Multi-frequency, multi-messenger astrophysics with Swift. The case of blazars

Paolo Giommi
ASDC, Agenzia Spaziale Italiana, Via del Politecnico s.n.c., Roma, Italy

Abstract
During its first 10 years of orbital operations Swift dedicated approximately 11% of its observing time to blazars, carrying out more than 12,000 observations of ~1,600 different objects, for a total exposure time of over 25 million seconds. This is probably the largest contribution to multi-frequency (optical, UV, soft and hard X-rays) and multi-temporal data archives about this type of sources. In this paper I briefly discuss the impact that Swift is having on blazar multi-frequency and time-domain astrophysics, as well as how it is contributing to the opening of the era of multi-messenger astronomy. Finally, I present some preliminary results from a systematic analysis of a very large number of Swift XRT observations of blazars. All the "science ready" data products that are being generated by this project will be publicly released. Specifically, deconvolved X-ray spectra and best fit spectral parameters will be available through the ASDC "SED builder" tool (https://tools.asdc.asi.it/SED) and by means of interactive tables (http://www.asdc.asi.it/xrtspectra). Innovative data visualisation methods (see e.g. http://youtu.be/nAZYcXcUGW8) are being developed to help exploiting this new large data set as well as data form other multi-frequency archives.

Keywords: Active Galactic Nuclei; black hole physics; BL Lac objects; radiation mechanisms: non-thermal;

1. Introduction
Blazars are a small subgroup of AGN that are well known for their extreme observational properties such as superluminal motion and highly variable non-thermal emission across the entire electromagnetic spectrum, from radio waves to the highest energy $\gamma$-rays. Their unique properties are attributed to emission of radiation by energetic particles that move towards us in a magnetic field within a relativistic jet that happens to be pointing close to our line of sight [1,2].

Blazars come in two flavours: FSRQs and BL Lacertae objects (BL Lacs). The main difference is in their optical spectra, with the former displaying broad emission lines and the latter being instead characterised by either a featureless continuum, or by a spectrum that displays only absorption features (usually from the host galaxy) or weak narrow emission lines [3].

Figure 1. The SED of the blazar 3C454.3 assembled with over 60,000 flux measurements obtained with many space and ground-based observatories. The contribution of all Swift instruments (UVOT, XRT and BAT) is highlighted by the three grey vertical bands.

1paolo.giommi@asdc.asi.it
The radio to γ-ray Spectral Energy Distribution (SED) of blazars always displays two broad humps when plotted in νf(ν) vs ν space (see e.g. fig. 1).

It is widely accepted that the radiation associated to the low-frequency hump in the SED of blazars is due to synchrotron emission from relativistic electrons in the jet. The nature of the high energy emission, may instead be attributed to two intrinsically different approaches, generally referred to as leptonic and hadronic models.

The peak energy of the synchrotron component (ν_peak) ranges from about 10^{12.5} Hz to over 10^{18} Hz reflecting the maximum energy at which particles can be accelerated. Sources where ν_peak is less than 10^{14} Hz are called low synchrotron peaked blazars (LBL), while those where ν_peak > 10^{15} Hz are called high energy peaked blazars or HBL.

For a long time blazar research has been confined to a small community of specialists. Since a few years this has been rapidly changing as these sources are now receiving more and more attention after they have been found to be the largest population of extragalactic sources in microwave (between ∼ 30 and ∼ 200 GHz), and γ-ray surveys, as well as the most common objects appearing in catalogs of TeV detected sources. Most of the blazars found in microwave survey are of the LBL type (both FSRQs and BL Lacs), while HBL BL Lacs dominate the γ-ray extragalactic sky.

Blazars are powerful extragalactic sources capable of accelerating particles to very high energies and therefore they are considered as prime candidates for multimessenger astrophysics.

