Decrypting and Modeling the High-Energy Emission of Blazars

ISSI International Team Proposal 2008

ABSTRACT

Blazars are a class of active galactic nuclei characterized by an extremely variable X-ray and/or gamma-ray emission. Although we know that every blazar with strong gamma-ray emission contains a prominent jet of magnetized plasma flowing out of the nucleus at near-light speeds, astrophysicists have thus far failed to determine how and where the jet produces the gamma-rays and X-rays. Understanding this will help us to constrain the jet formation mechanism and the physical conditions close to the black hole. The imminent launch of NASA's *GLAST* mission will provide an almost continuous monitoring of several tens of bright blazars in the gamma-ray domain. These observations together with complementary multi-wavelength measurements by existing (*MAGIC*, *AGILE*, *INTEGRAL*, *XMM-Newton* and *Swift*) or upcoming facilities like *Planck* will open a new era in the characterization of the spectral evolution of strong outbursts. Our Team — composed of both theoreticians and observers — has the objective to properly interpret and model these unprecedented observations. The Team will work in three complementary areas: 1) on the definition of the optimal observational strategy to constrain the flaring behavior both in the frequency and time range; 2) on the identification of the most likely scenario for the high-energy emission of blazars; 3) on the development of a model than can be adjusted to the observations in order to probe the physical conditions in the jet and the characteristics of particle acceleration events. Since the low-energy emission component of blazars — from the radio to the optical range — is well understood in terms of synchrotron emission in propagating shock waves, we first plan to investigate the contribution of the necessarily associated synchrotron self-Compton (SSC) emission at high-energies. We will then assess whether another process has to be invoked in addition for a full description of the observations. The ISSI Team meetings will result in the publication of a refined model for the SSC emission of shock waves in a relativistic jet, as well as a paper on the application of this model to observations. If successful, the same methodology will be applied on the longer-term to several other jet sources, possibly including also microquasars and gamma-ray bursts and shall result in a much deeper understanding of the physical conditions in various kinds of relativistic jets.

SCIENTIFIC RATIONALE

Astrophysical jets arise whenever there is strong accretion of matter in a disk around a massive compact object. In the Milky-Way, they can result from accretion onto a protostar in Herbig-Haro objects, a white dwarf in cataclysmic variables or onto a neutron star or a black hole in microquasars. The most powerful jets in the universe are launched by super-massive black holes at the centre of active galaxies. These jets can extend over distances far beyond the size of their host galaxies. Due to relativistic boosting, the most luminous and variable jet sources are those with the jet pointing in a direction close to the line of sight. Such sources are called blazars and form a distinct class of active galactic nuclei (AGN).

The radiation of blazars is dominated by the emission of the jet and is generally composed of two main components: one at low energy in the radio-to-optical domain, and one at high energy in the X-ray and gamma-ray range. The low-energy emission is well understood as being due to synchrotron radiation of relativistic electrons (and possibly positrons) in the jet. This radiation is now known to be mainly emitted by the structures observed through radio interferometry to propagate at the base of the jet with apparent velocities exceeding the speed of light (e.g. Türler et al. 1999; Savolainen et al. 2002).

On the other hand, the origin of the high-energy emission is still much debated. The most likely interpretation is that this X-ray and gamma-ray component is due to inverse-Compton scattering of ambient photons by the relativistic electrons in the jet. It was long thought to be emitted very close to the black hole at the apex of the jet with an important contribution to the seed photons being optical and ultra-violet radiation from the accretion disk and/or the broad-line region. This external Compton scenario was applied by Hartman et al. (2001) on one of the most complete datasets currently available. The resulting fit to the data of 3C 279 during the high-state of June 1991 is shown in Fig. 1.

Although the fit gives a good description of the data, the main assumption of the model is disproved by recent studies showing that the emission of the high-energy component is co-spatial with the synchrotron emission (Jorstad et al. 2001; Lähteenmäki & Valtaoja 2003; Lindfors et al. 2006; Sikora et al. 2008). As this arises further down the jet flow at a distance of typically 1–10 pc, the radiation field of the optical and ultra-violet photons will not be strong enough to account for the observed gamma-ray emission. Although infrared photons from a dust torus can still be invoked as the seed photons (e.g. Sikora et al. 2008), there is now an urgent need to rethink the high-energy emission of blazars and to develop a new model to be tested and constrained by the unprecedented observations that *GLAST* together with other new facilities will provide in the years to come.

