proximity and hence their high brightness, the temporal and spectral properties of GBHs are much better known and can be used to infer information about their more powerful, extragalactic analogs. Indeed, considerable progress in this field has been made by multiwavelength-correlated studies of GBHs in different spectral states, which allow one to study the link between accretion (generally probed by the X-ray emission) and jet properties (in the radio regime) on “human” timescales. It is now well established that GBHs undergo state transitions, switching between two main states: the low/hard (LS) and the high/soft (HS) states passing through soft and hard intermediate states (IS), which are also called very high states (VHS) when they occur at high values of accretion rate (see McClintock & Remillard 2006 and Done et al. 2007 for recent comprehensive reviews on GBHs). Each spectral state is unambiguously characterized by a specific combination of temporal and spectral X-ray properties and by well-defined radio features (see Fender et al. 2004).

In the study of the disk–jet link, one of the most interesting spectral states is the IS/VHS, which is generally characterized by powerful transient relativistic ejections in the radio coupled with highly variable X-ray emission that is unambiguously associated with the accretion flow. This is unlike the LS, where the origin of X-rays is still a matter of debate (e.g., Markoff et al. 2003; Zdziarski et al. 2004).

Unfortunately, the physical conditions that lead to the transient relativistic ejections during the IS/VHS are still poorly understood mostly because of their short duration in GBHs. Since the dynamical timescales are proportional to the BH mass, it is not possible in individual AGNs to observe long-term phenomena occurring in GBHs such as the canonical spectral transitions. AGNs, however, may provide better constraints on short-lived GBH phenomena and hence shed light on jet formation and the interplay between accretion and ejection processes.

In the framework of AGN–GBH unification, the Narrow-line Seyfert 1 galaxies (NLS1s) are the best candidates for large-scale analogs of GBHs in the IS/VHS. NLS1s are historically identified by their optical emission line properties: $[O\text{iii}]/H\beta$ is less than 3 and FWHM $H\beta$ is less than 2000 km s$^{-1}$ (Osterbrock & Pogge 1985; Goodrich 1989). They are seldom radio-loud (Komossa et al. 2006), although recent studies reveal the existence of several NLS1s characterized by very high radio loudness (e.g., Yuan et al. 2008). Recently, a few of these very radio-loud NLS1s have been detected at $\gamma$-ray energies.
by the Fermi/LAT collaboration, confirming that these sources possess relativistic jets that are observed at small viewing angles (Abdo et al. 2009a, 2009b, 2009c; Foschini et al. 2009). In the X-rays, NLS1s are generally characterized by steep spectra and strong variability (e.g., Brandt et al. 1999; Leighly 1999a, 1999b; Grupe et al. 2001). Based on these properties, it has been suggested that NLS1s are AGNs in their early phase (Grupe 1999b; Grupe et al. 2001). Based on these properties, it has been suggested that NLS1s are AGNs in their early phase (Grupe 1999b; Grupe et al. 2001). Based on these properties, it has been suggested that NLS1s are AGNs in their early phase (Grupe 1999b; Grupe et al. 2001). Based on these properties, it has been suggested that NLS1s are AGNs in their early phase (Grupe 1999b; Grupe et al. 2001).

The main goal of this work is to shed light on the energetics of this powerful source using multiwavelength data. After describing the observations and data reduction in Section 2, we first try to assess the role played by the jet emission beyond the radio band (in Section 3) and then to constrain the BH mass in PKS 0558−504 without the use of optical measurements (in Section 4). In Section 5, we describe the multiwavelength behavior of PKS 0558−504 based on a ten-day multiwavelength campaign carried out with the Swift X-ray Telescope (XRT) and UV/Optical Telescope (UVOT) simultaneously with the deep XMM-Newton observations in 2008 September, and complemented with one radio observation with the Australia Telescope Compact Array (ATCA). Finally, in Section 6 we discuss the implications of the main results and draw our conclusions. Hereafter, we adopt a cosmology with $H_0 = 71 \text{ km s}^{-1} \text{ Mpc}^{-1}$, $\Omega_\Lambda = 0.73$, and $\Omega_M = 0.27$ (Bennet et al. 2003); with the assumed cosmological parameters, the luminosity distance of PKS 0558−504 is 642 Mpc.

### 2. OBSERVATIONS AND DATA REDUCTION

#### 2.1. Swift

PKS 0558−504 was observed by the Swift gamma-ray burst explorer mission (Gehrels et al. 2004) between 2008 September 9 and 16. The details of this intense monitoring campaign are summarized in Tables 1 and 2. The Swift XRT (Burrows et al. 2005) observations were all performed in Windowed Timing mode (WT; Hill et al. 2004) in order to avoid the effects of pile-up. Data were reduced by the task xrtpipeline version 0.12.1, which is included in the HEASOFT package 6.8. Source and background photons were selected in boxes 40 pixels long. Only single and double events (GRADES 0 to 2) were used. Source photons for the light curve and spectra were extracted with XSELECT. The auxiliary response files (ARFs) were created using xrtmkarf version 0.5.6 and the response matrix swxwt0ta2s6_20010101v011.rmf.

