Blazar Compton Efficiencies

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Abstract. The Fermi gamma-ray space telescope has dramatically increased the number of gamma-ray blazars known and means that for the first time, a large sample of blazars selected by the strength of their inverse Compton emission exists. We have cross-identified the blazars listed in the first Fermi-LAT catalog (1FGL) with the CRATES radio catalogue. Using the 8.4 GHz flux density as a proxy for the jet power, we have computed their Compton efficiencies, a measure of the ability of the jet to convert the power in the ultrarelativistic jet electrons into gamma-rays through the inverse Compton process. We have compared the Compton efficiencies of the two blazar subsets, BL Lacs and FSRQs, and find no evidence that they are different. We also do not find an anti-correlation between Compton efficiency and synchrotron peak frequency.

1. Introduction

The blazar sub-set of radio-loud active galactic nuclei represent some of the most energetic objects in the universe and are seen to dominate the extragalactic gamma-ray sky (e.g. Abdo et al. 2010a). However the nature of high energy blazar emission is still unclear. The distinct two-peak shape in log-space of blazar spectral energy distributions reveals that there are two emission mechanisms at work. The low energy SED is attributed to synchrotron emission produced by ultra-relativistic jet electrons. The origin of the high energy emission is more contentious, and both hadronic and leptonic emission models have been proposed (see contributions by Dermer and Reimer in these proceedings). This work does not consider contributions from hadronic emission processes and instead focuses on the leptonic source of high-energy blazar emission, i.e. inverse Compton scattering of low energy photons by the synchrotron electrons.

There are two possible origins for the seed photons required by the inverse Compton process. They can be produced in the jet via the synchrotron emission process (synchrotron self-Compton, SSC) or they can be from AGN regions external to the jet, such as the broad line region or the accretion disk (external Compton, EC). One open issue in blazar research is the importance of external photons; it has been proposed that the ratio of EC to SSC emission can account for the range of spectral energy distributions seen amongst blazars and subsequently give rise to the “blazar sequence”, an observed anti-correlation between synchrotron peak frequency and radio luminosity (Fossati et al. 1998).

The theoretical explanation of the blazar sequence uses the abundance of external photons that are available to be upscattered through the inverse Compton process (Ghisellini et al. 1998). Although more recently this has been extended to include black hole mass and accretion rate (Ghisellini et al. 2008), in this work we only consider the role of external photons. The argument is that increasing the number of photons available to be scattered decreases the synchrotron
cut-off frequency, and hence the SED synchrotron peak frequency. Therefore the more external photons, the lower the synchrotron peak frequency, as seen between the two types of blazar: flat spectrum radio quasars (FSRQs) whose optical spectra show strong broad emission lines and BL Lac objects where there is no evidence for an external source of photons. This has been interpreted both as strong evidence for the blazar sequence (e.g. Fossati et al. 1998, Ghisellini et al. 2008) and as evidence that BL Lacs and FSRQs are physically different classes of objects (e.g. Anton & Browne 2005).

The Fermi gamma-ray space telescope has dramatically increased the number of known gamma-ray blazars. This means that for the first time, we can investigate large samples of blazars selected solely on the strength of their inverse Compton emission.

2. Compton efficiency

We introduce the concept of “Compton efficiency” as a measure of how efficiently a blazar converts power in the form of relativistic jet electrons into high-energy emission via the inverse Compton emission mechanism. We picture a jet where the energy losses are dominated by SSC emission and then increase the number of external photons. This will result in the integrated gamma-ray luminosity increasing and the synchrotron peak frequency decreasing, however the low frequency radio synchrotron emission is unaffected. Therefore, we define Compton efficiency, $\epsilon$, as the ratio of the emission at the high energy (inverse Compton) SED peak to the compact nuclear radio emission, i.e.

$$\epsilon = \log_{10} \left( \frac{\nu S_{\nu}}{\nu S_{\nu}} \right)_{\text{IC, peak}}, \quad (1)$$

In our definition of Compton efficiency, we use the radio emission as a proxy for the jet power because emission at such low frequencies is unaffected by the energy loss processes. We use $\nu S_{\nu}$ to measure the strength of the gamma-ray emission, where $\nu_{\text{IC, peak}}$ and $S_{\nu, \text{IC, peak}}$ are the frequency and the flux density respectively at the SED inverse Compton peak. This is so that we are probing the maximum energy output: using a gamma-ray flux in a specific band would probe different parts of the SED from blazar to blazar. In the context of the blazar sequence, ignoring differences in black hole mass and accretion rate, FSRQs should have higher $\epsilon$ than BL Lacs because there are more photons available to reduce the jet energy.

