PROCEEDINGS OF SCIENCE

Black-Hole Engine Kinematics, Flares from PKS 2155-304, and Multiwavelength Blazar Analysis

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Kinematical and luminosity relations for black-hole jet sources are reviewed. If the TeV flares observed from PKS 2155-304 in 2006 July are assumed to originate from a black hole with mass $\approx 10^8 M_8 M_\odot$, then the ~ 5 minute variability timescale is consistent with the light-travel time across the Schwarzschild radius of the black hole if $M_8 \sim 1$. The absolute jet power in a synchrotron/SSC model exceeds, however, the Eddington luminosity for a black hole with $M_8 \sim 1$ unless the jet is highly efficient. The maximum Blandford-Znajek power is $\sim 10^{46} M_8$ ergs s^{-1} if the magnetic-field energy density threading the horizon is equated with the luminous energy density in the vicinity of the black hole. An external Compton component can relax power requirements, so a black hole with mass $\sim 10^8 M_\odot$ could explain the observed flaring behavior. For the Swift and HESS data taken in 2006 July, relativistic outflows with bulk Lorentz factor $\Gamma \gtrsim 30$ satisfy γ-γ attenuation limits. If this system harbors a binary black hole, then the accretion disk from a more massive, $\sim 10^9 M_\odot$ black-hole primary would make an additional external radiation component. Dual thermal accretion disk signatures would confirm this scenario.

Workshop on Blazar Variability across the Electromagnetic Spectrum
April 22-25 2008
Palaiseau, France

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PoS(BLAZARS2008)019

1. Introduction

HESS observations (Aharonian et al., 2007) of extraordinary γ-ray activity in PKS 2155-304 show flaring time scales as short as $t_v \approx 300$ s in a succession of ~ 200 GeV – 4 TeV outbursts lasting more than 60 minutes on 27 – 28 July, 2006. The apparent isotropic TeV power of the observed radiation during peak activity is $\gtrsim 3 \times 10^{46}$ ergs s^{-1}. At a redshift $z = 0.116$ and luminosity distance $d_L \cong 540$ Mpc, attenuation by the extragalactic background light (EBL) means that the isotropic γ-ray power, including GeV γ-rays, can be a factor ~ 10 greater. The TeV spectrum is described by a broken power law with number indices $\sim 2.7 - 3$.

RXTE and Swift observations began on July 29th, revealing a synchrotron component peaking at UV/soft X-ray energies with energy flux ~ 5 – 10 less than the TeV energy flux (Foschini et al., 2007). The optical emission is poorly correlated with the X-ray emission, and the optical flux can remain high when the X-ray flux becomes low and the spectrum steep (Foschini et al., 2008). The γ-ray energy flux is comparable to the synchrotron (radio to 10 keV) energy flux in low states. Estimates of internal γ-γ absorption already indicate $\delta_{\rm D} \gtrsim 50$ (Begelman et al., 2008). Detailed synchrotron/SSC blazar modeling (Finke et al., 2008) of the RXTE/Swift and HESS contemporaneous (but not simultaneous) data, taking into account internal source and γ-γ absorption for different EBL models, requires large Doppler factors, $\delta_{\rm D} \gtrsim 100$, for $t_v = 300$ s. These results are in accord with large Doppler factors encountered previously when using a synchrotron/SSC scenario to model BL Lac objects (e.g., Krawczynski et al., 2002). If the mass of the supermassive black-hole engine is $\sim 10^8 M_8 M_\odot$, then its Schwarzschild timescale is

$$t_{\rm S} = \frac{R_{\rm S}}{c} = \frac{2GM}{c^3} = 990 M_8 \text{ s} \cong 10^3 M_8 \text{ s}. \quad (1.1)$$

Interpreting the variability time scale $t_v = 300 t_{5m}$ s, $t_{5m} \sim 1$, as a limit on the engine size scale means that the black hole powering the TeV emission from PKS 2155-304 has mass $M_8 \sim 0.5$.

Different than the approach of Begelman et al. (2008), who postulate patchy flaring regions or enhanced localized emission regions from jet instabilities, or Levinson (2007), who considers jet deceleration by radiative drag from intense localized radiation fields near the jet, we consider implications of requiring that the engine size scale, characterized by the $R_{\rm S}$, be defined in terms of the measured variability time scale t_v.