The UVOT (Roming et al. 2005) observed PKS 0558−504 in all six filters. The exposure times in each of the filters per segment are given in Table 1, and the corresponding magnitudes are given in Table 2. The UVOT data were reduced and analyzed as described in Poole et al. (2008). Source photons were extracted from the co-added image files for each segment with a radius of 5″. Background photons were selected in a nearby source-free region with $r = 20″$. Magnitudes and fluxes were measured using the UVOT tool uvotsource. All magnitudes listed in Table 2 were corrected for Galactic reddening ($E_{B-V} = 0.044$; Schlegel et al. 1998). The correction factors were based on the standard reddening correction curves by Cardelli et al. (1989) as described by Equation (2) in Roming et al. (2009).

### Table 1

| Segment | Start Time | End Time | MJD | $T_{\text{XRT}}$ | $T_V$ | $T_B$ | $T_U$ | $T_{\text{UVW1}}$ | $T_{\text{UVM2}}$ | $T_{\text{UVW2}}$ |
|---------|------------|----------|-----|-----------------|-------|-------|-------|-----------------|-----------------|-----------------|
| 001     | 2008 Sep 7 08:10 | 2008 Sep 7 11:36 | 54716.41 | 2215 | 122 | 122 | 122 | 244 | 358 | 488 |
| 002     | 2008 Sep 8 01:50 | 2008 Sep 8 06:50 | 54717.20 | 2429 | 199 | 199 | 199 | 399 | 358 | 798 |
| 003     | 2008 Sep 9 09:52 | 2008 Sep 9 11:48 | 54718.45 | 2327 | 191 | 191 | 191 | 381 | 532 | 763 |
| 004     | 2008 Sep 10 00:15 | 2008 Sep 10 18:20 | 54719.39 | 2203 | 181 | 181 | 181 | 361 | 509 | 724 |
| 005     | 2008 Sep 11 13:21 | 2008 Sep 11 19:59 | 54720.69 | 1897 | 163 | 163 | 163 | 326 | 344 | 653 |
| 006     | 2008 Sep 12 00:36 | 2008 Sep 12 05:37 | 54721.15 | 2008 | 155 | 155 | 155 | 310 | 483 | 621 |
| 007     | 2008 Sep 13 15:09 | 2008 Sep 13 18:40 | 54722.68 | 1869 | 148 | 148 | 148 | 296 | 447 | 594 |
| 008     | 2008 Sep 14 00:42 | 2008 Sep 14 05:40 | 54723.13 | 2363 | 240 | 240 | 240 | 483 | 682 | 966 |
| 009     | 2008 Sep 15 16:56 | 2008 Sep 15 21:54 | 54724.80 | 2353 | 184 | 184 | 184 | 369 | 557 | 739 |
| 010     | 2008 Sep 16 07:20 | 2008 Sep 16 12:11 | 54725.90 | 2072 | 165 | 165 | 165 | 330 | 461 | 660 |
2.2. XMM-Newton

PKS 0558–504 was observed by XMM-Newton from 2008 September 9, 1:19 UT to 2008 September 16, 12:02 UT. The EPIC pn and MOS1 cameras were operated in small window mode, the MOS2 in timing mode, and both RGSs in spectroscopy mode. In the present work we only use EPIC pn data, which were processed with the XMM-Newton Science Analysis Software (SAS) 8.0. The recorded single and double events were screened to remove known hot pixels and other data flagged as bad; only data with PATTERN ≤ 4, FLAG = 0 were used. A more detailed description of the XMM-Newton data analysis can be found in Papadakis et al. (2010b).

2.3. ATCA

Radio monitoring observations of the PKS 0558–504 with the ATCA commenced in 2006 April. The observation session that overlapped with the Swift and XMM-Newton monitoring campaigns was carried out on 2008 September 16, 22:50 UT. The source showed a slightly inverted spectrum between 18.5 and 4.8 GHz ($\alpha \simeq 0.3$, where the flux density $f_\nu$ is related to the spectral index $\alpha$ by the relation $f_\nu \propto \nu^{-\alpha}$). The peak flux density of 0.09 ± 0.01 Jy was measured at 4.8 GHz. Our previous images at this frequency indicate that almost 80% of radio intensity originates from the bright unresolved core, as shown in Figure 1. No flux density fluctuations were detected on intra-hourly timescales.

2.4. SED Fitting

The broadband spectral analysis was performed using the XSPEC v.12.4 software package (Arnaud 1996). We used FLX2XSP in FT00LS to transform the optical and UV fluxes into suitable units for XSPEC. All the X-ray spectra were rebinned so that each bin contained at least 20 counts for the $\chi^2$ statistic to be valid.