Note that our Compton efficiency measure is different to the ‘Compton dominance’ that has been used by e.g. Ghisellini et al. (2008). Compton dominance measures the ratio of the output at the two SED peaks and is perhaps a better measure of the importance of external photons. However, synchrotron peak measurements are only available for $< 20\%$ of the 1FGL blazars from Abdo et al. (2010a) and we feel that only considering these bright sources would introduce additional selection biases to our results. In addition, we note that Abdo et al. (2010a) present a relationship between then synchrotron peak output, the synchrotron peak frequency and the radio flux density, indicating that the radio emission can be taken as a good proxy for the jet power.

3. Sample

We use the first Fermi-LAT (Large Area Telescope) catalogue (1FGL) (Abdo et al. 2010b) and cross-correlate with the Combined Radio All-Sky Targeted Eight GHz Survey (CRATES) (Healey et al. 2007). This gives a sample of 224 FSRQs and 167 BL Lacs which are compact flat spectrum radio sources and have been detected in the 0.1–100 GeV energy range during the first 11 months of science observations with Fermi. Further details of the selection process are given in Gupta et al. (2011).
4. Results

The left panel of Figure 1 plots the 1FGL 1–100 GeV flux against the CRATES 8.4 GHz flux density for FSRQs and BL Lacs. There is a weak positive correlation (Spearman rank test coefficient $\rho = 0.293$) in agreement with the same correlation reported by elsewhere (e.g. Abdo et al. 2010b, Ghirlanda et al. 2010, Peel et al. 2011). The right panel of Figure 1 plots $\nu S_\nu$ at the inverse Compton peak against $\nu S_\nu$ at 8.4 GHz. These quantities show a stronger correlation (Spearman rank test coefficient $\rho = 0.534$), indicating that the correlation between radio and gamma-ray emission is real and that the spread in the left panel is partly due to the spread in inverse Compton peak frequencies. In both panels of Figure 1 there is an indication that, for a given gamma-ray measurement, BL Lacs on average have a lower radio measurement compared to the FSRQs. This would suggest that BL Lacs have higher Compton efficiencies than FSRQs.

The left panel of Figure 2 plots the Compton efficiency distributions for BL Lacs (green dashed) and FSRQs (blue dotted). There is no separation between the two types of blazar and the K-S test gives a probability $P = 38\%$ that the two distributions are drawn from the same parent population. The median
Figure 3. Synchrotron peak frequency against Compton efficiency for BL Lacs (green filled triangles) and FSRQs (blue unfilled circles). A positive correlation is seen for BL Lacs while there is no correlation for FSRQs.

Compton efficiencies are $\epsilon = 2.44$ for the FSRQs and $\epsilon = 2.47$ for the BL Lacs and a Wilcoxon rank sum test on the two distributions does not reject the null hypothesis that the two medians are equal (at the 5% level, $P = 0.51$). These results indicate that BL Lacs and FSRQs are indistinguishable in terms of Compton efficiencies, although we do also find evidence that this could be due to selection effects (shown in right panel of Figure 2, see Section 5).

Figure 3 plots Compton efficiency against synchrotron peak frequency for a sub-sample of our objects that are included in the spectral energy distribution fitting by Abdo et al. (2010a). There is no correlation for the FSRQs (Spearman rank test coefficient $\rho = 0.088$) and a positive correlation for the BL Lacs (Spearman rank test coefficient $\rho = 0.532$).

