THE SPECTRAL SEQUENCE OF BLAZARS – STATUS AND PERSPECTIVES

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The present status of the blazar spectral sequence is discussed, including new findings about blazars selected with different criteria than the original complete radio-samples. Despite extensive searches of blazars “breaking” the sequence, the original idea proposed 10 years ago, still seems to hold. On the other hand the forthcoming launch of the GLAST satellite will provide a new selection band for blazars and blazar related populations as well as fantastic progress on the spectra and variability behaviour of presently known blazars. The order of magnitude increase in sensitivity of GLAST will allow to detect γ-rays from jets with lower power and/or lower beaming factor, thus sampling a much wider population.

Keywords: Blazars – BL Lac Objects – Flat-Spectrum Radio Quasars – Relativistic Jets – Gamma-Ray Observations

1. Introduction

The blazar spectral sequence was introduced 10 years ago [8, 10] in view of understanding the systematic differences in broad–band spectral properties from X–ray selected BL Lacs to radio–selected BL Lacs to Flat Spectrum Radio Quasars (FSRQ). The spectral energy distributions (SEDs) of all these sources (unified under the term “blazars”) are dominated by the beamed non-thermal emission of a relativistic jet. From the results of the Compton Gamma–Ray Observatory, the BeppoSAX satellite and Cherenkov telescopes, it emerged that all SEDs were characterized by two peaks, commonly attributed to Synchrotron and Inverse Compton (IC) radiation respectively, emitted by a population of relativistic electrons, with seed photons possibly provided by the synchrotron radiation itself (SSC), the accretion disk or the broad line region (EC). Both peaks appeared to shift to lower frequency from the first class to the next.

Phenomenologically, all the sources of the three complete samples available at the time were grouped together and divided in radio luminosity bins (each spanning a decade) irrespective of the original classification and the average SEDs for each bin were computed. The results strongly suggested that the source’s luminosity is a fundamental parameter driving the overall shape of the SEDs, hence the concept of a “blazar spectral sequence”, implying a link of the main spectral and evolutionary properties of blazars with the physics of jets and the “central engine”.

Modelling the SEDs of individual objects indicated that the physical parameters of the radiating region in the jets vary systematically with increasing luminosity in the sense of an increase of the radiation energy density of the seed photons available for the inverse Compton process and a decrease of the energy of the electrons contributing most to the emission. A complete description of the spectral modelling used here is given in [4, 12]. The model includes synchrotron and Inverse Compton radiation from a population of relativistic electrons whose energy distribution is determined by injection and energy losses in a finite time $R/c$ where $R$ is the size of the emitting region. Jets immersed in strong radiation fields will then have electron distributions with spectral breaks at lower energies.

The blazar sequence can also be understood in terms of a cosmological decrease in the average accretion rate $\dot{m}$ onto the central SMBHs. At high–redshift, FSRQs are characterized by high accretion rates and $L_{\text{jet}} \simeq L_{\text{disk}}$; on the other hand, at low–redshift, BL Lac objects do not show signatures of an accretion disk in the optical band and $L_{\text{jet}} > L_{\text{disk}}$,
implying low radiative efficiency for the accretion flow (i.e. largely sub–Eddington accretion rates) unless one is prepared to accept that the jet power largely exceeds the accretion power. The transition from near–Eddington to sub–Eddington accretion rates with decreasing redshift is naturally explained by the cosmological decrease in the availability of gas and increase in the black hole masses at the centers of galaxies [2, 3, 17, 18, 23]. It is important to note that the same conceptual trend could apply to the FRI/FRII dicothomy [11].

It is therefore of paramount importance to test and extend the original blazar sequence suggestion, by removing the bias introduced by the incomplete and non–homogeneous coverage at γ–ray energies and by producing independent and larger samples of blazars. With the advent of GLAST both aspects will receive unprecedented momentum.

Here we discuss new objects with peculiar characteristics, found as a result of systematic programs or serendipitously, which may already challenge the sequence concept.

2. New data, new sources

One key–prediction of the sequence concept is the lack of FSRQ with a synchrotron peak in the UV/X–ray energy band; therefore such objects have been extensively searched (see [20] and references therein). Some authors [1, 15, 21] claimed the discovery of such “anomalous” blazars mainly on the basis of their broad band spectral indices, that is ratios of radio/optical/X–ray fluxes. However a knowledge of the spectra within each band is essential to confirm the claim.

For the above reasons we recently started new observations with Swift of FSRQs in the only X–ray selected sample of broad line radio loud AGN [27], derived from the Einstein Medium Sensitivity Survey (EMSS) [14]. X–ray selection allows to probe Radio Loud Quasars 10–100 times weaker in the radio than classical samples and by analogy with the case of X–ray selected BL Lacs, Radio Loud Quasars with a high frequency synchrotron peak could be expected. Moreover, Swift provides not only spectral data in the X–ray band but also simultaneous fluxes in different optical/UV bands, yielding precious information on the shape of the optical to X–ray SED.