3. RADIO PROPERTIES OF PKS 0558–504

Despite the fact that PKS 0558–504 was one of the first radio-loud NLS1s ever discovered, it was not until this project that its radio properties and activity have been studied in deserving detail. Our multiwavelength radio monitoring and imaging program with the ATCA and the VLBI shows the long-term variability pattern similar to flat spectrum, low-luminosity compact radio sources (Falcke et al. 2000). A detailed description of the radio properties will be presented elsewhere (L. Kedziora-Chudczer et al. 2010, in preparation).
the two branches are nearly horizontal and well separated at low values of the Eddington ratio, as \( \lambda_{Edd} \) increases the branch slopes become negative and the branches broaden with substantial overlap at large values of the Eddington ratio. Unfortunately, the super-Eddington accretion rate in PKS 0558−504 (see Section 5.2) coupled with the lack of a clear distinction between the two branches at large values of the Eddington ratio hampers the study of the radio loudness for PKS 0558−504 using the log \( R - \log \lambda_{Edd} \) plot.

Nevertheless, the radio loudness of PKS 0558−504 can be quantitatively assessed by comparing it with the findings of Panessa et al. (2007) who carried out a detailed investigation of radio loudness in two large samples of radio-quiet Seyfert galaxies and low-luminosity radio galaxies (LLRGs). In this study, both the classical radio-loudness parameter \( R \) and the X-ray radio-loudness \( R_x \equiv vL_v(6 \text{ cm})/L_{2-10 \text{ keV}} \) were used; the latter parameter was introduced by Terashima & Wilson (2003) to circumvent extinction problems that usually affect the optical measurements and may lead to overestimates of \( R \). Using nearly simultaneous radio, optical, and X-ray observations (we have used the flux values measured during the last day of the XMM-Newton–Swift campaign because they are almost contemporaneous with the ATCA observation) for the log \( R - \log R_x \) plot, PKS 0558−504 appears to be fully consistent with radio-quiet Seyfert galaxies and inconsistent with radio-loud objects, as visually demonstrated in Figure 2, where the boundaries have been determined by Panessa et al. (2007).

Figure 2. Classical radio-loudness \( R \) plotted vs. the X-ray radio-loudness \( R_x \). PKS 0558−504 is well within the radio-quiet region and apparently inconsistent with radio-loud objects. The boundaries between radio-loud and radio-quiet objects have been determined by Panessa et al. (2007) using two large samples of radio-quiet Seyfert galaxies and LLRGs.

(A color version of this figure is available in the online journal.)

In conclusion, the extended radio emission and the symmetric location of the lobes in PKS 0558−504, which are reminiscent of the typical structure observed in FRI radio galaxies, argue against a highly beamed source. This is confirmed by the simultaneous radio-loudness parameters that are in full agreement with radio-quiet Seyfert galaxies. On the other hand, our VLBI imaging at 2.3 GHz (L. Kedziora-Chudczer et al. 2010, in preparation), which shows a one-sided parsec-scale jet, suggests that the presence of beamed emission cannot be ruled out for PKS 0558−504 in the radio band. For the sake of clarity and for historical reasons in the remainder of the paper, we will maintain the classification of radio-loud NLS1 for PKS 0558−504.

4. BLACK HOLE MASS OF PKS 0558−504

In order to determine the accretion rate of PKS 0558−504 and investigate its energetics, it is first necessary to constrain the mass of the supermassive black hole (SMBH). Here, we report four different and independent measurements of \( M_{\text{BH}} \) for PKS 0558−504.

1. As with many AGNs for which there are no direct measurements from reverberation mapping, the \( M_{\text{BH}} \) in PKS 0558−504 has been estimated from the virial relationship \( M_{\text{BH}} = f R (\Delta V)^2 / G \) (where \( f \) is an unknown geometric factor, and \( R \) and \( (\Delta V)^2 \) are the radius and velocity dispersion of broad-line region (BLR), respectively). This yielded \( M_{\text{BH}} \approx 6 \times 10^6 M_\odot \) (Papadakis et al. 2010b), which is relatively small when compared to the typical masses of radio-loud AGNs (e.g., McLure & Jarvis 2004), but fully consistent with the values derived in NLS1s using the same method (e.g., Grupe & Mathur 2004).

Given that the optical measurements \( L_{\text{bol}}(6000 \text{ Å}) \) (Corbin & Smith 2000) and \( H_\beta \) (Corbin 1997) are non-simultaneous, and given the uncertainty on the geometric factor \( f \) and the controversy about the application of the virial method to NLS1s (see, e.g., Marconi et al. 2008; Decarli et al. 2008; but also Netzer 2009), it is also important to constrain \( M_{\text{BH}} \) with alternative techniques that are independent of optical measurements and any assumption on the BLR.