In Section 2, the kinematics of relativistic outflows from black-hole jets are reviewed and applied to the flares of PKS 2155-304. The implications of the model are described in Section 3, and summary and conclusions are given in Section 4.

2. Kinematics

The causality condition for variability is that for large amplitude flaring, light travel time limitations restrict the temporal variability to timescale $\Delta t' \gtrsim \Delta r'/c$ in the comoving frame. From the time transformation, where z is the source redshift, $t_v = (1+z)\Delta t'/\delta_{\rm D}$, so

$$t_v \gtrsim \frac{\Delta r'}{c\delta_D}(1+z) \text{ or } \Delta r' \lesssim \frac{c\delta_{\rm D} t_v}{1+z}\ , \quad (2.1)$$

where z is the source redshift. In the comoving frame, the characteristic size scale, $\Delta r'$, must be larger by a factor of Γ larger than stationary frame size scale, Δr_*, so that length contraction in the stationary frame recovers a size scale given by Δr_*; thus $\Delta r' \cong \Gamma \Delta r_*$. Taking the black-hole engine sizescale

$$\Delta r_* \cong r_S \tag{2.2}$$

gives

$$t_v \gtrsim \frac{(1+z)}{c}\frac{\Gamma}{\delta_{\rm D}} r_{\rm S} \gtrsim \frac{(1+z)}{2c}\, r_{\rm S}\ . \tag{2.3}$$

Thus the 5 minute variability time scale of PKS 2155-304 essentially corresponds to the Schwarzschild radius of a black hole with $\approx 10^8 M_\odot$ (see also Levinson, 2008).

This is in contrast to the reasoning given by Aharonian et al. (2007) and the MAGIC Coll. (2008), who take the stationary frame sizescale equal to the comoving sizescale of the emission region, $\Delta r' \cong \Delta r_*$. This gives a lower limit to the Doppler factor but is based upon a supposition that assumes the comoving emission sizescale corresponds to the Schwarzschild radius of the black hole.

The νF_ν spectral flux from jetted outflow is

$$f_\varepsilon = \frac{\delta_{\rm D}^4}{4\pi d_L^2}\varepsilon' L'(\varepsilon') = \frac{\delta_{\rm D}^4}{d_L^2} V_b' \varepsilon' j'(\varepsilon',\Omega')\ , \tag{2.4}$$

so that the comoving luminosity

$$L' = \frac{4\pi d_L^2 \Phi_E}{\delta_{\rm D}^4}\ , \tag{2.5}$$

where $\Phi_E = \int_0^\infty d\varepsilon\, \varepsilon^{-1} f_\varepsilon$ is the measured bolometric energy flux. The apparent isotropic luminosity is therefore

$$L_{iso} = 4\pi d_L^2 \Phi_E = 4\pi d_L^2 \int_0^\infty d\varepsilon\, \frac{f_\varepsilon}{\varepsilon}\ . \tag{2.6}$$

The absolute luminosity in electromagnetic radiation is related to the measured apparent isotropic luminosity through the beaming factor f_b, so that $L_{abs} = f_b L_{iso}$. The beaming factor for a two-sided top-hat jet source is

$$f_b \cong 1 - \cos\theta_j \ \stackrel{\Gamma \gg 1}{\rightarrow}\ \frac{\theta_j^2}{2} \cong \frac{1}{2\Gamma^2}\ . \tag{2.7}$$

Thus $f_b^{-1} \cong 2\Gamma^2 \cong 200,\ 1800$ for $\Gamma = 10,\ 30$. The analysis of Jorstad et al. (2005) for radio galaxies, BL Lac objects, and flat spectrum quasars gives $\theta_j \cong 0.6/\Gamma$. Note also that Nieppola et al. (2008) use an expression corresponding to eq. (2.5) to relate the measured energy flux to the absolute jet luminosity, though this actually relates it to the comoving luminosity.

