Size-Luminosity scaling and Inverse Compton Seed Photons in Blazars

Markos Georganopoulos and John G. Kirk

Max Planck Institut für Kernphysik, Postfach 10 39 80, D-69029, Heidelberg, Germany

Apostolos Mastichiadis

Department of Astronomy, University of Athens, GR 15784, Athens, Greece

Abstract. We present preliminary results of our work on blazar unification. We assume that all blazars have a broad line region (BLR) and that the size of the BLR scales with the power of the source in a manner similar to that derived through reverberation mapping in radio quiet active galactic nuclei (AGNs). Using a self-consistent emission model that includes particle acceleration we show that according to this scaling, in weak sources like MKN 421, the inverse Compton (IC) scattering losses are dominated by synchrotron-self Compton scattering (SSC), while in powerful sources, like 3C 279, they are dominated by external Compton (EC) scattering of BLR photons. In agreement with other workers, we show that even in the powerful sources that are dominated by EC scattering, the hard X-ray emission is due to SSC. Finally, we show that this scaling reproduces well the observed sequence of blazar properties with luminosity.

1. Introduction

Blazars have been shown to exhibit a sequence of properties as a function of source power (Fossati et al. 1998). As the source power increases, the emission line luminosity and the ratio of Compton to synchrotron luminosity increase, while the synchrotron peak frequency $\nu_s$ and the IC peak frequency decrease. Recent multiwavelength studies support this scheme (e.g. Kubo et al. 1998), although the result that the ratio of the Compton to synchrotron luminosity increases with source luminosity suffers from limited statistics, and should be only considered tentative.

The initial division of blazars into flat spectrum radio quasars (FSRQs) and BL Lacertae objects (BLs) was based on the equivalent width (EW) of the broad emission lines. Sources with EW $> 5$ Å were classified as FSRQs and sources with EW $< 5$ Å as BLs. This difference in the EW of the emission lines has been interpreted as absence of a substantial BLR in BLs, and has been used to advance the idea that in BLs the GeV-TeV emission is due to SSC, while in FSRQs the GeV emission is due to EC. However, the EW criterion does not
correspond to a dichotomy (Scarpa & Falomo 1997), because a weak BLR is present in BLs as well. Additionally, it is not the BLR luminosity $L_B$ that is relevant for the EC luminosity, but the BLR photon energy density $U_E$ that is measured in the comoving frame of the non-thermal source. One needs to know not only $L_B$, but also the BLR radius $R_B$ and the location of the non-thermal emitter relative to the BLR in order to quantify the relative importance of SSC versus EC emission.

The size of the BLR has been measured only for radio quiet AGNs through reverberation mapping (Kaspi et al. 2000), and it has been found to scale with the ionizing luminosity $L_{\text{acc}}$ of the accretion disk as $R_B \propto L_{\text{acc}}^{0.7}$. It was additionally found that, assuming Keplerian motions for the BLR clouds, the mass of the central object scales with the ionizing luminosity as $M \propto L_{\text{acc}}^{0.5}$.

Here we assume the scalings apply also to radio loud AGN and examine the implications for blazars. Following the formalism of internal shocks propagating in a conical jet (Rees 1978), we scale the location $D_{\text{blob}}$ and the radius $R_{\text{blob}}$ of the non-thermal spherical emitter with the mass $M$ of the central object. We assume that $L_B$ is a fraction of $L_{\text{acc}}$ and scale the kinetic luminosity and the Poynting flux of the blob with $L_{\text{acc}}$.

