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Probing the physics of compact extragalactic sources over multiple scales

E. Pian[1], M. Anghinolfi[2], S. Ciroi[3], F. Panessa[4], C. M. Raiteri[5], S. Vercellone[6], L. Bassani[1], A. Bazzano[4], M. Berton[3], G. Bodo[5], G. Bruni[4], P. Calcidese[7,5], A. Capetti[5], M. I. Carnerero[5], J. M. Christille[7,5], A. Gardini[8], G. Ghisellini[6], V. Kulikovskiy[2], A. Malizia[1], M. Molina[1], E. Palazzi[1], P. Rafanelli[3], C. Righi[6], P. Rossi[5], M. Sanguineti[2,9], F. Tavecchio[6], P. Ubertini[4], F. Ursini[10], M. Villata[5], and C. Zanni[5]

[1] INAF - Osservatorio di Astrofisica e Scienza dello Spazio, Via P. Gobetti 101, I-40129 Bologna, Italy, e-mail: elena.pian@inaf.it
[2] INFN - Sezione di Genova, Via Dodecaneso 33, I-16146 Genova, Italy
[3] Dipartimento di Fisica e Astronomia "G. Galilei", Università degli Studi di Padova, Vicolo dell'Osservatorio 3, 35122, Padova, Italy; INAF, Osservatorio Astronomico di Padova, Vicolo dell'Osservatorio 5, 35122, Padova, Italy
[4] INAF - IAPS Roma, Via Fosso del Cavaliere 100, I-00133 Roma, Italy
[5] INAF - Osservatorio Astrofisico di Torino, via Osservatorio 20, I-10025 Pino Torinese, Italy
[6] INAF - Osservatorio Astronomico di Brera, Via E. Bianchi 46, 23807 Merate, Italy
[7] Osservatorio Astronomico della Regione Autonoma Valle d'Aosta, I-11020 Nus, Italy
[8] Instituto de Astrofisica de Andalucia, CSIC, Granada, Spain
[9] Dipartimento di Fisica, Università degli Studi di Genova, Via Dodecaneso 33, I-16146 Genova, Italy
[10] Dipartimento di Matematica e Fisica, Università degli Studi Roma Tre, Via della Vasca Navale 84, 00146, Roma, Italy

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Abstract. We report here on research made on extragalactic high-energy sources by our collaboration under funding program ASI-INAF n. 2017-14-H.0. We focussed in particular on blazars and fast radio bursts (FRB). We explored the variability of blazars at various wavelengths on a multitude of time scales, that led to a novel, theory-driven description of the jet geometry and dynamics over many time scales from intraday to several months. Blazar jet investigation included a structured jet model to account for hadronic processes that gave rise to neutrino emission in blazar TXS0506+056, as detected with IceCube. The search for FRB counterparts yielded upper limits on their hard X-ray emission obtained with the *INTEGRAL* satellite and the detection of hard X-ray bursts with *AGILE* and *INTEGRAL* from a Galactic magnetar that produced a FRB on 28 April 2020.

Key words. Galaxies: active – Galaxies: jets – Relativistic processes – Acceleration of particles – Radiation mechanisms: non-thermal – BL Lacertae objects: general

1. Introduction

Virtually all highly variable multi-wavelength extragalactic sources are characterized by relativistic kinematics, high compactness, and very often jetted geometry (Kumar & Zhang 2015; Romero et al. 2017; Blandford et al. 2019; Katz 2019). Their extreme physical conditions are generally due to central black holes of 1-to-10^8 $M_\odot$, or to rapidly rotating highly magnetized neutron stars, whose rotation or accretion energy is transferred to the emitting regions via poorly known mechanisms. These dramatic physical regimes make extragalactic compact sources also excellent multi-messenger emitter candidates (gravitational waves, TeV-PeV neutrinos, ultra-high-energy cosmic rays).

In an attempt to elucidate the interplay between the central engine, the possible accretion disk and jet, the observed electromagnetic emission at all wavelengths, and their occasionally observed non-electromagnetic signals (in particular high-energy neutrinos), we have set out to investigate some classes of extragalactic high-energy sources: blazars, including radio-weak BL Lac objects, and fast radio bursts (FRB). In this paper we report some selected results, that capture their essential nature and physics, obtained by members of our team, either as leaders or as co-investigators in external collaborations, through research supported by the ASI funding program ASI-INAF n. 2017-14-H.0 (*Attivitá di Studio per la comunitá scientifica di Astrofisica delle Alte Energie e Fisica Astroparticellare*).

