Optical identifications of celestial high energy sources with the Telescopio Nazionale Galileo

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Abstract.
To ascertain the nature of celestial high energy sources, it is crucial to identify their optical counterparts. However, the currently available astronomical public optical databases do not provide an adequate support for a systematic high energy sources identification work. In particular, the optical limiting magnitude represents a severe limitation since the deepest flux limits reached by X-ray surveys require of course similarly deeper optical catalogs to homogeneously sample the available parameter space. Nonetheless, dedicated spectroscopic campaigns are being carried out successfully with the Telescopio Nazionale Galileo (TNG), a 4-m class telescope. To set up a winning observational campaign, the first and most important step is to define a strong science case, as it will allow for selections of good targets for observations: the key is to increase the identification efficiency while keeping down the required telescope time. In this context, as the Principal Investigator, I will give an overview of the first spectroscopic campaign carried out at the TNG to identify Swift X-ray serendipitous sources, and I will show the valuable results achieved with only one night of observations. As a second example, I will review the strategy for the northern-sky classification of candidate blazars associated to unidentified Fermi γ-ray sources, and I will show the results coming from the related observational campaign at TNG I have been involved during the last two years.

1. Matter of interest
“The problem of optical identification of high energy (X- and γ-ray) sources is a classic in modern astronomy. It is only through the optical studies that one can gain complete understanding of objects [..]” [1].

Currently available astronomical public optical databases do not provide an adequate support for a systematic high energy sources identification work [see e.g. 2]. The main issues to solve are essentially related to the poor positional accuracy of high energy sources coordinates with respect to optical ones; on the other hand, the limiting magnitude of available optical surveys can represents a severe limitation as the deepest flux limits reached by current high energy missions requires of course similarly deeper optical catalogs to homogeneously sample the parameter space.

To date, the deepest wide optical survey, the Sloan Digital Sky Survey [SDSS; 3], has a limiting magnitude of $r' \sim 22$. Much deeper serendipitous optical surveys can be built performing observations with 8m-class telescopes, such as the VLT, the Gemini, and with the HST. Such surveys would be surely incomplete in terms of color coverage, but they would give a valuable support for some identification works if the science data centers would provide the advanced...
data products - e.g. fully reduced and calibrated frames, image stacks, and object catalogs - needed for this kind of projects. The next planned surveys, such as VISTA [4], Pan-STARRS [5] and LSST [6], will surely provide useful data for optical identifications of faint high energy sources. Moreover, next generation world-class telescope, such as the E-ELT, the GMT and the TMT will ensure a major step forward in the next decade for optical/near-infrared follow-up.

Nonetheless, dedicated spectroscopic campaigns of relatively faint sources are being carried out successfully with the 3.58m Telescopio Nazionale Galileo (TNG), La Palma (Canary Islands - Spain). Here I will review two science cases for which the contribution from the TNG proved to be crucial, namely the optical spectroscopy of serendipitous candidate Active Galactic Nuclei (AGN) detected with the Swift satellite, and the optical follow-up of candidate blazars detected by the Fermi Gamma-Ray Space Telescope.

1.1. Optical follow-up of Swift serendipitous AGN candidates selected for X-ray variability studies

Statistical properties of X-ray variability may provide clues for understanding the underlying X-ray emission. In the optical domain, ensemble analyses based on variability of SDSS data sets provided a detailed description of the dependence of variability on luminosity, redshift, wavelength and time lag between observations, via a structure function (SF) analysis [7; 8]. Recently, a similar study in the X-ray domain [9], based on two different serendipitously selected samples extracted from the catalogs of XMM-Newton [10] and Swift [S3XGF; 11], gives statistically consistent results in the two cases, with the SF described by a power law of the time lag, with exponent $b = 0.10 \pm 0.01$ (XMM-Newton) or $b = 0.07 \pm 0.04$ (Swift). This would correspond to a Power Density Spectrum (PDS) with power law exponent $\sim 1.2$ for the case of a single-power-law PDS, which is within the range of exponents found for nearby Seyferts [12]. The two samples are complementary since XMM-Newton data probe timescales within the range from months to a few years in the rest-frame, while Swift typical monitoring times range from some days to a few weeks in the rest-frame. Moreover, XMM-Newton suffers for rather sparse sampling, providing only two epochs for the majority of sources, whereas Swift provides a sampling at intermediate time-scales (hours to a few months in the observed frame).

To build an ensemble SF of the AGN, it is necessary: i) to ascertain the AGN nature of the X-ray serendipitous sources, excluding possible X-ray emitting stars or galaxies, and ii) to measure the redshift in order to group all the individual flux variations of different objects in bins of rest-frame time lag. Analysis of Swift GRB fields, observed between January 2005 and June 2007, overlapping the area covered by the Data Release 7 of the Sloan Digital Sky Survey (SDSS-DR7 13) allowed us to identify only 27 sampled-well-enough (i.e. at least, 100 photons in the lightcurve) serendipitous X-ray sources with quasi-stellar-objects (QSOs) of known redshift to built the SF shown in Fig. 6 of [9], providing a curve of growth of the X-ray variability with respect to rest-frame time lag $\tau \leq 10$ days.

To extend the Swift SF to have a better sampling at longer timescales, I lead a dedicated spectroscopy campaign to observe a group of serendipitous S3XGF sources, selected to have long exposure, a good sampling of the X-ray lightcurve and an optical counterpart in the SDSS-DR7 brighter than $g' = 21.5$. Spectroscopic observations were carried out on July 15/16 2010 with the DOLORES spectrograph at the TNG. DOLORES Grism LR-B and long-slit mode, with 1.5 arcsec slit, were chosen to have the spectral resolution needed to distinguish broad and narrow emission lines. I give some information on data reduction in Appendix A.