2. One possible alternative method is based on the so-called “fundamental plane” of BHs introduced by Merloni et al. (2003; see also Falcke et al. 2004), where \( M_{\text{BH}} \) is related to both the X-ray and radio luminosities in any accreting BH system. Recently, this relationship has been refined by Gültekin et al. (2009) by utilizing only sources with BH masses that have been determined dynamically. Using the latter relationship in combination with quasi-simultaneous measurements of the radio and X-ray emission in PKS 0558−504, we derive \( M_{\text{BH}} \approx 3 \times 10^8 M_\odot \), which is larger than the value obtained from the virial theorem by a factor of \( \sim 4 \). This finding does not depend on the nearly simultaneous nature of the observations, since we derive a very similar value for \( M_{\text{BH}} \) by using radio and \( RXTE \) luminosities averaged over an interval of one year.

3. For AGNs with evenly sampled long-term coverage in the X-ray band, a viable technique to estimate the mass of the BH is based on the relationship \( \log M_{\text{BH}} = (\log T_\text{H} + 0.98 \log L_{\text{bol}} + 2.32)/2.1 \), where \( M_{\text{BH}} \) is in \( 10^6 M_\odot \) units, \( L_{\text{bol}} \) is the bolometric luminosity in units of \( 10^{44} \text{ erg s}^{-1} \), and \( T_\text{H} \) is the time break in days derived from power spectral density (McHardy et al. 2006). PKS 0558−504 has been regularly monitored with \( RXTE \) since 2004 March, making it possible to estimate \( M_{\text{BH}} \) with the formula above. The main findings of a detailed temporal study that combined the long-term \( RXTE \) light curve and the deep XMM-Newton observation in 2008 September are reported by Papadakis et al. (2010a) and suggest that \( M_{\text{BH}} \approx 2-3 \times 10^8 M_\odot \).

4. An additional independent way to determine the mass in BH systems relies on the fact that hard X-rays are produced by the Comptonization process in both stellar BHs and SMBHs. Recently, Shaposhnikov & Titarchuk (2009)
discovered that GBHs present a universal scalable relationship between the photon index and the normalization of the bulk motion Comptonization (BMC) model during their spectral transitions. They also demonstrate that this relationship can be used to estimate the mass of any GBHs by simply scaling the $M_{\text{BH}}$ value from a suitable reference source. We have started testing the extension of this method to SMBHs and the encouraging results will be published elsewhere (M. Gliozzi et al. 2010, in preparation). Here we apply this method to PKS 0558−504 after describing the basic characteristics of the BMC model and this scaling technique.

Although it was historically developed to describe the Comptonization of thermal seed photons by a relativistic converging flow (Titarchuk et al. 1997), the BMC model is a generic Comptonization model able to describe the thermal Comptonization (i.e., the inverse Compton scattering produced by electrons with a Maxwellian energy distribution) and the BMC (where the seed photons are scattered-off electrons with bulk relativistic motion) equally well. The BMC model is characterized by four free parameters: (1) the temperature of the thermal seed photons $kT$, (2) the energy spectral index $\alpha$ (which is related to the photon index by the relation $\Gamma = 1 + \alpha$), (3) a parameter $\log A$ related to the Comptonization fraction $f$ (i.e., the ratio between the number of Compton-scattered photons and the number of seed photons) by the relation $f = A/(1 + A)$, and (4) the normalization $N_{\text{BMC}}$.

In simple terms, the necessary steps to derive $M_{\text{BH}}$ with this method can be summarized as follows.

1. Construct a $\Gamma$–$N_{\text{BMC}}$ plot for a GBH of known mass and distance, which will be used as a reference (hereafter denoted by the subscript “r”).
2. Compute the normalization ratio between the target of interest (hereafter denoted by the subscript “t”) and the reference object $N_{\text{BMC,t}}/N_{\text{BMC,r}}$ at the value of $\Gamma$ measured for the AGN.
3. Derive the unknown BH mass using the following equation:

$$M_{\text{BH,t}} = M_{\text{BH,r}} \times (N_{\text{BMC,t}}/N_{\text{BMC,r}}) \times (d_l/d_r)^2 \times f_G.$$  (1)

where $M_{\text{BH,t}}$ is the BH mass of the GBH reference object, $N_{\text{BMC,t}}$ and $N_{\text{BMC,r}}$ are the respective BMC normalizations for the target and reference objects, $d_l$ and $d_r$ are the corresponding distances, and $f_G = \cos \theta_l / \cos \theta_r$ is a geometrical factor that depends on the respective inclination angles.