These luminosities can be compared to the Eddington luminosity, assuming that the jet power ultimately derives from the accretion power. The Eddington luminosity

$$L_{\rm Edd} = \frac{4\pi G M m_H c}{\sigma_{\rm T}} \cong 1.26\times 10^{46} M_8\ \ {\rm ergs\ s^{-1}}\ . \tag{2.8}$$

The Eddington ratio

$$\ell_{\rm Edd} = \frac{\eta_f \dot m c^2}{L_{\rm Edd}}\ , \tag{2.9}$$

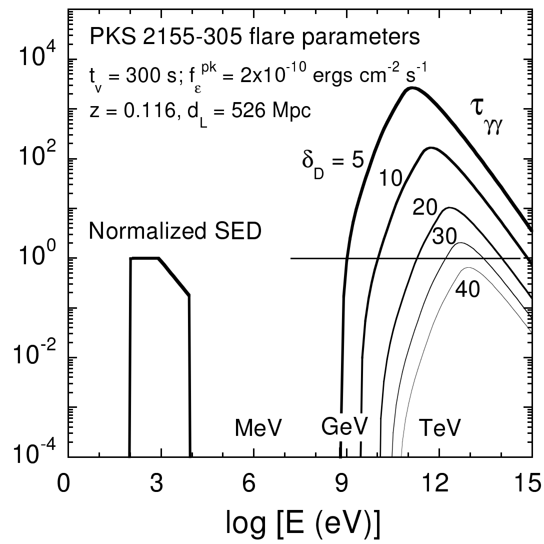

Figure 1: Normalized SED for the target photons of PKS 2155-304, and the optical depth $\tau_{\gamma\gamma}$ to absorption of γ rays with energy E off the target photon distribution as a function of the Doppler factor of the outflow.

where η_f is the efficiency to transform the gravitational potential energy of accreting matter to escaping radiation.

If jets are powered by accretion, assumed to be Eddington-limited, then $L_{iso} \cong L_{abs}/f_b \ll 2\Gamma^2 L_{\rm Edd}$, so

$$\Gamma \gg \sqrt{\frac{4\pi d_L^2 \Phi_E}{2L_{\rm Edd}}} \cong 1.2\sqrt{\frac{\Phi_{-9}}{M_8}} \cong 1.5\sqrt{\frac{\Phi_{-9}}{t_v(300\ {\rm s})}} \tag{2.10}$$

and Φ_{-9} is the bolometric source γ-ray luminosity in units of 10^{-9} ergs cm^{-2} s^{-1}.

Corrections for the EBL and the addition of the GeV energy flux, the level of which will be determined from GLAST observations, could show that $\Phi_{-9} \sim 10$, so that $\Gamma \gtrsim 5$. Already from γ-γ arguments, however, $\Gamma \gtrsim 30$. For example, the minimum Doppler factor from the requirement that the emission region is transparent, namely $\tau_{\gamma\gamma}(E) < 1$, is given for a broken power-law target synchrotron photon spectrum by the expression

$$\delta_{\rm D} \gtrsim \begin{cases} 29\varepsilon_6^{0.23} t_{5m}^{-0.14}\ , & \varepsilon_6 < t_{5m}^{-1/2} \\ 29.5\varepsilon_6^{0.15} t_{5m}^{-0.18}\ , & \varepsilon_6 > t_{5m}^{-1/2} \end{cases} \tag{2.11}$$

(e.g., Dondi & Ghisellini, 1995; Dermer et al., 2007), where $10^6\varepsilon_6 m_e c^2$ is the photon energy, so that $\varepsilon_6 = 1$ corresponds to ≈ 500 GeV photons. When $\varepsilon_6 \approx 10$, $\delta_{\rm D} \gtrsim 50$, in agreement with Begelman et al. (2008) and Finke et al. (2008), though the multi-TeV emission is not certain to be as variable as the more numerous photons near the low-energy threshold of the γ-ray telescopes unless one assumes that the variability is attributed to cooling.

Fig. 1 shows a calculation of $\tau_{\gamma\gamma}$ using a target photon synchrotron spectrum approximated by the normalized SED shown in the figure (compare Fig. 2) A broader synchrotron spectrum would more effectively attenuate the γ rays, but even with this minimal target SED, $\delta_{\rm D} \gtrsim 30$ is required for $\tau_{\gamma\gamma} < 1$ for photons observed with 1 TeV energies.