2. Results

2.1. Blazars as high-energy neutrino emitters

Blazars, the most luminous extragalactic persistent sources at all wavelengths, have spectral energy distributions dominated by nonthermal radiation (Falomo et al. 2014; Romero et al. 2017). While the emission at radio-to-UV wavelengths, sporting high degree of linear polarization, is due to synchrotron process in powerful relativistic jets directed at small angles with respect to the observer (see also Section 2.2), the nature of the radiation at higher energies, up to TeV, can be diverse, depending on the jet composition, which is not completely known. If it is fully leptonic, hard X-rays and gamma-rays are produced via inverse Compton scattering, while a hadronic component would cause proton cascades, pion production and attendant TeV-PeV neutrinos. The latter then represent a critical diagnostic of jet composition, as fully leptonic processes do not produce high-energy neutrinos.

With the advent of large water and ice experiments for the detection of high-energy neutrinos of astrophysical origin, the identification of the emitters has become more compelling (Albert et al. 2017; Halzen 2019). A search for an association between VLBI radio-selected blazars and the arrival directions of the track-like events detected by ANTARES in 13 years of operation has led to some findings that – with further work and analysis – may hint at candidate neutrino-emitting blazars (Aublin et al. 2011).

On 22 September 2017 IceCube recorded a ~300 TeV neutrino event (IceCube-170922A) that appeared to be spatially and temporally coincident with a flare from the known blazar TXS0506+056 at redshift 0.34 (Paiano et al. 2018), that was detected and monitored at all wavelengths from radio to >200 GeV (IceCube Collaboration et al. 2018). The IceCube alert was followed up also by a search for signals in the ANTARES detector, which however did not return any positive coincidental detection (Albert et al. 2018). The first firm association of a high energy neutrino signal with a flaring blazar unavoidably points to a lepto-hadronic – as opposed to fully leptonic – composition of the jets of blazars and radio-galaxies, that represent their off-axis viewed, un-beamed parent population (Urry & Padovani 1995; Blandford et al. 2019).

Modelling of the multi-wavelength emission of TXS0506+056 in terms of a hybrid leptonic and hadronic jet composition proved to be difficult, as the jet power is predicted to be several orders of magnitude in excess of the Eddington luminosity (Gao et al. 2019). In order to circumvent this problem, Ansoldi et al. (2018) have proposed that the emitting region is inhomogeneous, with an inner, faster "spine" surrounded by a slower "layer".

A far-reaching consequence of the detection of IceCube-170922A in connection with a flaring blazar is that the apparent presence of hadrons in blazar jets makes them excellent candidates as accelerators of ultra-high-energy cosmic rays (Pian 2019).

2.2. Blazar variability on multiple time-scales

Highly relativistic conditions ($\Gamma \sim 10-20$) and small viewing angles (~5-10 deg) foreshorten the time-scales and magnify the amplitude of intrinsic luminosity variations in blazars, making them appear much more violently variable than their un-aberrated radio-loud AGN counterparts. The variations of their multi-wavelength spectral energy distributions are an indirect but cogent diagnostic of the central engine workings and emission mechanisms, up to high redshifts (Vercellone et al. 2019).

Blazar intra-day optical variability has long been the subject of investigation (Wagner & Witzel 1995), as it not only carries information on the jet sub-structure on the smallest size scales, but also helps in discriminating intrinsic effects from extrinsic ones that only affect radio wavelength emission (e.g. interstellar scintillation).

The current satellites devoted to optical monitoring of nearby stars and extrasolar planets offer an excellent opportunity for the observation of optically bright and variable blazars down to their time-resolution limit. Coupled with dedicated ground-based optical and orbiting high-energy facilities these space-based uninterrupted optical time series return unprecedented information on blazar jet geometry and dynamics.

Two blazar sources known for their short-term variability, BL Lac objects S5 0716+714 and S4 0954+65, were studied with the TESS space telescope uninterruptedly during periods of about one month with a cadence of 2 minutes, and with supporting observations from the ground through WEBT. The former source was observed also in UV and X-rays with the Neil Gehrels *Swift* Observatory. A progressive de-trending of the TESS light curve by means of cubic spline interpolations through the binned fluxes, with decreasing time bins, yielded decomposed light curves that were then analysed with classical tools for time-series analysis (periodogram, autocorrelation, and structure functions).