2. The scaling and its application

Under this scheme, the radius of the BLR scales as $R_B \propto L_{\text{acc}}^{0.7}$, and the distance of the blob from the center of the system scales as $D_{\text{blob}} \propto M \propto L_{\text{acc}}^{0.5}$. Therefore, we assume that for powerful sources the blob radiates from inside the BLR, $D_{\text{blob}} < R_B$. However, if we consider increasingly weaker sources, $R_B$ falls faster than $D_{\text{blob}}$ and, below some critical luminosity, the blob radiates from outside the BLR. For a blob inside the BLR, $U_E \propto (L_B/R_B^2)\Gamma^2$, where $\Gamma$ is the bulk motion Lorentz factor of the blob. For a blob outside the BLR, the solid angle subtended by the BLR, as seen by the blob, is reduced. This affects $U_E$ in two ways. The first is the usual geometric $1/r^2$ factor, and the second is a relativistic de-boosting that, for $D_{\text{blob}} \gg R_B$, gives $U_E \propto (L_B/D_{\text{blob}}^2)\Gamma^2$ (Dermer & Schlickeiser 1994). The second effect dominates if the blob is located less than a few $R_B$ away from the BLR. For example, for $\Gamma = 10$, $U_E$ at a distance of $10 R_B$ is smaller than $U_E$ inside the BLR by a factor of $10^2$ due to the usual $1/r^2$ and by a factor of $\approx 10^4$ due to relativistic de-boosting.

We apply this scaling using a model (Georganopoulos & Kirk 2000) for the blob which includes both particle acceleration and radiative losses with IC scattering losses treated in the Thomson regime. Particles are accelerated in an acceleration zone and escape into a radiation zone, before they eventually escape out of the system.

This simplified picture is intended to represent particles which are accelerated by a shock front, escape it, and radiate downstream before the compressed plasma re-expands. Whilst undergoing acceleration, particles simultaneously suffer synchrotron losses and losses by Compton scattering of both photons of external origin (EC) and synchrotron photons (SSC) from the radiation zone. In the radiation zone, EC, SSC and synchrotron losses occur until the particle finally escapes after a time $t_{\text{esc}} = 3R_{\text{blob}}/c$. The electron energy distribution (EED) is computed self-consistently, taking account of these processes.
Our assumption about the scaling of the Poynting flux implies a constant magnetic field, which we take to be $B = 0.2$ G. The blob is assumed to move with a Lorentz factor $\Gamma = 15$ at an angle $\theta = 1/\Gamma$ with respect to the line of sight. Low energy particles ($\gamma_0 = 10$) are injected into the blob at a rate of $Q = 0.1$ cm$^{-3}$ s$^{-1}$. Also $L_B = 0.01L_{\text{acc}}$. For $L_{\text{acc}} = 10^{44}$ erg s$^{-1}$, reverberation mapping gives $R_B \approx 8.6 \times 10^{16}$ cm. We assume that at this luminosity $R_B = D_{\text{blob}}$ and $R_{\text{blob}} = 2 \times 10^{15}$ cm.

In Fig.1, we let $L_{\text{acc}}$ vary from $10^{42}$ erg s$^{-1}$ to $10^{46}$ erg s$^{-1}$, and follow the behavior of the system. In the lower panel $R_B$, $D_{\text{blob}}$, and $R_{\text{blob}}$ are plotted as a function of $L_{\text{acc}}$. For weak sources, the blob is located outside the BLR ($D_{\text{blob}} > R_B$). As the source power increases, the blob gradually approaches and eventually enters the BLR. In the middle panel of Fig.1 we see how this affects $U_E$ (the magnetic field energy density $U_B$ is constant under the adopted scaling). For weak sources, $U_E$ is much smaller than both $U_B$ and the self-consistently derived synchrotron photon density $U_S$. Gradually $U_E$ increases, and eventually, for bright sources, dominates over both $U_B$ and $U_S$. In the upper panel of Fig.1 we plot the self-consistently derived break $\gamma_{\text{break}}$ in the EED. Note that $\gamma_{\text{break}}$ decreases as the power of the source decreases.