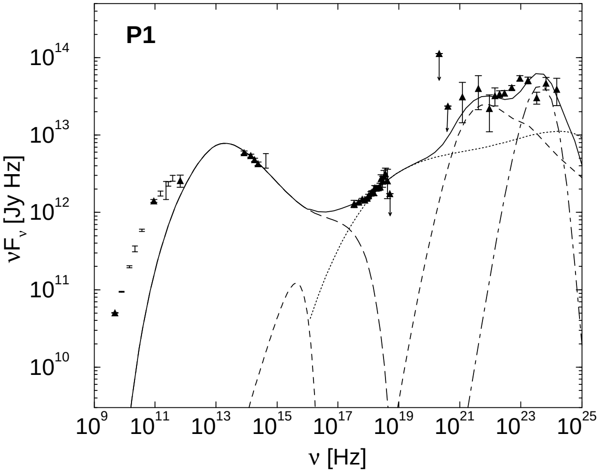

Fig. 1. *Modeling by Hartman et al. (2001) of the emission of 3C 279 during the high-state of June 1991*

PROJECT DESCRIPTION

The objective outlined above will be addressed by a very competent international Team that has worked in the field since many years. The Team will bring together expertise in three complementary areas: observation, theory, and modeling. The progress we hope to achieve in these three areas by proposing an ISSI international Team is described below.

Observational strategy

A first aspect of our project is the definition of strategies to get the most appropriate dataset to study the variable multi-wavelength emission of blazars. The new data expected from NASA's *GLAST* mission to be launched in the coming months will provide a huge improvement compared to the observations of the 1990's by the Compton Gamma-Ray Observatory (CGRO). The gain will be both in sensitivity and time coverage in a crucial high-energy gamma-ray range where the emission of many blazars is peaking. The fact that the *GLAST* data for the 22 brightest blazars (including 3C 279, 3C 454.3, Mrk 501, etc.) will be immediately public[1] is the main driver for having an ISSI Team project starting this year.

However, as the sources of interest are highly variable and emit over the entire electromagnetic spectrum, these observations will have to be complemented by measurements at other wavelengths to really test and constrain physical jet models. The *GLAST* measurements will be ideally complemented in the gamma-ray domain by observations with the Italian *AGILE* satellite and by ground-based Cherenkov telescopes — like *HESS* and *MAGIC* — to detect a signal at very high-energies (in the TeV range). In the X-rays, we foresee coordinated observations with ESA's *INTEGRAL* and *XMM-Newton* missions or with NASA's *Swift* satellite, whereas at longer wavelength, optical, infrared and submillimeter-to-radio monitoring observations will constrain the lower energy component. The possible use of radio interferometric imaging of the inner jet of blazars will also be discussed.

The coordination of such multi-wavelength observations will be possible thanks to a Team member being part of the *MAGIC* collaboration and others being experienced users of the X-ray facilities listed above or having access to ground based observatories in the optical-to-radio domain. We will investigate how

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[1] see: http://glast.gsfc.nasa.gov/ssc/data/policy/LAT_Monitored_Sources.html

to best trigger target of opportunity observations on space missions based on regular monitoring of a small sample of sources at optical, infrared or submillimeter frequencies. In particular, a very promising opportunity comes with the launch at the end of the year of ESA's *Planck* mission. The *Planck* survey of the sky at radio frequencies can be used as a trigger for multi-wavelength campaigns on blazars found serendipitously to be in an unexpected and interesting high-radio state. The Planck Quick Detection System (QDS) has been especially developed in Finland for this purpose and the leaders of the Planck proposal on the study of blazar physics are Team members.

Theoretical developments

Many different theoretical models have been proposed to explain the high-energy emission of blazars (see Böttcher 2007, for a review). Our Team foresees to review the main hadronic and leptonic jet emission models trying to identify which are best suited to successfully describe the observations. However, we think that one of the most natural explanations for the high-energy emission has not yet been enough investigated and exploited. Therefore, our main theoretical objective is to develop a model in which the high-energy component has a common physical origin with the low-energy emission, as suggested by recent studies (see above). The idea is that the shock waves observed to be moving in the inner jet and emitting synchrotron radiation would necessarily also be the site of high-energy emission via the synchrotron self-Compton (SSC) process. This radiation arises naturally due to the up-scattering of synchrotron photons by the same relativistic electron population in the jet producing this synchrotron emission.