Significant characteristic variability time-scales of about 1.7, 0.5, and 0.2 days were identified in S5 0716+714. Variability on the shortest time-scale ($\lesssim$ 0.2d) is strongly chromatic and likely due to intrinsic energetic processes involving jet substructures ($\sim 10^{-3}$ pc). By contrast, flux variations on time-scales $\gtrsim$ 0.5 d are quasi-achromatic and probably due to Doppler factor changes (Raiteri et al. 2021a).

S4 0954+65 exhibits variability on time-scales ranging from a few hours to a few days, although with un-repeating patterns. The time series also contain the suggestion of a quasi-periodicity of $\sim$1 month, that could be associated with a rotating inhomogeneous helical jet, whose pitch angle changes in time (Raiteri et al. 2021b).

2.3. Radio-weak BL Lac objects

AGN come in various flavours owing both to intrinsically different basic properties (central black hole mass, spin, and accretion rate; jet or outflow strength; circumnuclear gas density) and to viewing angle effects. Several missions, among which primarily *Fermi* and *INTEGRAL*, thanks to their long lifetime, their long uniform looks and survey observing strategies, have harnessed these diverse phenomenologies and set the conditions for a in-depth unifying analysis of AGN sub-classes (Malizia et al. 2020, 2021; Berton et al. 2021; Foschini et al. 2021). Among these, most intriguing are the "radio-weak" BL Lacs, a variety that emerged while searching for low-energy counterparts of the unidentified or unassociated gamma-ray sources listed in the *Fermi* catalogs (Massaro et al. 2017). They share the multi-wavelength properties of BL Lacs, but lack strong radio emission.

Of the few hitherto known radio-weak BL Lac candidates, J1544–0639 (z = 0.171) appears noteworthy in that it was first detected thanks to an outburst it underwent in May 2017. The flare, first detected by *Fermi*/LAT on 2017 May 15, was on for two consecutive weeks, with a flux peak on May 21st. Follow-up observations in X-rays with *Swift*/XRT, and in optical and radio from the ground revealed a transient counterpart (Bruni et al. 2018). The properties of this source – notably the ratio between the radio and X-ray luminosities and the optical spectral discontinuity associated with the Ca II H&K break – suggest that the viewing angle toward its radio jet is not particularly small, which may account for the radio-weakness. This, together with the fact that the radio-to-gamma-ray spectral energy distribution is typical of a low-power BL Lac, may confirm J1544–0639 as a member of the newly proposed sub-class of radio-weak BL Lacs.

A pointing with the *XMM-Newton* in February 2018 detected X-ray flux variability of a factor of ~2-3 on a time-scale of 10 ks, with a harder-when-brighter behaviour, typical of BL Lacs. The X-ray spectrum is described by a variable broken power law, with a break energy of ~3 keV consistent with radiative cooling due to Comptonization of broad-line region photons. A flux excess at ~0.2 keV is consistent with bulk Comptonization in the jet (Ursini et al. 2019).

2.4. Relativistic magnetohydrodynamic simulations of jets

Synchrotron sources have polarized spectra, reflecting the structure and ordering pattern of their magnetic fields. As an example, linear polarized percentages between a few and ~30% are commonly measured in blazar and GRB optical and radio spectra. The expectation that the X-ray light of compact sources may be equally or even more polarized led to the design of the Imaging X-ray Polarimetry Explorer (IXPE), recently launched by NASA Weisskopf et al. (2016). However, polarimetric data are notoriously difficult to interpret, as they are prone to subtle intrinsic and extrinsic effects (superposition of different emission components of different polarization, spurious polarization by foreground dust or gas medium, Faraday rotation...). The interpretation of multi-wavelength polarimetry must thus be guided by precise predictions.

By studying the synchrotron polarization signatures of particles accelerated by the kink instability in a magnetically dominated plasma column, Bodo et al. (2021) have found that the non-linear stage of the kink instability generates current sheets, where particles can be efficiently accelerated via magnetic reconnection.