2.1. EMSS Blazars

The optical and X–ray data obtained for the first 4 FSRQs observed with Swift are presented in Fig. 1 together with archival radio data and theoretical models for the SEDs. The objects are ordered in redshift and present very similar SEDs: in all cases the
optical emission is likely associated with the “blue bump”, that is the thermal emission from the accretion disk. The X-ray emission is rather hard suggesting an IC component with “external” seed photons if ascribed to the jet, as chosen in Fig 1. However a contribution of X-ray emission from the accretion disk is possible. The strength of the non thermal (jet) emission relative to the accretion disk, as estimated in Fig 1, increases with increasing redshift. This may suggest that at low redshifts, where lower X-ray luminosities can be detected, sources with weaker jets relative to the intensity of the accretion disk are found. The weakness may be intrinsic or due to a larger viewing angle causing a lower beaming factor.

The $\gamma$-ray fluxes predicted from the models are uncertain, as they depend on the shape of the relativistic electron spectrum at relatively modest energies, where the constraints are poor, as well as on the photon density at the site of the emission region. There is thus some freedom in the parameter choice and we have followed the criterion to minimize the observed bolometric luminosity. Despite this “economic” choice, the predicted $\gamma$-ray emission falls close to the GLAST sensitivity limit, which is also shown in Fig. 1. Taking into account variability, it is likely that some of these objects will be detected by GLAST, in particular MS 0402 – 362 which has the highest X-ray to optical ratio, i.e. the largest jet to accretion power ratio. The GLAST data would provide important constraints to the model parameters.

### 2.2. The role of the viewing angle and GLAST

In order to estimate the effect of different viewing angles on the appearance of the SED of a given object with respect to the blazar sequence we use the SED model for the well known blazar 3C 454.3 [26]. We compute model SEDs with the same physical parameters but different viewing angles ($< 10^\circ$), assuming a homogeneous jet. The results are shown in Fig. 2 overlayed on the sequence SEDs. Clearly the $\gamma$-ray emission depends strongly on the viewing angle while the synchrotron emission is less affected and the blue bump luminosity remains constant. We conclude that the very existence (up to now) of the sequence is probably due to the fact that the sensitivity limits of the initial surveys only allowed the most beamed objects to be detected. This situation will change dramatically with GLAST which will be able to detect blazars at larger viewing angles. We also recall that “structured jets” [13] may show significant $\gamma$-ray emission over a larger range of angles.

![Fig. 2. Example of how the SED of a blazar (3C 454.3) changes by changing the viewing angle, hence the Doppler factor. Note that the EC component varies the most, since this emission is anisotropic even in the comoving frame. We show for comparison the SED corresponding of the blazar sequence.](image)

#### 2.3. New very luminous blazars

A number of highly luminous (high $z$) blazars have been discovered recently (e.g. GB 1428+4217, $z = 4.72$ [7]; PMN J0525–3343, $z = 4.4$ [6]; RX J1028.6–0844, $z = 4.276$ [28]; Q0906+6930, $z = 5.47$ [22]; RBS 315, $z = 2.69$ [25]). All exhibit a very hard X-ray spectrum, which indicates an inverse Compton origin for the high energy radiation in agreement with the sequence trends. However few data at hard X-rays exist for these objects. Instead, the BAT instrument onboard Swift, discovered a new ”hard X-ray selected” blazar, SDSS J074625.87+244901.2, with extremely high luminosity. Its spectrum in the 10-100 keV band points to a largely dominant inverse Compton peak in agreement with expectations from the sequence [19].

Two extremely high luminosity objects discovered recently: SDSS J081009.94+384757.0 ($z = 3.945990$; [15]) and MG3 J223519+2217 ($z = 3.668$; [1]) have been claimed to show a synchrotron peak in hard X-rays, violating the sequence dramatically. If
correct, this suggestion would require extremely high values of both, magnetic field and particle energies.

In order to verify these claims, we reanalysed the existing data from Swift and INTEGRAL to better constrain the SEDs of these two sources. The results are displayed in Fig 3. In both cases the SED from the optical to the X-ray range appears to be concave pointing to an Inverse Compton origin for the X-ray to \( \gamma \)-ray emission as in the “standard” model for the sequence SEDs [10]. While hard X-ray data for SDSS J081009.94+384757.0 are lacking, the INTEGRAL data for MG3 J225155+2217, show that its SED compares well with SDSS J074625.87+244901.2. Both objects are extreme in luminosity and hard X-ray to optical ratio, suggesting an extension of the sequence to higher luminosities in the sense of an even higher Compton “dominance” and a \( \gamma \)-ray peak at relatively low energies, in the 1–10 MeV range. GLAST observations will be crucial to understand the high energy emission of these sources. Note that, at the intensity level recorded recently a GLAST detection of J225155+2217 is expected despite its soft spectrum in the 10 MeV–10 GeV range, while the same is not true for J081009.94+384757.0.

Fig. 3. The SEDs of the two high–z blazars discussed in the text, together with the proposed models.