The above formula is readily obtained by considering that (1) the normalization is a function of luminosity and distance: $N_{\text{BMC}} \propto L/d^2$, and (2) the luminosity of an accreting BH system can be expressed by $L \propto \eta m_{\text{BH}}$, where $\eta$ is the radiative efficiency. The only assumptions are that different sources in the same spectral state have similar values of $\eta$ and $m$, and that the photon index is a reliable indicator for the spectral state. This is in broad agreement with the positive correlation between the photon index and accretion rate found in bright AGNs (e.g., Shemmer et al. 2006; Papadakis et al. 2009).

Figure 3 shows the $\Gamma$–$N_{\text{BMC}}$ diagram for PKS 0558−504 in comparison with the primary reference source GRO J1655−40, a well-known microquasar whose parameters are tightly constrained: $M_{\text{BH}}/M_\odot = 6.3 \pm 0.3$, $i = 70^\circ \pm 1^\circ$, $d = 3.2 \pm 0.2$ kpc (Greene et al. 2001; Hjellming & Rupen 1995). For PKS 0558−504, we fitted the 2–10 keV energy band of the seven relatively long segments (with exposures up to 20 ks) that best describe the spectral evolution of the source during the 2008 September XMM-Newton campaign (Papadakis et al. 2010b) and the ten short segments (2 ks exposures) simultaneous with the Swift observation, which will be described below. For the spectral fits, the temperature of the thermal seed photons was kept frozen at the best-fit value obtained from the broadband spectral energy distribution (SED) fit ($kT = 8–23$ eV; see Section 5.2), whereas the other parameters were free to vary. The 2–10 keV spectra of all segments were adequately fitted (typically $\chi^2_\text{red} \approx 0.9–0.95$) with one BMC model absorbed by Galactic $N_H$.

As expected, due to the longer timescales associated with SMBHs, the PKS 0558–504 trend in the $\Gamma$–$N_{\text{BMC}}$ diagram is restricted to a small portion of the trend shown by GRO J1655–40 during its 2005 spectral evolution between LS and HS. Interestingly, the short-term spectral behavior of PKS 0558–504 appears to be consistent with GRO J1655–40 in its highly accreting state.

Substituting in Equation (1) a distance of 624 Mpc and $N_{\text{BMC,t}}/N_{\text{BMC,r}} = 8 \times 10^{-2}$, obtained from Figure 3, we derive for PKS 0558−504 $M_{\text{BH}} \simeq (3 \times 10^8 M_\odot) \times f_G$. Although the inclination angle of PKS 0558−504 is unknown, the nearly symmetric position of the lobe-like radio structures suggests that the system is not seen pole-on. If we conservatively assume $i = 30^\circ–45^\circ$, then $f_G \simeq 0.4–0.5$, leading to a mass estimate of $M_{\text{BH}} \simeq 1.5 \times 10^8 M_\odot$.

In summary, all the optically independent methods consistently yield $M_{\text{BH}}$ values of the order of a few units in $10^8 M_\odot$, which is about a factor of ~5 larger than the value derived from the virial theorem. Interestingly, this is in agreement with the corrective factor proposed by Marconi et al. (2008). However, a systematic study of the $M_{\text{BH}}$ distribution of well-defined samples of NLS1s and Broad-line Seyfert 1 galaxies obtained with optically independent methods is necessary before drawing any general conclusion. Considering all four methods, the $M_{\text{BH}}$ in PKS 0558−504 ranges between $6 \times 10^7$ and $3 \times 10^8 M_\odot$, with a mean of $1.8 \times 10^8 M_\odot$.

![Figure 3.](image-url)
According to a $\chi^2$ test, no significant variability is present in the $U$, $B$, and $V$ bands ($P_{\chi^2} \approx 0.9-0.95$) and only marginal variability is detected in the UVW1 band ($P_{\chi^2} \approx 0.2$), as suggested by a visual inspection of the four bottom panels of Figure 4. On the other hand, the two higher energy UV bands (UVW2 and UVM2) and the X-ray range all show statistically significant variability ($P_{\chi^2} < 10^{-4}$). There are, however, qualitative and quantitative differences between the UV and X-ray light curves: the former only show moderate variability, $F_{\text{var, MW2}} = (3.0 \pm 1.4)\%$, $F_{\text{var, W2}} = (4.1 \pm 0.5)\%$ (where $F_{\text{var}}$ is the fractional variability that measures the normalized variance corrected for the statistical uncertainties), which appears to be associated with only two data points (specifically the third and fourth points in Figure 4) that are significantly lower than the others. On the other hand, the XRT light curve shows strong variability ($F_{\text{var, XRT}} = (28.6 \pm 0.9)\%$) throughout the entire eight-day interval.

In conclusion, the Swift campaign in 2008 September confirms the presence of strong variability in the X-ray band of PKS 0558–504 and reveals the presence of moderate variability in the UV bands, whereas the optical bands appear to be consistent with the hypothesis of constant flux over short timescales.