X-ray and optical radiation emitting particles are followed self-consistently as they propagate away from their injection sites while cooling. Although the cooling times of X-ray emitting particles are shorter than those of particles emitting in optical band, the expected degree of polarization in these bands is roughly the same, because the optical emitting particles, similarly to the X-ray emitting particles, do not travel far from the current sheet where they were injected, owing to insufficient kink-generated turbulence. On the other hand, the polarization angle shows a different temporal evolution between the two bands, as the regions probed by X-ray and optical emitting particles are different. These results can help constrain whether kink-induced reconnection (as opposed to shocks) can be the source of multi-wavelength emission in BL Lac objects.

2.5. Magnetar SGR 1935+2154 as a *rosetta stone* for fast radio bursts

FRBs are millisecond transients of extragalactic nature ($z = 0.05 - 2$), some of which were observed to repeat either with apparently random recurrence, or – in two cases – with a measured period (Petroff et al. 2019; Nicastro et al. 2021). About 800 events have been catalogued to date (The CHIME/FRB Collaboration et al. 2021). Their GHz energy outputs range from $\sim 10^{34}$ to $\sim 10^{43}$ erg, but no counterpart at higher frequencies has so far been detected, barring host galaxies of a few of them. Upper limits to their hard X-ray emission were estimated with *INTEGRAL* for FRB 180301, 180309, and 180311 (Savchenko et al. 2018a,b,c). Searches with ANTARES for neutrinos of energy $\gtrsim 100$ GeV from FRB 150610, 151206, 151230 and 160102 in a time window of 2 days centered on the FRB detection time did not return detections (Bhandari et al. 2018).

On 28 April 2020, CHIME/FRB Collaboration et al. (2020) reported the detection of a FRB from a direction consistent with the location of the known Galactic magnetar SGR 1935+2154 ($\sim$ 10 kpc). Assuming coincidence, the FRB total energy at radio wavelengths is 3×10^{34} erg, i.e. 3 orders of magnitude higher than the burst energy of any radio-emitting magnetar detected thus far, but 30 times dimmer than the weakest extragalactic FRB (Bochenek et al. 2020), and 8-9 orders of magnitude lower than that of the most distant and radio-luminous detected FRBs (Shannon et al. 2018; Pol et al. 2019).

Hard X-ray bursts were detected simultaneously with the radio ones by various satellites from SGR 1935+2154 (Li et al. 2021; Ridnaia et al. 2021; Tavani et al. 2021), among which, notably, IBIS aboard the *INTEGRAL* mission (Mereghetti et al. 2020), indicating that the magnetar was undergoing a period of high activity and corroborating its association with the detected FRB200428. While this detection may suggest that SGR 1935+2154 is a Galactic blueprint of fast radio bursters, and the key to their interpretation, the properties of the extragalactic FRBs are too diverse to be straightforwardly reconciled to a single paradigm.

3. Conclusions

The highlights of our research on blazars and FRBs show that their study benefits in a critical way from a multi-wavelength and multi-messenger approach based on repeated observations with a range of cadences, that can simultaneously cover variability of radiation and particles.

The present and near-future wide-field facilities will enhance the effectiveness of surveys for the search and monitoring of blazars across wavelengths and timescales (e.g. LSST, eROSITA, Fermi-LAT, CTA), while the recently launched IXPE satellite and medium-size ground-based optical telescopes will secure the measurements of polarization, which represents the hallmark of blazar continua. The coupling of these observations with the operations of sensitive neutrino detectors (IceCube, KM3NeT) will help assembling a sizeable sample of neutrino-emitting blazars. While only one blazar is presently confirmed to be a high-energy neutrino source, many candidates have been proposed, notably PKS0735+178 (IceCube Collaboration 2021; Kadler et al. 2021; Dzhilkibaev et al. 2021; La Mura & Fermi-LAT Collaboration 2021; D'Ammando 2021; Falomo et al. 2021; Lindfors et al. 2021; Petkov et al. 2021). When these and future candidates will be confirmed or rejected, it will be possible to select and constrain the subtype of blazar sources and identify the conditions in blazar jets that are more conducive to hadron processes.

Besides CHIME, many radio facilities are developing systematic programs for search and follow-up of FRBs, including repeaters; accordingly, ground-based and orbiting telescopes and instruments are being lined up for the detection and identification of counterparts at wavelengths shorter than radio, or to set stringent limits on them. An important outcome of this exercise will be the optimization of this search, which may require not only a very fast response to FRB signals but also very rapid time sampling (e.g. millisecond timescale optical photometry).

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