X–RAY EMISSION IN GAMMA-RAY BLAZARS

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1. Low entropy inner jets

As shown by Maraschi (this volume) the overall spectral energy distribution (SED) of the blazars detected by EGRET shows two peaks, in a $\nu \cdot \nu F(\nu)$ plot. With few exceptions, the minimum between these two peaks occurs in the X–ray range. We can exploit this observational fact to constrain the models proposed to account for the SED of blazars, and to reach an important conclusion: the conversion of the primary power carried by the jet into radiation occurs primarily at some distance from the central powerhouse.

Assume in fact that part of the $\gamma$–ray radiation is absorbed by $\gamma$–$\gamma$ collisions (Blandford & Levinson 1995). This implies that, in the comoving frame of the jet/blob emitting the high energy radiation, there is a sufficient amount of target X–rays. The pairs created in this way are relativistic, and can emit at lower frequencies, or escape, if their cooling time is sufficiently long. In the first case, all the absorbed power in the $\gamma$–ray band reappears at lower energies, namely the X–ray band. Therefore it is inevitable to predict that the X–ray luminosity should be of the same order of the $\gamma$–ray luminosity.

A way out of this is to assume that the cooling time of the pairs is longer than their escape time. In this case only a fraction of the power absorbed in the $\gamma$–ray band is reprocessed into radiation of softer energy, mainly X–rays. This model then requires that there are sufficient X–rays to absorb the $\gamma$–rays, but not enough photons for Compton cooling. In principle, this is possible, because the scattering between pairs and X–rays occurs in the inefficient Klein Nishina regime, but it is highly unlikely, because the X–ray emission should always be accompanied by at least a comparable amount of optical UV radiation. Requiring efficient absorption of $\gamma$–rays, therefore, implies short cooling times of the pairs, resulting in an excess of X–ray emission (Ghisellini & Madau 1996). Since this is not observed, we conclude that:

• The $\gamma$–ray emitting region is transparent.

• In order to be transparent, it must be at some distance from the (X–ray emitting) accretion disk. On the other hand, the short variability timescales observed at high energies limit the dimensions of the source, and hence its location in the jet. By combining both limits, we can derive a typical distance at which dissipation occurs, of few hundreds Schwarzschild radii.

• In the inner part of the jet, energy must be transported efficiently, without dissipation. Possibilities are: i) cold (in the comoving frame) protons with bulk Lorentz factor $\Gamma$; ii) Poynting flux. The kinetic luminosity carried by the protons is

$$L_k = \pi r^2 n_p \beta m_p c^3 \rightarrow \tau_p \sim 5 \times 10^{-2} \left( \frac{L_{k,46}}{\Gamma_1 r_{14}} \right)$$

where $r$ is the cross sectional radius of the jet, $\tau_p = \sigma_T n_p r$, $\Gamma = 10 \Gamma_1$ and $L_k = 10^{46} L_{k,46}$ erg/s. As Sikora (this volume) points out, cold electrons of the same optical depth would produce an observable bump at $\sim 1$ keV by scattering ambient UV photons coming from the accretion disk and from the broad line region. This bump is not observed, leaving Poynting flux as the only viable possibility.
2. One or two electron populations?

Mannheim (1993, see also this volume) suggested that the overall emission in blazars can be the result of two different electron populations, both emitting by the synchrotron mechanism. Radiation losses can in fact limit the maximum attainable Lorentz factors of accelerated electrons, but are not important for protons, which can therefore reach ultra-relativistic energies. By interacting with the photons produced by the 'primary' electrons, an $e^\pm$ pair cascade develops, with the created pairs reaching Lorentz factors up to $\gamma \sim 10^{10}$ or more. The first population of electrons should be responsible for the first (low energy) synchrotron peak, while the pairs produced by the protons produce the high energy peak. In this scenario the location of the two peaks are somewhat unrelated, corresponding to the maximum energy of the two electron populations.