5.2. Broadband SED

One of the best ways to get insights into the energetics of the central engine in PKS 0558–504 and in AGNs in general is to study the broadband SED, as demonstrated by numerous successful past studies (e.g., see Elvis et al. 1994). However, one of the major problems in this field has been the lack of truly contemporaneous observations in different energy bands, which could lead to inaccurate results in virtue of the fast variability of AGNs. Recently, this kind of study has markedly improved with the advent of Swift, thanks to its ability of observing simultaneously in several energy bands coupled with its highly flexible schedule.

Here we analyze the contemporaneous SEDs of PKS 0558–504 obtained with the Swift UVOT and XMM-Newton EPIC pn during a simultaneous campaign in 2008 September. The choice of using 2000 s segments of the EPIC pn instead of the Swift XRT data is dictated by the much higher throughput of the EPIC camera that allows a more detailed spectral analysis of the X-ray spectrum.

Following the procedure adopted by Vasudevan & Fabian (2009), we converted the UVOT fluxes using the FLX2XSP command in FT00LS. The resulting spectra were then combined with the 0.3–10 keV EPIC spectra and fitted in XSPEC with a model that comprises a disk and two Comptonization components: DISKPN+WABS(BMC+BMC). Only the Comptonization models are absorbed by the Galactic $N_H$, because the optical and UV data were already corrected for absorption.

As explained in Section 4, the BMC is a simple but comprehensive Comptonization model that can fit both thermal and bulk Comptonization processes. The use of a Comptonization model to parameterize the soft excess below 2 keV is guided by a thorough spectral analysis of the highest quality XMM-Newton spectra, which suggests that this component may arise from a hot “skin” in the innermost part of the disk in objects that accrete at rates close to or above the Eddington limit (Papadakis et al. 2010b). For the hard X-rays, we also used a BMC model instead of the phenomenological power-law model (PL) because the BMC parameters are computed in a self-consistent way, and, unlike the PL, the power law produced by the BMC does not extend to arbitrarily low energies and thus
affects neither the normalization of the thermal component nor the amount of local absorption.

The DISKPN model (Gierlińska et al. 1999) has three parameters: $T_{\text{max}}$, $R_{\text{in}}$, and the normalization that depend on the BH mass, the distance, the inclination angle $i$, and the color factor $\beta$. The latter two quantities, which are unknown for PKS 0558–504, were kept fixed to $i = 0^\circ$ and $\beta = 1$ since they only marginally affect the luminosity derived from the direct integration of the SED (see Vasudevan & Fabian 2009). In order to determine the maximum temperature of the accretion disk, we first fitted the UVOT data with only the DISKPN model, fixing $R_{\text{in}} = 6 R_\odot$ and the normalization to two different values corresponding to $M_{\text{BH}} = 6 \times 10^7 M_\odot$ and $M_{\text{BH}} = 2.5 \times 10^8 M_\odot$, respectively. The resulting best-fit temperatures were, respectively, $\sim 23$ eV and $\sim 8$ eV. If the normalization of the DISKPN model is left free to vary, the resulting value derived for the BH mass is $M_{\text{BH}} = (2.5–2.7) \times 10^8 M_\odot$, which is in good agreement with the values inferred from the three model-independent techniques described in Section 4.

We then fitted the X-ray spectra by linking the temperature of seed photons of both Comptonization models to $T_{\text{max}}$. The resulting best-fit parameters for the BMC components and the corresponding luminosities are reported in Table 3 for the conservative assumption that $M_{\text{BH}} = 2.5 \times 10^8 M_\odot$. The values of the reduced $\chi^2$ for the X-ray spectral fits range between 0.9 and 1.2, whereas for the overall broadband fits, $\chi^2_\nu$ are of the order of 1.4–1.5. Note that the BMC parameters and the X-ray luminosity are almost insensitive to the choice of $kT$, whereas the bolometric luminosity $L_{\text{bol}}$ is significantly affected by this choice: $L_{\text{bol}}$ increases by a factor of $\sim 3$ when $kT = 23$ eV (i.e., for $M_{\text{BH}} = 6 \times 10^7 M_\odot$).

Since a very detailed X-ray spectral analysis has already been performed and reported elsewhere (see Papadakis et al. 2010b), we focus here on the broadband SED. Figure 5 illustrates three different SEDs corresponding, respectively, to (1) segment 001 in the top panel, which represents the case of average optical–UV flux and average X-ray emission; (2) segment 002 in the middle panel, which refers to the highest X-ray emission level; and (3) segment 003 in the bottom panel, which represents the case of low optical/UV emission. Whereas the X-ray emission varies considerably from day to day with luminosity changes by up to a factor of $\sim 2$, the changes in the optical/UV band are barely noticeable and correspond to variations of $L_{\text{bol}}$ lower than 10%.