The shock model of Marscher & Gear (1985) describes analytically the expected emission of a shock wave propagating in a relativistic jet flow. The basic principle is that a disturbance at the base of the jet becomes supersonic further down the flow and creates a shock wave. Relativistic electrons are then accelerated at the shock front and emit synchrotron radiation in the compressed plasma and magnetic fields behind the shock. Despite the successful application of the model to radio-optical flares (e.g. Türler et al. 2000; Lindfors et al. 2006), the SSC X-ray and gamma-ray emission expected from a shock has never been calculated properly. Björnsson & Aslaksen (2000) have proposed modifications to the model that Türler & Lindfors (2007) found to be compatible with infrared to radio observations of flares in several Galactic and extragalactic relativistic jet sources. In addition, Marscher et al. (1992) have produced low-frequency light curves for shocks moving through turbulence. Otherwise, the model remains undeveloped.

The natural step forward is to include the associated high-energy emission. The work of Björnsson & Aslaksen (2000) provides a strong basis for the theoretical developments we wish to achieve. They study the effect of multiple Compton scattering and propose analytical formula for the expected SSC component. We will assess to what extent these developments should be integrated into the new model. Another important issue is the proper inclusion of the effects of light-travel delays on the light curves and, especially, on the energy losses of the electrons responsible for the emission (Sokolov et al. 2004; Graff et al. 2007). Putting all this together we plan to devise a complete self-consistent model for the SSC emission of shock waves in relativistic jets to be published as a new reference model.

Modeling of the observations

To evaluate how well the model foreseen above can account for the high-energy emission of blazars, it is necessary to confront it to the observations. We developed already an innovative approach to test and constrain jet emission models with time-variable multi-wavelength observations of jet sources (Türler et al. 1999, 2000). The method consists in fitting a series of both physical and observational model parameters to the most complete available dataset of a given source. Several parameters are used to describe a typical (average) outburst, while other parameters define the specificities of individual outbursts identified in the radio-to-infrared lightcurves of the source. First used for the study of the blazar 3C 273, this methodology was recently also applied to 3C 279 (Lindfors et al. 2006), as well as to some activity periods of the microquasars GRS 1915+105 (Türler et al. 2004) and Cyg X-3 (Lindfors et al. 2007, Miller-Jones et al., in prep.).

With this broad experience on many different datasets, we are confident that we can also incorporate in the modeling the various improvements of the theoretical model outlined above. The addition of the high-energy component in the X-ray and gamma-ray range will be the most critical development, but this was already done in a simplified manner by Lindfors et al. (2005). This study was a first attempt of fitting a multi-component SSC model to the data of 3C 279 previously used by Hartman et al. (2001). The model was able to reproduce the X-ray emission, but failed to reach the intensity observed at higher energies (see Fig. 2).

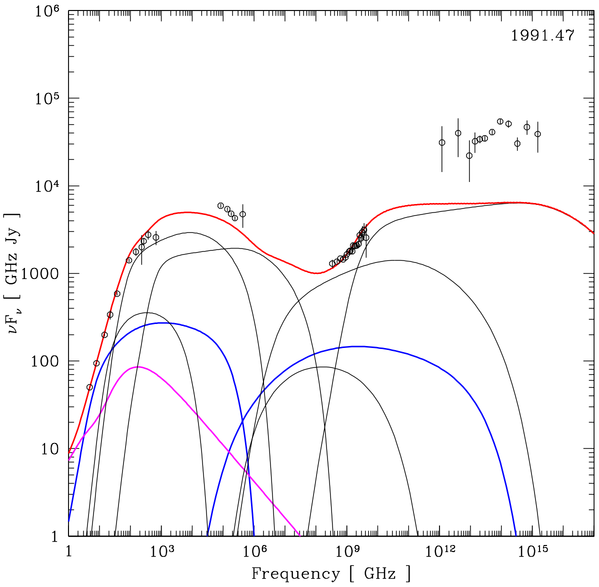

Fig. 2. *Simplified SSC modeling by Lindfors et al. (2005) of the emission of 3C 279 during the high-state of June 1991. The total spectrum is the combination of the SSC emission by a succession of shock waves forming and propagating in the jet flow. For an animated figure see: http://isdc.unige.ch/∼turler/jets/*