2. Swift and blazars

During its first ten years in orbit the Swift observatory carried out more than 12,000 observations of approximately 1,600 blazars, for a total of ≈ 25.3 Ms of X-Ray Telescope (XRT, [7]) net exposure time, or approximately 11% of the entire scientific program. About 50% of the objects listed in the most up to date catalog of blazars (BZCAT, 5th edition [8]) have been observed at least once. Some of the well known and best studied objects have been observed hundreds of times. Examples are the BL Lacs MRK 421 with 635 observations, MRK501 with 412 observations, and the FSRQ 3C454.3 with 419 observations. Fig. 2 illustrates how the rate of blazar observations evolved in time, showing a rapid increase between 2005 and 2009, followed by an approximately constant level of 1,500 observations per year. This is quite a large number of observations reflecting a scientific strategy which reserves to blazars a sizeable fraction of the Swift overall observing program. The full data set is available from the official Swift archives in the U.S. (http://swift.gsfc.nasa.gov/), Italy (http://swift.asdc.asi.it/), and U.K. (http://www.swift.ac.uk/). However, current archive facilities only provide basic data sets and software packages for the data reduction. Scientific analysis must be carried out by the user by means of mission specific and additional analysis software. This is usually done for a single exposure or for a limited number of observations; clearly normal users could hardly manage to analyse the entire data set. To facilitate the use of this valuable public archive at ASDC, also as part of the Swift team, we started a program to systematically analyse Swift blazar data to provide higher level “science ready” products and results, such as deconvolved spectra and best fit parameters for different spectral models.

An example of the remarkable contribution of Swift to multi-frequency studies of blazars is given by the SED of 3C454.3 shown in Fig. 1 where the simultaneous data obtained from the three Swift instruments, UVOT, XRT and BAT during the 419 observations carried out at the time of writing, is highlighted by three vertical bands.

3. Swift XRT Data Analysis

At the ASI Science Data Center (ASDC) we have processed in a uniform way, using the latest reduction
software and calibration available, all XRT observations of blazars pointed by Swift at least 10 times (approximately 120 blazars). The processing was carried out both on the overall data collected during each observation and also on a orbit by orbit basis, thus allowing a time resolution of the order of 1.5 hours.

The results of the analysis of approximately 5,000 XRT observations (and nearly 9,000 orbits) will be published shortly [9]. The high level data products, such as deconvolved spectral data, light curves, best fit parameters etc, will be available on-line within the ASDC SED builder tool (https://tools.asdc.asi.it/SED) and through interactive tables (http://www.asdc.asi.it/xrtspectra), a preview of which is shown in fig. 4. Best fit spectral parameters are given for the most commonly used (power law and log parabola) spectral models, for each observation and for every orbit during which sufficient statistics is collected for a spectral analysis. UVOT and BAT data for the same blazar sample will also be processed and the results will be published in a similar way in the future. In the following we show some preliminary results of this work, which will lead to the establishment of one of the largest existing databases of high level scientific products and results on blazars.

One example of these results is illustrated in fig. 3 where the distributions of the best fit power law spectral indices are shown for the subsamples of FSRQs and BL Lacs. Fig. 5 shows instead how the spectral slope depends on source intensity for the special case of MRK 421. The tight correlation apparent from this plot is well known, however the very large amount of data plotted in fig. 5 provides unprecedented statistics both in spectral slope and in flux range, this last spanning a factor of \(\approx 500\), probably a record value for soft X-ray variability of AGN.

4. Time domain data

The remarkable number of measurements accumulated over the last several years, thanks to Swift and many other space and ground-based observatories, are enabling new approaches to the analysis of luminosity variability in all parts of the electromagnetic spectrum. In this contribution blazars are used to provide some examples of how this new opportunity is being exploited.

Fig. 6 shows the light-curve of 3C454.3 in the \(\gamma\)-ray, X-ray, optical and radio band. It has been built using the same data set used to assemble the SED of fig. 1. A simple visual inspection of this figure reveals that the light curves at different frequencies share a similar behaviour, but also show significant differences. One technique used to quantify these differences is to calculate the discrete cross correlation function (DCCF) [10] between the light curves at different energies. Fig. 7 shows the DCCF of 3C454.3 obtained by comparing the \(\gamma\)-ray light curve (1 GeV from Fermi-LAT observations) with data taken in different energy bands, namely 1 keV, 1 mm, 37 GHz and 15 GHz. As can easily be seen in fig. 4 the amount of correlation with \(\gamma\)-rays is maximum for 1 mm data, with no significant time lag. All other light curves compared to 1GeV data show a lower level of correlation and significant time lags, ranging from about one month at 1KeV to several months in the radio band, depending on the frequency. This result reflects the complexity of the emission processes.
Figure 4. The first few lines of the interactive table through which the results of the ASDC XRT spectral analysis of blazars will be available on-line at http://www.asdc.asi.it/xrtspectra/

Figure 6. Multi-frequency light curve of the blazar 3C454.3. In this plot the same $\gamma$-ray, X-ray, optical and radio data extracted from the data set used for the SED of fig1 is used to illustrate the different behaviour in this source at different energies.