In Fig.2 we plot basic observable quantities as a function of $L_{\text{acc}}$. In the lower panel we plot the synchrotron luminosity $L_S$, the SSC luminosity $L_{\text{SSC}}$, and...
and the EC luminosity $E_{EC}$. At low powers, $L_{EC}$ is much weaker than $L_{SSC}$ and $L_{S}$ that are roughly equal. As the source power increases, $L_{EC}$ gradually dominates over $L_{SSC}$ and $L_{S}$, and we end up with an EC dominated source. In the middle panel we plot the peak frequencies of the three emission components. Note how the synchrotron peak frequency $\nu_S$ decreases as the source power increases. Similar behavior is also seen for the SSC peak frequency $\nu_{SSC}$ and the EC peak frequency $\nu_{EC}$. Finally in the upper panel of Fig.1 we plot the ratio $L_S/L_{acc}$ (solid line) of the synchrotron to accretion disk luminosity and the ratio $L_C/L_S$ of the IC luminosity to synchrotron luminosity. $L_S$ dominates over $L_{acc}$ in weak sources in agreement with the lack of a thermal component and weak emission lines in weak sources like BLs. $L_{acc}$ becomes more significant for powerful sources, again in agreement with the strong emission lines of FSRQs and the accretion disk signature observed in some FSRQs (e.g. in 3C 279, Pian et al 1999). The dominance of the Compton over the synchrotron emission increases as the source power increases, in agreement with observations (e.g. Kubo et al. 1998). Note, however, that the observational case for an increasing Compton dominance with source power is based on poor statistics due to the limited sensitivity of the CGRO.
In Fig. 3 we plot the synchrotron luminosity $L_s$ versus the synchrotron peak frequency $\nu_s$ for the blazars studied by Sambruna, Maraschi & Urry (1996) and Kubo et al. (1998). On top of the data points we plot the model tracks as a function of $L_{\text{acc}}$ for a range of observing angles. Note that these tracks represent two model derived quantities, $L_S$ and $\nu_S$ as $L_{\text{acc}}$ varies. The model covers rather well the observed parameter space. Given the track of the model under an angle $\theta = 0^\circ$, we do not expect that any powerful ($L_S \approx 10^{47} \text{ erg s}^{-1}$) sources with high peak frequencies $\nu_S \approx 10^{17} \text{ Hz}$ exist. The discovery of such sources would pose a serious problem for this model.

3. The luminosity scaling

In Fig. 4 we plot the peak luminosities of the three emission mechanisms for 5 model sources with $L_{\text{acc}}$ ranging from $10^{42}$ up to $10^{46} \text{ erg s}^{-1}$. The behavior of the model is in good agreement with the general characteristics of the observed luminosity sequence (compare with Fig. 12 of Fossati et al. 1998). The synchrotron peak frequency decreases from $10^{18} \text{ Hz}$ down to $10^{12} \text{ Hz}$, as the
Figure 4. The model luminosity sequence. The synchrotron (circles), SSC (triangles), and EC (squares) luminosity as a function of frequency for 5 model sources of different intrinsic power. The broken lines link points from a single model.

synchrotron power increases. The Compton peak frequency in weak sources is in the TeV regime ($\approx 10^{25-26}$ Hz) and it is due to SSC, while in powerful sources it is in the GeV regime ($\approx 10^{23}$ Hz) and it is due to EC. According to the model, although in these bright sources the energy losses are dominated by EC, the hard X-ray emission is due to SSC, in agreement with resent observations (Kubo et al. 1998).

We note here that Fig.4 corresponds to sources that are oriented at an angle $\theta = 1/\Gamma$. In reality one should expect a range of angles, which will give rise to significant scattering around the presented trend. This scattering is visible in the work of Fossati et al. (1998) and indicates that a proper unification scheme for blazars should include the effects of orientation.

References

Dermer, C. D., & Schlickeiser, R. 1994, ApJS, 90, 945
Fossati, G., et al. 1998, MNRAS, 299, 433
Georganopoulos, M. & Kirk, J.G. 2000, in preparation
Kaspi, S., et al. 2000, ApJ533, 631
Kubo, H., et al. 1998, ApJ, 504, 693
Pian, E. et al. 1999, ApJ, 521, 112
Rees, M.J. 1978, MNRAS, 184, 61
Sambruna, R. M., Maraschi, L., & Urry, C. M. 1996, ApJ, 463, 444
Scarpa, R., Falomo, R. 1997, A&A, 325, 109