The theoretical developments we foresee will result in a redefinition of the spectrum and evolution of the high-energy emission component with a new set of parameters to be fitted to the most complete existing or new datasets of blazars. We expect the more complete model to better match the observations in the gamma-ray range, but we cannot exclude that another process has still to be invoked to get a good description of the observations. In this case, our review of alternative explanations for the high-energy emission of blazars will help us to identify the process that could explain the missing radiation not accounted for by SSC emission of shock waves.

Schedule of the project and Team meetings

We plan to have two Team meetings at the ISSI in Bern each lasting one week. It is expected that all Team members participate in both meetings. We foresee the first meeting to be held in winter 2008–2009 and the second in summer 2009. The first meeting would start with two days of presentations of the work of the participants relevant to the project and on the review in a Journal-Club way of other publications in the field. The three remaining days would be devoted to discussions of the three aspects of the project described above. After a first round all together for half a day on each topic we plan to have three splinter meetings for an additional day. The last afternoon would be used to summarize the meeting results and to define the organization of the work to be conducted separately, but with frequent e-mail and teleconference contact, by the Team members. The second meeting at the ISSI in Bern will serve to present the work that has been achieved and to discuss further the points which are the most critical for the success of the project as a whole. The advancement of the publications shall also be discussed and the final details settled.

Expected output of the project

The Team's study will decide definitively whether the currently most promising scenario for the generation of gamma-rays and X-rays in blazars — relativistic shock waves propagating down the jet — actually works. If not, then the Team will declare that a different type of model needs to be developed. The immediate outcome we expect from this ISSI Team proposal are two articles in refereed journals. The first article would be devoted to the theoretical developments we propose for a realistic self-consistent model of the SSC emission of shock waves in a relativistic jet. It might also include, but not be limited to, a critical review of previously proposed scenarii for the high-energy emission of blazars. The second paper would be on the application of this model to the best set of observations available around the time of the second ISSI meeting (summer 2009).

On the long-term, we expect this project to allow us to apply the newly developed model and methodology on the datasets of many different jet sources. This would not be limited to blazars, but would possibly also include Galactic microquasars or even gamma-ray bursts, for which inverse-Compton emission of synchrotron radiation has not been considered much yet. This will allow us to investigate how the physical conditions in the jet and the acceleration mechanisms scale with the mass of the black hole over eight orders of magnitude from about ten to a billion solar masses. The ultimate outcome of the project shall therefore be a deep understanding of the physical conditions and the processes at work in various types of relativistic jets.

Added value provided by the ISSI

It is essential that this project is being conducted in 2008–2009 in parallel to the early operational phase of two space missions that are expected to make a very important contribution to the characterization of the emission of blazars. These missions are *GLAST* monitoring the high-energy gamma-ray sky and *Planck* providing a survey in the submillimeter-to-radio domain. This space aspect of the project is exactly in the scope of an ISSI International Team. ISSI will provide a solid frame allowing this project to come to maturity around the time when we will have plenty of new observations to be analyzed. The ideal location of ISSI at the centre of Europe will offer a place away from other duties and constraints where our Team — composed of members from both sides of the Atlantic — will be able to do very efficient advances on this project. Without the ISSI facilities and the unique opportunity offered to have these working meetings all together at much reduced costs for the participants we do really think this important project will not materialize or at least not early enough to be ready for the analysis of data from the upcoming space missions. The support of ISSI is therefore essential to reach the goals of this project.

Required facilities and expected financial support

We do not require special facilities for our Team meetings. We need a meeting room with computer projection facilities, a white or black board, and if possible Internet access (through WiFi). For the foreseen splinter meetings, it would be very valuable to be able to use for some half-day meetings two additional small rooms even with no or limited capabilities for Internet access and computer projection. The expected financial support from ISSI is limited to the living expenses of all Team members while residing in Bern.

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