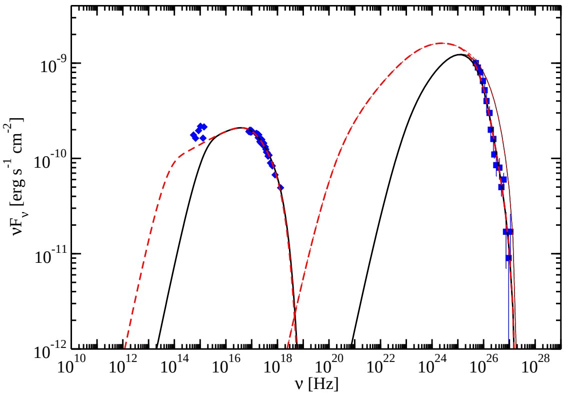

Figure 2: Spectral model for PKS 2155-304 for different parameters. Dashed curve: Model 8 from Finke et al. (2008). Solid curve: Same as Model 8 but with $\gamma_{min} = 5000$ rather than $\gamma_{min} = 1000$.

3. Model Implications

Already we have assumed a number of specific models: a top-hat jet for the beaming factor, and a standard jet in the γ-γ constraint on δ_D, where electrons and photons are isotropically distributed in a plasma with random magnetic field directions in a fluid well defined by a single bulk flow Lorentz factor. Our starting hypothesis is that the engine timescale sets the variability timescale. We furthermore assume that lineless BL Lac objects like PKS 2155-304, Mrk 421, and Mrk 501 (unlike BL Lac itself) are well described by a synchrotron/SSC model.

We have recently completed a detailed synchrotron/SSC spectral analysis of PKS 2155-304 and Mrk 421 (Finke et al., 2008). Our approach differs from the standard technique of injecting electrons and evolving them in response to energy losses. Instead we use the lower-energy synchrotron portion of the spectrum to infer the electron distribution function, and use this distribution to calculate the SSC radiation. The best-fit model is obtained from a numerical χ^2 minimization technique, given a specified intensity of the (in general, z-dependent) EBL. With this approach, we can precisely calculate the absolute jet power and the source luminosity and obtain the radiative efficiency.

Our solutions have a very small radiative efficiency; in order to fit both synchrotron optical and X-rays and TeV γ rays in a synchrotron/SSC model for PKS 2155-304, we find that the magnetic field is required to be nearly two orders of magnitude below the equipartition strength. An example of the spectral fitting is shown in Fig. 2. Absolute jet powers $\gtrsim 3 \times 10^{46}$ ergs s^{-1} are required in the dashed curve in Fig. 1 (Model 8 of Finke et al., 2008) with $t_{5m} = 1$, the EBL of Primack et al. (2005), and $\gamma_{min} = 1000$, where γ_{min} is the minimum electron Lorentz factor of the electron distribution. The dashed curve shows the same model except with $\gamma_{min} = 5000$. The higher low-energy cutoff leads to a change for absolute jet power from $P_j = 2.8 \times 10^{46}$ ergs s^{-1} to $P_j = 8.1 \times 10^{45}$ ergs s^{-1}. The deduced Doppler factor is $\delta_D = 107$ in both cases.

Jet powers of this magnitude seems to violate our assumption that the accretion luminosity is Eddington-limited, because it requires a mass $M_8 \gtrsim 1$ to power the jet with, moreover, $\approx 100\%$ efficiency. Choosing a greater mass would be even more inconsistent with the measured variability timescale, which by hypothesis sets the engine size scale and the black hole mass. As we have seen, some reduction in the jet power can be achieved by fitting only the X-rays and significantly under-fitting the lower-frequency optical/UV synchrotron emission (see also Ghisellini & Tavecchio, 2008).

The unrealistically high efficiency means either that the model breaks down or that the basic assumption of sub-Eddington luminosity is wrong. Eddington ratios much larger than unity may be generated by rapid flares representing enhanced accretion episodes, for example, an accretion instability or the capture of a star. In GRBs this ratio is about 10^{14}, but the accretion torus thought to power GRBs represents a very different system than the gas accreting on the supermassive black hole of an AGN. The spectrum and intensity of the accretion-disk emission could reveal the accretion luminosity, but is difficult to detect from a blazar during flaring periods. During low states, or for misaligned jets like 3C 273, the accretion disk radiation can be detected. For example, during a low state of 3C 279, a flat spectrum radio quasar, Pian et al. (1999) detected the disk emission at the level of $\sim 10^{46}$ ergs s^{-1} in UV. Detection of disk emission from BL Lac objects has proven more difficult.