In conclusion, the overall SEDs of PKS 0558–504 during the 2008 September campaign are reasonably well fitted with a disk model parameterizing the optical/UV emission and two Comptonization components to describe the X-ray spectra. The SED appears to be dominated by a nearly constant disk component, with a variable X-ray contribution which represents about 1/100 of the $L_{\text{bol}}$ with the assumption that $M_{\text{BH}} = 2.5 \times 10^8 M_\odot$. The X-ray contribution is further reduced by a factor of $\sim 3$ if $M_{\text{BH}} = 6 \times 10^7 M_\odot$.

6. DISCUSSION

6.1. Jet Contribution

The main goal of this work is to investigate the energetics of the radio-loud NLS1 PKS 0558–504 and thus shed some light on the nature of its central engine. To this end, it is first necessary to assess the role played by the jet and more specifically whether the jet may dominate the high-energy emission of PKS 0558–504. The findings based on the ATCA observations reported in Section 3—the radio-loudness measurements consistent with radio-quiet Seyfert galaxies and the extended and symmetric FRI-like radio structure which is at odds with the compact radio emission typical of very radio-loud NLS1s—disfavor a jet-dominated scenario, which however appears to be the most likely scenario for the very radio-loud NLS1s recently detected with the Fermi/LAT.

This preliminary conclusion is supported by several independent pieces of evidence from studies at higher energies, which can be summarized as follows: (1) the X-ray spectral and temporal variability appears to be fully consistent with the typical behavior of radio-quiet Seyfert galaxies (Papadakis et al. 2010a, 2010b); (2) the long-term spectral variability in the 2–15 keV energy band is inconsistent with the characteristic trend observed in blazars with $KXT$ (Gliozzi et al. 2007); (3) unlike highly beamed AGNs, PKS 0558–504 is not detected at very high energy either in the GeV range (the first year Fermi/LAT
The main result from the analysis of the broadband SED (described in Section 5) is that the emission of PKS 0558–504 is dominated by a weakly variable UV bump ($F_{\text{var,UV}} \simeq 4\%$), which is commonly associated with the emission from the accretion disk. Conversely, the X-ray radiation, which we have interpreted as emission from two Comptonization components, appears to be highly variable ($F_{\text{var,X}} \simeq 30\%$) but encompasses only a small fraction of the total emission. It is instructive to assess in a more quantitative way which of the variable components (UV or X-rays) is energetically more important. Since $F_{\text{var}}$ provides a measurement of the variability normalized over the average flux, a measurement of the “true” variability (hereafter var$_{\text{UV}}$ and var$_{\text{X}}$, respectively) can be obtained by multiplying $F_{\text{var}}$ by the respective average flux. This test yields var$_{\text{X}}$/var$_{\text{UV}} = 1.3$, indicating that the X-ray component is the dominant variable component.

In order to get helpful insights into the nature of the central engine in PKS 0558–504, it is crucial to constrain its accretion rate in terms of Eddington units. This information can be readily obtained by using the mass of the central BH and measuring the bolometric luminosity. Depending on the method used (see Section 4), the BH mass of PKS 0558–504 may range between $6 \times 10^7 M_{\odot}$ and $3 \times 10^8 M_{\odot}$. To be conservative, in the rest of the paper we will assume $M_{\text{BH}} = 2.5 \times 10^8 M_{\odot}$, which corresponds to an Eddington luminosity of $L_{\text{Edd}} = 3.25 \times 10^{46}$ erg s$^{-1}$ (note that this choice of $M_{\text{BH}}$ does not affect either the main findings or our conclusions). Combining this value with the average bolometric luminosity derived from the direct integration of the broadband SED (see Table 3) leads to an accretion rate of $\dot{M}_{\text{BH}} \equiv L_{\text{bol}}/L_{\text{Edd}} \simeq 1.7$, which strongly suggests that PKS 0558–504 accretes at super-Eddington rate. Note that with the less conservative assumption of $M_{\text{BH}} = 6 \times 10^7 M_{\odot}$ (which corresponds to a lower Eddington luminosity and a higher bolometric luminosity), the accretion rate in Eddington units would be of the order of $\dot{M}_{\text{Edd}} \simeq 25$.

Having measured the X-ray and bolometric luminosity over a period of 10 days, it is possible not only to compute the average bolometric correction $\kappa_{2-10\text{keV}} \equiv L_{2-10\text{keV}}/L_{\text{bol}}$ but also to investigate if it varies over time. From Table 3, we infer that $\kappa_{2-10\text{keV}}$ indeed varies by a factor of $\sim 2.5$, and ranges between 108 and 249, with an average value of $162 \pm 39$ (where the error quoted is 1σ). The large value of $\kappa_{2-10\text{keV}}$ appears to be in qualitative agreement with recent studies that suggest that the X-ray bolometric correction is directly proportional to the Eddington ratio (e.g., Vasudevan & Fabian 2007, 2009). A more quantitative comparison can be performed using the recent results presented by Lusso et al. (2010), which are based on the optical and X-ray studies of a sample of 545 X-ray selected type 1 AGNs from the XMM-COSMOS survey. More specifically, by plugging $\dot{\lambda}_{\text{Edd}} = 1.7$ (the value of the Eddington ratio derived for PKS 0558–504) into Equation (14) of Lusso et al. (2010), we derive $\kappa_{2-10\text{keV}} = 151^{+34}_{-20}$, which is fully consistent with the average value empirically derived from the SED.