Figure 7. The Discrete Cross Correlation Function on multi-frequency data of 3C345.3 illustrating how different energy bands (15 GHz, 37 GHz, 1mm, and 1 keV) show different time delay with respect to the $\gamma$-ray emission at 1 GeV.

in blazars, which exhibit different dynamical timescales in various parts of the electromagnetic spectrum. This implies that while the use of simultaneous data, often obtained through complex observational campaigns involving ground and space based observatories (see e.g. [11]), is necessary to understand the physics of blazars, it is probably not sufficient for a fair estimation of model parameters.

A completely new technique to visualise variability in the SED of cosmic sources is to run in a sequence a set of frames, each representing the SED in a particular time interval, just like in a movie. Of course, this can be done only if a sufficiently large number of multi-frequency measurements are available at all times. This is a requirement that is quite demanding but that has been already met by some of the bright and well known sources. As an example, fig. 8 shows two frames of such a movie, which was built combining over 60,000 multi-frequency flux measurements of the blazar 3C454.3. The full movie can be accessed on-line at http://youtu.be/nAZYcXcUGW8.
5. Blazars and multi-messenger astrophysics

Due to their large luminosity and SEDs often reaching the highest observed γ-ray energies, blazars are the most powerful and most energetic cosmic accelerators known.

An estimate of the maximum energy at which particles are accelerated within this scenario can be obtained by measuring the peak (in $\nu f(\nu)$ space) of the synchrotron hump, $\nu_{\text{peak}}$. Swift is sensitive in the soft and hard X-ray bands, where the $\nu_{\text{peak}}$ of the most energetic blazars is located. Having observed about 50% of the known blazars the Swift archive provides the largest potential for the measurement of the synchrotron peak, and therefore the maximum energy at which particles can be accelerated in blazars.

5.1. Neutrinos from blazars?

Since their detection at very high γ-ray energies by Cherenkov telescopes, HBL blazars (sometimes also called TeV blazars) have been considered as candidate sources of neutrinos [12, 13].

Recently Padovani & Resconi (2014) [14], on the grounds of positional and energetic diagnostics, suggested that seven BL Lac objects could be related to neutrino events reported by the IceCube collaboration [15]. Other authors [16] have also argued in favour of a possible association of blazars in the TANAMI sample with ICECube neutrinos.

Fig. 9 shows the SED of the BL Lac object MRK 421, (one of the sources reported in [14]) including the expected flux from the twin γ-ray photons assuming that the IceCube neutrino with ID 9 is indeed associated to this bright BL Lac object. Petropoulou and collaborators [17] recently showed that the SED of this object can be interpreted in terms of a one-zone lepto-hadronic model. Assuming that this model is correct Padovani et al. (in preparation) have estimated the total neutrino cosmic background from the entire population of blazars, and compared it with IceCube data, obtaining encouraging results.

5.2. Could blazars be the sources of UHECRs?

The origin of Ultra High Energy Cosmic Rays (UHECRs) is a major question that after many years of observations still remains unanswered [18]. Many such particles with energy exceeding 50 EeV have been detected by the most sensitive cosmic ray observatories such as the Telescope Array in the northern hemisphere and the Pierre Auger observatory in the south. Their arriving...
directions are not correlated with the Galactic coordinates and their energy is so large that they are not expected to be deflected much by magnetic fields, therefore retaining the information about the source of origin. High expectations have therefore been expressed in the literature for the association of UHECRs with extragalactic objects. Attempts have been made to associate AGN to UHECRs \cite{19, 20} by cross-matching the positions of Swift-BAT detected AGN with Auger UHECRs finding a likely association with a confidence level of 98\%. The search was limited to sources closer than 100 Mpc since extragalactic UHECRs are expected to be severely attenuated primarily because of pion photoproduction interactions with the cosmic microwave background (CMB) radiation, the so called GZK effect. This level of statistical confidence, however, was not confirmed by subsequent searches \cite{21}, which were limited to mostly radio quiet AGN.