The conflict between the masses inferred from the variability timescale and the jet power is, unfortunately, not resolved if the assumption that accretion is the source of the jet power is wrong. In the spin paradigm (Blandford et al., 1990; Dermer & Menon, 2009), black-hole jets are powered by the rotational energy stored in the spinning black hole. The Blandford-Znajek mechanism extracts that energy through electrodynamic processes in the black hole magnetosphere. The BZ power

$$L_{BZ} \cong 10^{45} \varepsilon B_4^2 M_8^2 \text{ ergs s}^{-1} \tag{3.1}$$

(Levinson, 2006), where B_4 is the mean magnetic field near the black hole in units of 10 kG, and $\varepsilon \lesssim 0.1$ is an efficiency factor.

We reproduce this relation by a qualitative estimate. The equipartition magnetic field and related Poynting power can be estimated by treating the black hole magnetospheric system as a magnetic dipole produced by a current flowing near the black hole (analogous to a pulsar model). The magnetized accretion disk of the black hole rotates at the rate $\Omega(R_0)$ at radius R_0 from the center of the black hole. R_0 may coincide with the radius where energy dissipation is largest, the innermost radius defined by the spin of the black hole, or the inner edge of the accretion disk. Energy is lost when the magnetic-field lines are disrupted at the light cylinder of radius $R_{\rm LC} = c/\Omega_{\rm LC}$, corresponding to a transition from the near-field to the wave field. For a dipole magnetic field, $B(R_{LC}) \simeq B_0(R_0/R_{LC})^3$ with $B_0 = B(R_0)$, so that the energy-loss rate in Poynting flux is

$$P_{\rm P} \cong 4\pi R_{LC}^2 \frac{B_0^2}{8\pi}\, c \left(\frac{R_0}{R_{LC}}\right)^6 \cong \frac{c}{2} B_0^2 R_0^6 R_{LC}^{-4} \,, \tag{3.2}$$

where the light-cylinder frequency is identified with the Keplerian orbital frequency at radius R_0; thus $\Omega_{LC} \approx \Omega_{\rm K}(R_0) = \sqrt{GM/R^3}$, and $\tilde{R}_{LC} = \tilde{R}_0^{3/2}$. (Tildes mean that the distances are rescaled in units of gravitational radii $R_g = GM/c^2$.)

The magnetic field is defined with respect to the observed radiant luminosity $L_{rad} = \ell_{\rm Edd} L_{\rm Edd}$ (eq. [2.8]) and size R_0 using the equipartion magnetic field which we define here in terms of the luminous energy density, giving

$$\frac{B_0^2}{8\pi} = \frac{L_{rad}}{4\pi R_0^2 c} \cong \frac{\ell_{\rm Edd} L_{\rm Edd}}{4\pi R_0^2 c} \,, \tag{3.3}$$

or

$$B_0(\text{Gauss}) \cong \frac{6\times 10^4}{\tilde{R}_0}\sqrt{\frac{\ell_{\rm Edd}}{M_8}}\;. \qquad (3.4)$$

This suggests that the inner magnetized regions surrounding supermassive black holes should have $\mathscr{O}$(kG) magnetic fields. Eqs. (3.2) and (3.3) together imply

$$P_{\rm P}(\text{ergs s}^{-1}) \simeq 10^{46}\,\frac{M_8\ell_{\rm Edd}}{\tilde{R}_0^2}\;. \qquad (3.5)$$

For accretion at $\ell_{\rm Edd}\sim$ 1-10% and energy dissipation at $\tilde{R}_0\sim 6$ (Schwarzschild metric) and $\tilde{R}_0\sim 3$ (rotating black hole), the Poynting power as estimated here is unlikely to be capable of satisfying jet power requirements in a synchrotron/SSC model for supermassive black-hole jets.