In synchrotron–Compton models, instead, a single electron population is responsible for both peaks of the SED. Even if we do not know (yet) the origin of the seed photons to be upscattered at high energies, both peaks are produced by the same electrons, of Lorentz factor, say, $\gamma_b$. A distribution of $\gamma_b$–values results in a corresponding distribution of peak energies of the synchrotron ($\nu_S$) and Compton ($\nu_C$) components. Therefore sources whose synchrotron component peaks in the far IR should have ‘Compton’ peaks in the MeV range, while sources with $\nu_S$ in the soft X–ray band should show a Compton peak in the GeV to TeV region. The three sources detected so far in the TeV band by Whipple indeed confirm this scenario.

Other evidence come from the (anti)-correlation found by Comastri et al. (1996) between $\alpha_{\nu o}$, the index connecting the 5 GHz flux with the optical (V band) flux, and $\alpha_{\nu \gamma}$, the index between 1 keV and 100 MeV. The found anticorrelation can be easily explained by a distribution of $\gamma_b$. If it is large, as in the Whipple detected BL Lacs, then $\nu_S$ is above the optical band, and the radio to optical index is flat. At the same time the X–ray flux is large with respect to the 100 MeV emission, since the synchrotron emission extends to the X–rays (it peaks there), while the $\gamma$–ray spectrum, at 100 MeV, is still rising. The reverse (flat $\alpha_{\nu \gamma}$ when $\alpha_{\nu o}$ is steep) corresponds instead to a small value of $\gamma_b$.

A distribution of $\gamma_b$ can also explain the correlation found by Comastri et al. (1996) between $\alpha_X$ and $\alpha_\gamma$. If $\alpha_X$ is steep, the X–rays are produced in the tail of the synchrotron component, which therefore should have a large $\nu_S$ and a large $\gamma_b$. This leads to a Compton peak in the GeV to TeV band, and then to a flat value of $\alpha_\gamma$ in the EGRET band.

We therefore conclude that it is easier to explain these correlations in the framework of models involving only one electron population. This implies that by monitoring the synchrotron emission around $\nu_S$ we monitor the same electrons producing the Compton flux close to $\nu_C$.

3. Fast variability of X–rays

In the X–ray band we probably reach the best trade off between fast variability and amount of photons needed to detect it. The light curve of the BL Lac object PKS 2155–304 (which was observed simultaneously with ASCA, EUVE and IUE; see Maraschi, this volume) is probably one of the best examples, together with the recent results about Mkn 421 observed by ASCA, in which delays between the hard and soft X–ray band have been observed (Takahashi et al. 1996). The symmetry (i.e. equal rise and decay times) of the flare of PKS 2155–304 in the ASCA band is highly indicative that the involved timescale is neither connected with the
acceleration nor the cooling timescales, but it is instead related to $R/c$. This immediately implies that:

- The cooling timescale is shorter than $R/c$. If the cooling is radiative, as it is likely especially at high energies, then we can set a limit on the magnetic field (see, e.g. Massaro et al. 1996).
- The electron distribution responsible for the emission is evolving rapidly, faster than $R/c$. The observer will see a convolution of different spectra, each produced in a different region of the source. Initially we see only the emission by fresh electrons located in the slice nearest to us. After a time $R/c$ we see the entire source: the back of it with fresh electrons, and the front of it with older electrons. In this way Chiaberge & Ghisellini (1996) could explain the time-delay between hard and soft X–ray observed in Mkn 421, as illustrated in Fig. 2.

4. Very flat X–ray indices?

The so called ‘MeV blazars’ are characterized by a steep ($\alpha > 1$) $\gamma$-ray spectrum, suggesting that the peak of their Compton component lies in the MeV range. This has been directly confirmed in some of these sources by COMPTEL data. Although not simultaneous, the X–ray data in these sources indicate a very large $\gamma$ to X–ray flux ratio, and hence a very flat X–ray spectral index, even flatter than $\alpha_x = 0.5$. If confirmed (by, e.g. SAX), this could give valuable information on the origin of the high energy emission. There can be several possible alternatives:

- Sikora et al. (1996) found that MeV blazars are the most difficult to be explained both in the SSC and in the external photon scenario. They suggest that in these sources the electron distribution is not the result of injection and cooling or escape, but it reaches a steady state through the competition of reacceleration and cooling. This leads to a particular electron energy where heating and cooling balance, which can be be of the order of 100 MeV. Such a peaked electron distribution, via Compton scattering, produces a very flat spectrum [$F(\nu) \propto \nu$].
- A flat electron distribution can also be the result of incomplete cooling. In fact, assume to continuously inject a power law distribution of electrons $Q(\gamma) \propto \gamma^{-s}$. If the cooling time at all energies is shorter than the escape time, the equilibrium electron distribution is $N(\gamma) = \int_\gamma Q(\gamma) d\gamma / \dot{\gamma}$, where $\dot{\gamma} \propto \gamma^2$ is the cooling rate for synchrotron and Compton losses. The flattest distribution is $N(\gamma) \propto \gamma^{-2}$, corresponding to $F(\nu) \propto \nu^{-0.5}$. However, if the cooling time is longer than the escape time, then $N(\gamma) \sim Q(\gamma) t_{\text{esc}}$, and in this case one can obtain a spectral index $\alpha$ flatter than 0.5. A break occurs for $t_{\text{cool}}(\gamma) = t_{\text{escape}}$. If Compton cooling is dominant, then $\gamma_b \sim 3\pi / \ell$ where $\ell = L \sigma_T / (Rmc^3)$ is the compactness as seen in the comoving frame of the blob, which is the sum of the locally produced synchrotron radiation and the externally produced (and Doppler boosted) emission.
- Assume that the high energy emission is the result of Compton scattering with external photons. In the comoving (primed) frame of the blob, these photons are seen bluishifted by $\sim \Gamma$. Assume also that their spectrum is not monochromatic, but it extends between $\nu'_1$ and $\nu'_2$. Above $\nu'_2$, all incident photons are used to form the Comptonized spectrum, but for $\nu < \nu'_2$ only part of the incident photons can be used. Then the Comptonized spectrum shows a break at $\nu'_2$, being flatter below. In the observing frame, this break is visible, because the Comptonized spectrum is Doppler boosted and blueshifted, while the incident spectrum (with respect to what the blob sees), is redshifted by a factor $\sim \Gamma$. 

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Figure 1: The overall spectrum of 0202+149 fitted by the external Compton model. The external photons are assumed to be distributed as a diluted blackbody. The fast rise in the soft X-ray band is due to the increasing (with energy) number of incident photons available for the inverse Compton process. Fig. 2: Time lags between hard and soft X-rays, TeV and optical emission in Mkn 421. High energy electrons are injected for a time $\sim R/c$, with $R = 10^{16}$ cm.

To illustrate the latter case, I have tried to model the overall spectrum of the blazar 0202+149, which has the flattest X-ray slope (as determined by ROSAT) of the $\gamma$-bright blazars analyzed by Comastri et al. (1996). As can be seen, the X-ray spectrum has a complex shape, which is the result of SSC and external Compton contributions. The former contributes below 0.1 keV. Above this energy, Compton scattering with radiation produced externally to the jet dominates, producing a very flat spectrum between 1 and 10 keV: in this band the power rises steeply with frequency because of the increasing number of photons that can be used for the scattering process. Above 10 keV all seed photons are used, and the spectrum has the canonical 0.5 slope.

- Cold (in the comoving frame) electrons participating to the bulk motion can contribute to the X-ray emission at $\nu \sim \Gamma^2 \nu_{UV} \sim 1$ keV, producing the “Sikora bump” (Sikora et al. 1996, see also this volume). Its amplitude depends on the scattering optical depth of these electrons. In this way Sikora et al. (1996) can constrain the amount of cold electrons and $e^\pm$ allowed to be present in the inner jet, since the “Sikora bump” is not (yet) observed. Note that even more stringent constraints can be derived in the very inner part of the jet, where the radiation coming directly from the accretion disk (neglected in Sikora et al. 1996) is likely to dominate the radiation energy density as seen by the jet (Ghisellini & Madau, 1996).

References

Chiaberge, M. & Ghisellini, G., 1996, in “Second Italian meeting on AGNs”, in press.