Blazars, particularly those with high energy synchrotron peak (HBL) that can be detected at TeV energies, are the extragalactic sources that can accelerate particles to the highest observed energies and therefore are also natural candidates as sources of UHECRs. In this context Tinyakov & Tkachev (2001, \cite{22}) searched for and found a high confidence correlation between BL Lacs and UHECRs. At ASDC in the months before the Swift 10 year meeting, we have tested this hypothesis by cross-matching the arriving directions of UHECRs from the TA and Auger samples with the position of the 1WHSP blazar sample \cite{23}, the most complete and largest sample of blazars of the type that are expected to emit at TeV energies. In particular we used the subset of 110 1WHSP blazars that are bright enough to be detected by the current generation of Cherenkov telescopes, and cross-matched it with the arrival directions of TA and Auger UHECRs obtaining a combined probability of chance occurrence lower than $10^{-3}$ \cite{24}. However, a preliminary verification of this encouraging result on the enlarged sample of UHECRs presented by the Auger collaboration in late 2014 \cite{25} does not seem to confirm the high level of significance of the correlation. To illustrate the status of the search at the time of writing \textbf{fig. 10} plots the arrival directions of the UHECRs from TA (red points) and Auger (blue and green circles) in Galactic coordinates, together with the positions of the 1WHSP sources that are expected to be above the sensitivity threshold of the current generation of TeV telescopes (grey points). The locations where there is a matching between blazars and UHECRs (within 3.2 degrees for the case of TA and 2.5 degrees for Auger) are indicated by open large circles.

Work is still in progress as we are currently using new Swift data to identify the sources with the largest synchrotron peak energy and therefore refine the sample by selecting the closest, most powerful and most energetic objects. The results will be presented in the future.

\textbf{6. Conclusion}

Since the start of its orbital operations Swift played a major role in accumulating one of the largest public archives of blazar data collected over a timespan of more than ten years. This is one of the richest multi-frequency public databases that is easily accessible through on-line data archives and results databases. In this paper it has been shown how, thanks to Swift and to many other space and ground-based astronomical
facilities, innovative techniques are emerging and are enabling significant progress in the analysis of multi-frequency, multi-temporal astronomical data. Multi-messenger astrophysics is the additional frontier. Although an irrefutable proof that blazars are connected to neutrinos or UHECRs has yet to be found, these sources are certainly among the most promising type of sources with the potential of opening soon this new and exciting window on the Universe.

7. Acknowledgments

Many of the results described in this paper have been obtained in cooperation with several collaborators. In particular, I wish to thank Paolo Padovani, Bruno Arsioli and Matteo Perri, with whom I have been working on several of the topics reported in this paper. I acknowledge the use of archival data and software tools from the ASDC, a facility managed by the Italian Space Agency (ASI). Part of this work is based on archival data from the NASA/IPAC Extragalactic Database (NED).