A more detailed derivation of the Blandford-Znajek power can be obtained by solving the constraint equation for black-hole electrodynamics (Menon & Dermer, 2005; Dermer & Menon, 2009), written in the 3+1 formalism of (Komissarov, 2004). There a solution for the fields and currents was found that generalizes the Blandford-Znajek split monopole solution to accommodate the case of a black hole for all values of $a^2 < M^2$, where a is the spin paramter Menon & Dermer (2005). The rate of energy extraction from the black-hole spin for this Ω_+ solution is

$$P_{\Omega_+} = \frac{\pi Q_0^2}{ar_+}\left[\arctan\frac{a}{r_+} - \frac{a}{2M}\right]\;. \qquad (3.6)$$

The charge Q_0 can be related to the magnetic field intensity $\bar{B}$ threading the event horizon of the black hole at the equator. This leads to a maximum Blandford-Znajek power

$$P_{\Omega_+} \cong 2\times 10^{46}\,\ell_{Edd}M_8 \quad \text{ergs s}^{-1} \qquad (3.7)$$

for the Ω_+ solution. Thus we see that the Blandford-Znajek process cannot extract energy at a rate much larger than the Eddington luminosity for a system whose radiative output is limited by the Eddington luminosity.

Rather than reject the hypothesis that the engine size scale determines the minimum variability time scale, we can in principle resolve the contradiction by abandoning the simple one-zone synchrotron/SSC model. Radiative efficiency in external Compton models improve with larger Γ values, as noted by Begelman et al. (2008) and Ghisellini & Tavecchio (2008), but the target radiation field provides additional opacity that must be carefully considered (Dermer et al., 2008). Other soft photon sources, for example, synchrotron radiation from the extended decelerating jet (Georganopoulos & Kazanas, 2003), or radiation from a slower moving sheath around a faster moving spine (Tavecchio & Ghisellini, 2008) could, if good spectral fits in such models can be obtained, relax the jet power constraints. Detailed spectral analyses and modeling studies are needed to determine if power requirements can be reduced in a jet blazar powered by $\sim 10^8$ Solar mass black hole by adding an external target radiation field.

4. Summary and Speculations

Until simultaneous optical, Swift, GLAST, and HESS data are available to model, it is uncertain whether an $\sim 10^8 M_\odot$ black hole can explain the variability and spectral behavior of PKS

2155-304. Supposing that it can, one question of interest is then how to satisfy the bulge/black-hole mass relation for the mass of the black hole in PKS 2155-304, which is estimated to be $\approx 1 - 2\times 10^9 M_\odot$ (Aharonian et al., 2007; Kotilainen et al., 1998). The dispersion in the black-hole/bulge luminosity relationship for AGN indicates that only $\lesssim 5\%$ of the sources are more than one order of magnitude away from the best-fit line (McLure & Dunlop, 2002). For PKS 2155-304 not to be an outlier on this plot, we assume that the mass of the black-hole system of this source exceeds $10^9 M_\odot$.

This can be realized if the $10^8 M_\odot$ black hole is a member of a binary system containing a larger $\sim 10^9 M_\odot$ black hole. The jetted black hole with its accretion disk may be assumed to define a fairly specific direction into which plasma is ejected. The orbital motion in the binary system produces a Parker-like spiral pattern from the outflowing jets, which may be related to the spiral rotation of the linear polarization of the position angle observed in sources like BL Lac (Marscher et al., 2008) and OJ 287 (e.g., Villata et al., 1998). Depending on how the jet precesses during its orbital motion, a converging collimation shock could be formed (Marscher et al., 2008).

A binary system of supermassive black holes would display dual accretion disk signatures, each of which can provide target photons for jet Compton scattering. As in the case of models of microquasars (reviewed recently by Bosch-Ramon, 2008), the external Compton γ-ray emission would display periodic signatures due to $\gamma\gamma$ attenuation and anisotropic Compton scattering. For systems with orbital periods $\lesssim 1 - 2$ years, GLAST can search for variations in spectra with orbital phase.

5. Acknowledgements

We thank Berrie Giebels for participation in this workshop, and Amir Levinson for useful correspondence and comments about this paper. The work of CDD is supported by the Office of Naval Research, and the research of JDF is supported by the GLAST Interdisciplinary Program.

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