Figure 5. Deconvolved EPIC pn spectra in the 0.4–10 keV energy range, combined with UVOT data. The overall SEDs are fitted with a diskpn model to parameterize the optical–UV emission and two BMC models to characterize the X-ray spectrum. The BMC models are absorbed by Galactic $N_{\text{H}}$, whereas the optical/UV data have been already corrected for Galactic absorption. The spectrum in the top panel (a) represents the case of average optical–UV flux and average X-ray emission. The middle panel (b) illustrates the case of high X-ray emission, whereas the bottom panel (c) represents the case of relatively low optical/UV emission.

(A color version of this figure is available in the online journal.)


Finally, it is instructive to compare PKS 0558−504 to GRS 1915+105, which is thought to be the only microquasar that regularly accretes at or above the Eddington limit. Interestingly, during its spectral transition from hard to soft, the X-ray spectra of GRS 1915+105 are well fitted by two BMC components (a hard component with $\Gamma_1 = 1.7-3$ and a soft component with $\Gamma_1 = 2.7-4.2$), which evolve following the trend shown in Figure 3 (Titarchuk & Semieina 2009). For GRS 1915+105 the location of the IS/VHS in the $\Gamma$--$N_{\text{BMC}}$ diagram is also consistent with the position of PKS 0558−504 (see Figure 13 of Titarchuk & Semieina 2009).

6.4. Conclusion

In conclusion, our multiwavelength analysis of the emission properties of PKS 0558−504, ranging between the radio and the hard X-rays, reveals that this source has a radio jet, though it is accreting at the Eddington level or above. All our findings appear to independently lend support to the hypothesis that PKS 0558−504 may be a large-scale analog of the IS observed in GBHs. But can we extend this analogy to the whole class of NLS1s? In other words, can PKS 0558−504 be considered a prototype of NLS1s? At first sight, the “radio loudness” of PKS 0558−504 seems to set this source in a small subclass of radio-loud NLS1s. However, $R = 10$ does not represent a strict boundary for the radio loudness; indeed, the radio loudness of PKS 0558−504 appears to be fully consistent with that of radio-quiet Seyfert galaxies according to both $R$ and $R_\gamma$ (see Figure 2). Bearing in mind that PKS 0558−504 is by far the brightest NLS1 in the X-ray band and that its X-ray luminosity is nearly 100 times the typical value of “normal” radio-quiet NLS1s, similar values of the order of $R_\gamma \lesssim 10^{-3}$ for “normal” NLS1s would correspond to radio fluxes of the order of 1 mJy or less. This would explain why only a small minority of NLS1s is detected in the radio band. Additionally, it must be pointed out that in the IS the radio ejections are transients; therefore, genuine radio-quiet NLS1 might still represent large-scale analogs of the IS.

It is also interesting to compare PKS 0558−504 with the radio-loud NLS1s recently detected at $\gamma$-rays. The latter are characterized by large values of the radio loudness ($R > 50$), by compact radio emission, and by SEDs that are dominated by two broad bumps typical of jet-dominated sources. Indeed, it has been argued that these very radio-loud NLS1 galaxies represent a third class of $\gamma$-ray emitting AGNs along with blazars and radio galaxies. From this perspective, PKS 0558−504 can play a crucial role since it may represent the prototype of NLS1s with a jet seen at large viewing angles. In other words, PKS 0558−504 may be the first representative of non-jet-dominated radio-loud NLS1s which are the parent population of the very radio-loud NLS1s detected by the Fermi/LAT. This is similar to radio galaxies that are considered the non-beamed parent population of blazars.

In summary, we can hypothesize that PKS 0558−504 is indeed a prototypical NLS1. Since the jet appears to dominate only in the radio band, the emission associated with the accretion flow can be cleanly separated from the emission related to the jet. This makes PKS 0558−504 an ideal system to study the disk–jet interaction. In this framework, important insights into the physical conditions leading to the formation of jets in highly accreting BH systems can be obtained by a systematic comparison of the spectral and temporal properties of PKS 0558−504 with the corresponding properties of other highly accreting NLS1s that do not show any evidence of radio jets, as
well as with NLS1s that are jet-dominated. We plan to pursue this approach in our future work.

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