References

[1] R. D. Blandford, M. J. Rees, Some comments on radiation mechanisms in Lactertids, in: A. M. Wolfe (Ed.), Pittsburgh Conference on BL Lac Objects, University of Pittsburgh, Pittsburgh, 1978, p. 328.
[2] C. M. Urry, P. Padovani, Unified schemes for radio-loud active galactic nuclei, PASP 107 (1995) 803.
[3] P. Giommi, P. Padovani, G. Polenta, S. Turriziani, V. D’Elia, S. Piranomonte, A simplified view of blazars: clearing the fog around long-standing selection effects, MNRAS 420 (2012) 2899–2911. arXiv:1110.4706 doi:10.1111/j.1365-2966.2011.20044.x
[4] M. Bottcher, A. Reimer, K. Sweeney, A. Prakash, Leptonic and Hadronic Modeling of Fermi-detected Blazars, ApJ 768 (2013) 54. arXiv:1304.0605 doi:10.1088/0004-637X/768/1/54
[5] P. Padovani, P. Giommi, The connection between x-ray- and radio-selected BL Lacertae objects, ApJ 444 (1995) 567–581. arXiv:arXiv:astro-ph/9412073 doi:10.1086/175631
[6] G. Gehrels, G. Chincarini, P. Giommi, K. O. Mason, J. A. Nousek, A. A. Wells, N. E. White, S. D. Barthelmy, D. N. Burrows, L. R. Cominsky, K. C. Hurley, F. E. Marshall, P. Meszaros, P. W. A. Roming, L. Angelini, L. M. Barbier, T. Belloni, S. Campa, P. A. Caraveo, et al., The Swift Gamma-Ray Burst Mission, ApJ 611 (2004) 1005–1020. doi:10.1086/422091
[7] D. N. Burrows, et al., The Swift X-Ray Telescope, Space Sci. Rev. 120 (2005) 165–195. arXiv:arXiv:astro-ph/0508071 doi:10.1007/s11214-005-5097-2
[8] E. Massaro, P. Giommi, C. Leto, P. Marchegiani, A. Maselli, M. Perri, S. Piranomonte, Multi-frequency Catalogue of Blazars (3rd Edition), 2011.
[9] P. Giommi, et al., The swift xrt spectral database, in preparation (2015).
[10] T. Alexander, Is AGN Variability Correlated with Other AGN Properties? ZDCF Analysis of Small Samples of Sparsely Light Curves, in: D. Maso, A. Sternberg, E. M. Leibowitz (Eds.), Astronomical Time Series, Vol. 218 of Astrophysics and Space Science Library, 1997, p. 163.
[11] P. Giommi, G. Polenta, A. L¨uhentenn¨aki, et al., Simultaneous Planck, Swift, and Fermi observations of X-ray and γ-ray selected blazars, A&A 541 (2012) A160. arXiv:1108.1114 doi:10.1051/0004-6361/201117529
[12] F. Halzen, R. A. Vazquez, The GRO/Whipple Observation of Blazars: Implications for Neutrino Astronomy, International Cosmic Ray Conference 1 (1993) 447.
[13] K. Mannheim, Neutrino oscillations and blazars, Astroparticle Physics 11 (1999) 49–57. arXiv:astro-ph/9812007 doi:10.1016/s0927-6505(99)00024-9
[14] P. Padovani, E. Resconi, Are both BL Lacs and pulsar wind nebulae the astrophysical counterparts of IceCube neutrino events?, MNRAS 443 (2014) 474–484. arXiv:1405.3036 doi:10.1093/mnras/stt1166
[15] M. G. Aartsen, M. Ackermann, J. Adams, J. A. Aguilar, M. Ahlers, M. Ahsens, D. Altman, T. Anderson, C. Arguelles, T. C. Arlen, et al., Observation of High-Energy Astrophysical Neutrinos in Three Years of IceCube Data, Physical Review Letters 113 (10) (2014) 101101. arXiv:1405.5303 doi:10.1103/PhysRevLett.113.101101
[16] J. Alexander, Is AGN Variability Correlated with Other AGN Properties? ZDCF Analysis of Small Samples of Sparsely Light Curves, in: D. Maso, A. Sternberg, E. M. Leibowitz (Eds.), Astronomical Time Series, Vol. 218 of Astrophysics and Space Science Library, 1997, p. 163.
[17] M. Petropoulou, S. Dimitrakoudis, P. Padovani, A. Mastichiadis, E. Resconi, Photodhadronic origin of γ-ray BL Lac emission: implications for IceCube neutrinos, MNRAS 448 (2015) 2412–2429. arXiv:1505.07115 doi:10.1093/mnras/stv179
[18] R. U. Abbasi, et al., Indications of Intermediate-scale Anisotropy of Cosmic Rays with Energy Greater Than 57 EeV in the Northern Sky Measured with the Surface Detector of the Telescope Array Experiment, ApJ 790 (2014) L21. doi:10.1088/2041-8205/790/2/L21
[19] M. R. George, A. C. Fabian, W. H. Baumgartner, R. F. Mushotzky, J. Tueller, On active galactic nuclei as sources of ultra-high energy cosmic rays, MNRAS 388 (2008) L59–L63. arXiv:0805.2053 doi:10.1111/j.1745-3933.2008.00499.x
[20] Pierre Auger Collaboration, J. Abraham, P. Abreu, M. Aglietta, C. Aguirre, D. Allard, I. Allekotte, J. Allen, P. Allison, J. Alvarez-Muñiz, et al., Correlation of the highest-energy cosmic rays with the positions of nearby active galactic nuclei, Astroparticle Physics 29 (2008) 188–204. arXiv:0712.2843 doi:10.1016/j.astropartphys.2008.01.002
[21] C. Macolino, Pierre Auger Collaboration, Anisotropy studies with the Pierre Auger Observatory, Journal of Physics Conference Series 375 (5) (2012) 052002. doi:10.1088/1742-6596/375/5/052002