5. Discussion

Our results indicate that BL Lacs and FSRQs are indistinguishable in terms of Compton efficiencies. In addition to this, we do not see an anti-correlation between Compton efficiency and synchrotron peak frequency. Before we draw conclusions from our results, we investigate the possibility that our results are due to selection biases. A more detailed discussion is given in Gupta et al. (2011) but the key points are summarised below.

5.1. Selection effects

We have only considered sources that have been identified as blazars in the 1FGL catalogue. There are 373 1FGL sources at $|b| > 10^\circ$ which have no association, so our results could be explained if the association process did not identify high Compton efficiency (i.e. low radio flux density) FSRQs. In addition to this, the sensitivity of the LAT depends on photon index, so it detects BL Lacs to a fainter flux limit than FSRQs (Abdo et al. 2010c).

There is evidence for a bias against FSRQs in Figure 1 where the number of FSRQs compared to BL Lacs decreases with radio flux density. We have therefore repeated our analysis only considering objects with radio flux density $S_{8.4 \text{ GHz}} > 100 \text{ mJy}$, shown in the right panel of Figure 2. There is now a difference in the Compton efficiency distributions for FSRQs and BL Lacs: there is only a 2.2% probability that the distributions have the same parent population (K-S test) and the Wilcoxon rank sum test rejects the null hypothesis that the medians ($\epsilon = 2.33$ for BL Lacs and $\epsilon = 2.40$ for FSRQs) are the same ($P = 0.012$). This implies that our result that the Compton efficiencies of BL Lacs and FSRQs are indistinguishable could just be a result of incompleteness at low radio flux densities (especially for FSRQs). However, further investigation
is currently underway, investigating the effects of other cuts (e.g. in gamma-ray flux).

5.2. Variability
Blazars are characterised by their variability, both on short and long time-scales. The CRATES radio measurements were made before the 1FGL observations so radio variability will increase the spread in Compton efficiencies. However, on these timescales (~10 years) radio flux densities are unlikely to vary by more than a factor of two (e.g. Jackson et al. 2010) which would not be able to account for the dispersion in our Compton efficiencies. This implies that our results cannot be explained by variability, although it would be useful to have simultaneous radio and gamma-ray measurements.

6. Summary and conclusion
The Compton efficiency parameter has been introduced as a way to quantify the amount of jet energy that is converted into high energy emission via the inverse Compton process. We cross-correlate the first Fermi-LAT catalogue with the CRATES radio catalogue and find that the Compton efficiencies for BL Lacs and FSRQs are not statistically different. We also find no evidence for an anti-correlation between Compton efficiency and synchrotron peak frequency. However, we do see evidence that our sample is incomplete at low radio flux densities which could influence, but not fully account for, our results.

Our results can be interpreted as evidence against the existence of the blazar sequence. However, a number of assumptions have been made due to the limitations of the data that is currently available. The release of larger and better defined samples from the Fermi mission will significantly improve these results. In particular, we await the release of improved SEDs of Fermi-detected blazars so that our Compton efficiency measure can be compared to the Compton dominance.

References
Abdo A. A. et al., 2010a, ApJ, 716, 30
Abdo A. A. et al., 2010b, ApJS, 188, 405
Abdo A. A. et al., 2010c, ApJ, 715, 429
Anton S., Browne I. W. A, 2005, MNRAS, 356, 225
Fossati G., Maraschi L., Celotti A., Comastri A., Ghisellini G., 1998, MNRAS, 299, 433
Ghirlanda G., Ghisellini G., Tavecchio F., Foschini L., 2010, MNRAS, 407, 791
Ghisellini G., Celotti A., Fossati G., Maraschi L., Comastri A., 1998, MNRAS, 301, 451
Ghisellini G., Tavecchio F., 2008, MNRAS, 387, 1669
Gupta J. A., Browne I. W. A., Peel M. W., Preprint astro-ph/1106.5172
Healey, S. E., Romani, R. W., Taylor, G. B., Sadler, E. M., Ricci, R., Murphy, T., Ulvestad, J. S., Winn, J. N., 2007, ApJS, 171, 61
Jackson N., Browne I. W. A., Battye R. A., Gabuzda D., Taylor A. C., 2010, MNRAS, 401, 1388
Peel M. W. et al., 2011, MNRAS, 410, 2690