15 objects were observed: among them, the AGN nature of 11 sources ($\sim 80\%$) was confirmed, and their redshifts were measured. These new identifications will enable the extension of the previously published X-ray SF up to rest-frame time lag of $\tau \sim 40$ days [14].
1.2. Optical identification of candidate blazars discovered by the Fermi Gamma-Ray Space Telescope

The Fermi Gamma-Ray Space Telescope was successfully launched in June 2008 and is now in full operational mode providing an unprecedented view of the high-energy $\gamma$-ray sky. One of Fermi’s primary goals is to investigate the physics of relativistic jets in AGN, to which end it is already making good progress towards an order-of-magnitude increase in the number of known $\gamma$-ray bright blazars. Blazars are rare extragalactic objects as they only make a fraction of radio loud AGN, which, in turn are much less abundant (10%) than the bulk of the AGN population. Typical AGN are radio-quiet and are found in large numbers at optical and X-ray frequencies. However, blazars strong emission at all wavelengths makes them the dominant type of extragalactic sources in those energy windows where the accretion onto a supermassive black hole, or other thermal mechanisms, do not produce much radiation. For instance, in the microwave band, [15] showed that blazars are the largest population of extragalactic objects. The same is true in the $\gamma$-ray band [16; 17], and at TeV energies where BL Lacs are the most frequent type of sources found in the high Galactic latitude sky [e.g. 17; 18, see e.g. the Web-based TeVCat 1 catalog for an updated list of TeV sources].

Blazars have been known and studied in different energy windows for over 40 years, however, many questions still remain open about their physics and demography, e.g., how are jets made and how are they accelerated? What is the jet matter content? How are the relativistic particles accelerated and why is the maximum acceleration so much higher in BL Lacs? What is the maximum acceleration that can be achieved? What are the mechanisms producing blazar variability and what is the blazar duty-cycle? What is the cosmological evolution of the different types of blazars, namely BL Lacs and Flat Spectrum Radio Quasars (FSRQs)?

Fermi, with its large sensitivity and unique capability of observing the entire sky every day, started a new era in $\gamma$-ray astronomy. Its great and unprecedented potential will lead to the detection of very large and statistically well defined samples, as well as to the monitoring of hundreds of blazars on different time scales and on a wide $\gamma$-ray energy band. These new $\gamma$-ray data sets, together with the others at different energy bands will be used to address many, if not all, of the questions listed above.

All types of blazars emit radiation across the entire electromagnetic spectrum through the widely recognized Synchrotron Self Compton (SSC) mechanism which is responsible for the well known double hump Spectral Energy Distribution (SED). However FSRQs and BL Lacs differ at least in i) the optical band, where the former show the broad lined spectrum typical of all QSOs whereas BL Lacs are featureless, and in ii) the energetics of the emitting particles with BL Lacs reaching in some cases much higher energies shifting to higher frequencies the peak of their synchrotron and inverse Compton power. Blazars can therefore be distinguished by the peak of their synchrotron emission, that is the main reason why one of the most effective ways of studying their properties is through the use of multi-frequency data.

The first year of sky-survey operation with the Fermi Large Area Telescope (LAT) revealed 1079 bright sources at high galactic latitude ($|b| >10$) indicating high-confidence associations of 700 of these sources with known AGN. About 20% of these are still unidentified [1LAC; 19].

In this context, a long observational campaign, led by S. Piranomonte, started at TNG in 2009, and I joined the team in 2010. The main goal was to complete the identification of the “northern” unidentified sources from 1LAC and to include them in the 2nd year Fermi LAT AGN catalogue [2LAC; 20].

Optical spectroscopy was then obtained for a wide sample of unidentified sources in the “northern” sky that show the typical hallmarks of blazars, such as radio loudness, flat radio spectrum etc, and are statistically associated (probability larger than 90%) with one of the still unclassified 1LAC $\gamma$-ray sources. In particular, 54 unclassified extragalactic LAT sources were observed with DOLORES at TNG between 2009-2010: 16 were already updated in 1LAC, and
21 new redshifts were measured (7 added in 1LAC, 14 updated recently in 2LAC). Other 10 unclassified LAT sources were selected to be observed by the end of March 2011. Different grisms and slits were chosen to achieve the best results. Data reduction is detailed in Appendix A. The campaign confirmed the blazar nature of all the over 60 candidates: among them, 85% are BL Lacs (20% with redshift), the rest are FSRQs (all with redshift) [21]. These spectroscopic identifications were crucial to identify all of the still unidentified high latitude radio loud sources in 1LAC and to insert them in the 2LAC, together with the results coming from similar campaigns carried at the Hobby-Eberley Telescope (HET), the 2.7m at McDonald Observatory, the NTT at La Silla, the 200′′ Hale Telescope at Mt. Palomar, the VLT, and the W. M. Keck Observatory [22–24].

The improved knowledge of the Fermi-LAT γ-ray sources will shortly lead to the construction of very large, statistically complete and absorption-unbiased samples of blazars enabling for the first time detailed studies of this puzzling class of sources.

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Appendix A.
All the spectra acquired with DOLORES at TNG were processed via standard data reduction using different IRAF packages [25], to obtain 1-dimensional calibrated extracted spectra: raw data were bias-subtracted and flat-fielded using tasks in the IRAF package noao.imred.ccdred, and the spectra were extracted, wavelength- and flux-calibrated using programs in the package noao.twodspec. Reference arcs were used to perform wavelength-calibration. Proper flux-calibration was obtained using spectrophotometric standard stars chosen from [26]. Spectra were cleaned of cosmic rays. Emission lines were visually identified and redshifts were estimated from these lines using the task rvidlines within the IRAF package noao.rv.

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