### 2.4. Intermediate luminosity blazars peaking at high frequencies

Let us discuss first the well known BL Lac object PKS 2155–304 (see Fig.4). This object is similar to, but more luminous than Mkn 421 and Mkn 501. In fact its “normal” state as described by the data of [9] (green dots) falls well on the sequence with the synchrotron peak around \( 10^{16} \) Hz [19], while on average Mkn 421 and Mkn 501 peak at somewhat higher frequencies, in agreement with the sequence. However, during flares, all these objects exhibit a trend of increasing peak frequency with increasing luminosity, contrary to the sequence trends. Thus we caution that the sequence “concept” applies only to average states. In the exceptional flaring state of July 28 2006, PKS 2155–304 changed its peak intensity by almost one order of magnitude, thus moving from luminosity class 2 to 3 and breaking the sequence during its high state.

The source RX J1456.0+5048 (\( z = 0.478567 \)) discovered by Giommi et al. (2008 in preparation) is close in properties to PKS 2155–304. The Swift data analysed by us are shown in Fig. 5 superimposed on the sequence average SEDs. The object exhibits a peak at high frequency (\( 10^{16} \) Hz) with a rather large peak X-ray luminosity (\( 10^{45} \) erg s\(^{-1} \)), falling in the central region of the sequence where the average SEDs nearly cross each other. The optical spectrum of this source exhibits very weak emission lines, approaching a BL Lac classification which reinforces the similarity to PKS 2155–304.
2.5. The intriguing case of RGB J1629+401

This blazar is particularly interesting, since it exhibits very unusual properties. It is known since some years and was suggested to be a FSRQ ($z = 0.271946$) with a synchrotron peak at X-ray energies [21]. In fact its SED, shown in Fig. 4 falls in the same region as PKS 2155–304 and RX J1456+504.

Fig. 5. The SED of the two “blue” quasars discussed in the text, together with the proposed model. For RGB J1629+401 we show two possible models, to show (blue) the effect of a possible X-ray corona associated to the disk accretion luminosity. In both cases we have superposed (thin solid lines) the average SEDs corresponding to the blazar sequence.

Its optical spectrum shows strong but narrow emission lines\(^a\). Due to its high optical luminosity ($M = -23$) it was classified as a radio–loud Narrow Line Type 1 Quasar by Komossa et al. [16, 29] in a systematic search for radio–loud NL objects of which NL Seyfert 1 galaxies are the most common. The mass of the black hole is estimated to be $2 \times 10^7$ solar masses and its X–ray luminosity is highly super–Eddington. However if the X–ray luminosity is attributed to a beamed jet, as suggested by the SED and by the strongly “inverted” spectral index in the radio, the latter estimate may be reduced. We note that the radiation energy density $U_{\text{ext}}$ derived from the observed luminosity of the narrow emission lines, assuming a distance from the black hole consistent with the line width ($\nu < 2000$ km/s) yields a value lower than found in broad line quasars. Since $U_{\text{ext}}$ is small, our model associates to this blazar a relatively large $\gamma_{\text{peak}}$, and then this source falls in the middle of the $\gamma_{\text{peak}} \propto U^{-1}$ branch of Fig. 6, though technically it can be defined as a quasar from the point of view of the brightness of its optical nucleus. We therefore believe that it is reasonable to hypothesize that this object hosts a strong relativistic jet. We recall that NL Type 1 quasars are rare among quasars and ”radio loudness” is rarer in NL quasars than in BL quasars [16]. Thus it is not surprising that such objects were not found in the radio–loud samples explored previously. Clearly RGB J1629+401 poses a number of questions that will need further studies. A detection at $\gamma$-ray energies could confirm the jet model but is not guaranteed at this average intensity level.

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\(^a\)http://cas.sdss.org/astrodr6/en/tools/explore/obj.asp?ra=247.2554958&dec=40.1332306

3. Discussion and Conclusions

Despite the efforts to search for objects which may violate the sequence trends no “strong outliers” have been found. Some claims from other authors seem unjustified, as we have shown.

The existence of the sequence can be traced back to a strong physical link between the energy of the electrons emitting most of the power and the total (radiative plus magnetic) energy densities. As dis-
cussed by [10] and [12] this trend can be the result of the balance between the cooling rate (measured by the amount of total energy density) and the (almost universal) acceleration rate of the electrons. The most powerful sources have a large amount of magnetic and radiation energy density, determining a severe cooling and thus a small value for the equilibrium Lorentz factor of the electrons. On the contrary, BL Lacs are characterized by a low level of cooling, explaining the large electron Lorentz factors in these sources.

In Fig. 6 the parameters derived for the sources discussed in this paper are compared with those determined for the group of blazars recently considered by [4]. Although RGB J1629+401 does not deviate significantly from other blazars in this parameter plane it should be stressed that its other characteristics, notably the estimated black hole mass and optical narrow line spectrum are at variance with previously known blazars. Searching for more objects like RGB J1629+401, could extend the “blazar phenomenon” to low masses and provide useful hints to understand the link between relativistic jets and black hole masses.

High–z objects show extreme ratios of inverse-Compton to synchrotron emission, which – with reference to the adopted SED model – corresponds to a high energy density of external radiation. It is easy to anticipate that in the study of this external Compton component GLAST will play a crucial role.

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