Unveiling the nature of the unidentified gamma-ray sources

F. Massaro
SLAC National Laboratory and Kavli Institute for Particle Astrophysics and Cosmology, 2575 Sand Hill Road, Menlo Park, CA 94025, USA
R. D’Abrusco, A. Paggi, H. A. Smith
Harvard - Smithsonian Astrophysical Observatory, 60 Garden Street, Cambridge, MA 02138, USA
N. Masetti
INAF - Istituto di Astrofisica Spaziale e Fisica Cosmica di Bologna, via Gobetti 101, 40129, Bologna, Italy
M. Girolletti
INAF Istituto di Radioastronomia, via Gobetti 101, 40129, Bologna, Italy
G. Tosti
Dipartimento di Fisica, Università degli Studi di Perugia, 06123 Perugia, Italy

One of the main scientific objectives of the recent Fermi mission is investigating the origin of the unidentified gamma-ray sources (UGSs). Despite the large improvements of Fermi in the gamma-ray source localization with respect to the past gamma-ray missions, about 1/3 of the gamma-ray objects detected do not have yet an assigned counterpart at low energies. We recently developed a new association method to identify if there is a γ-ray blazar candidate within the positional uncertainty region of a generic γ-ray source. This method is entirely based on the discovery that blazars, the largest known class of gamma-ray sources, can be recognized and separated from other extragalactic sources on the basis of their infrared colors. Here we summarize the results obtained by applying our association procedure to the unidentified γ-ray sources (UGSs) and to the active galaxies of uncertain type (AGUs) listed in the Second Fermi Large Area Telescope (LAT) catalog.

1. Introduction

Unveiling the nature of the Unidentified Gamma-ray Sources (UGSs) [Abdo et al. 2009] is one of the biggest challenges in contemporary gamma-ray astronomy. In particular, according to the Second Fermi Large Area Telescope (LAT) catalog [2FGL; Nolan et al. 2012], ∼1/3 of the γ-ray detected sources are still unassociated with their low energy counterparts. A large fraction of the UGSs are likely to be blazars, the rarest class of active galaxies, because their emission dominates the γ-ray sky [e.g., Mukherjee et al. 1997, Abdo et al. 2010].

However, due to the incompleteness of the current radio and X-ray surveys on the basis of the usual γ-ray association method is not always possible to find the blazar-like counterpart of an UGS. Additional attempts have also been recently developed to associate or to characterize the UGSs using either pointed Swift observations [e.g., Mirabal & Halpern 2009; Mirabal & Halpern 2009] or statistical approaches [e.g., Mirabal et al. 2010; Ackermann et al. 2012].

Blazar emission is characterized by high and variable polarization, apparent superluminal motions, and high luminosities, coupled with a flat radio spectrum that steepens toward the infrared-optical bands and together with rapid flux variability at all frequencies [e.g., Urry & Padovani 1995]. Their broad band spectral energy distributions show two main components: the low-energy one with power peaking in the range from the IR to the X-ray band, and the high-energy showing its maximum in the MeV – TeV energy range [e.g., Giommi et al. 2003].

Blazars come in two flavors: the BL Lac objects, characterized by featureless optical spectra and lower luminosity with respect to the second class composed of flat-spectrum radio quasars showing quasar-like optical spectra [Stickel et al. 1991; Stokke et al. 1991]. In the following we label the BL Lac objects as BZBs and the flat-spectrum radio quasars as BZQs, following the nomenclature of the Multifrequency Catalogue of Blazars [ROMA-BZCAT, Massaro et al. 2009; Massaro et al. 2010; Massaro et al. 2011a].

On the basis of the preliminary data release of the Wide-field Infrared Survey Explorer [WISE, see Wright et al. 2010, for more details], we discovered that in the 3-dimensional IR color space γ-ray emitting blazars lie in a distinct region, well separated from other extragalactic sources whose IR emission is dominated by thermal radiation [e.g., Massaro et al. 2011a, D’Abrusco et al. 2012]. According to D’Abrusco et al. (2013) we refer to the 3-dimensional region occupied by γ-ray emitting blazars as the locus, to its 2-dimensional projection in the [3.4]-[4.6]-[12] μm color-color diagram still maintain its historical definition as the WISE Gamma-ray Strip.

This WISE analysis led to the development of a new association method to recognize γ-ray blazar candidates for the unidentified γ-ray sources listed in the 2FGL Massaro et al. 2012a; Massaro et al. 2012b], as well as in the 4th INTEGRAL catalog [Massaro et al. 2012a].

Here we present the results achieved by applying a more conservative approach and several improvements recently made on the association procedure [see...
D’Abrusco et al. 2013, for more details], mostly based on the availability of the WISE full archive \(^1\), available since March 2012 [see also Cutri et al. 2012]. We analyzed all the UGSs listed in the 2FGL as well as the sample of the active galactic nuclei of uncertain type (AGUs) that have still unclear classification [Nolan et al. 2012]. We also performed an extensive literature search looking for multifrequency information on the γ-ray blazar candidates selected on the basis of their WISE colors to confirm their nature.

We remark that a detailed description of our multifrequency analysis and of the association procedure adopted, together with the lists of γ-ray blazar candidates, is presented in details in Massaro et al. (2013) and D’Abrusco et al. (2013), while here we only highlight the major results achieved.

2. RESULTS

A new association method has been recently developed based on the discovery that γ-ray emitting blazars lie in a distinct region in the WISE 3-dimensional color space, separated from that occupied by other extragalactic and galactic sources [Massaro et al. 2011, D’Abrusco et al. 2012]. According to D’Abrusco et al. (2013) the 3-dimensional region occupied by γ-ray emitting blazars is the locus: its 2-dimensional projection in the [3.4]-[4.6]-[12] μm parameter space, retains its historical definition of WISE Gamma-ray Strip [Massaro et al. 2011]. Additional improvements, mostly based on the WISE all-sky data release, available since March 2012 [Cutri et al. 2012], and on a new parametrization of the locus in the parameter space of its principal components have been subsequently developed D’Abrusco et al. 2013.

Then we applied our new association procedure searching for new γ-ray blazar candidates in the two samples: the unidentified gamma-ray sources (UGSs), and the active galaxies of uncertain type (AGUs), as listed in the 2FGL [Nolan et al. 2012]. We also perform an extensive archival search to see if the sources associated with our method, show additional blazar-like characteristics; as, for example, the presence of a radio counterpart and/or of a spectrum that could be featureless as for BZBs or similar to those of broad-line quasars as generally occurs in BZQs.

We found 62 γ-ray blazar candidates for the UGSs without any γ-ray analysis flag and 49 for those with γ-ray analysis flag, out of a total of 590 sources investigated. For the AGU sample, we confirmed the blazar-like nature of 87 out 210 of AGUs analyzed on the basis of their IR colors. Figure 1 shows the 3-dimensional color plot comparing the IR colors of the selected γ-ray blazar candidates with the blazar population that constitutes the locus.

We searched in the following major radio, infrared, and X-ray surveys as well as in the NASA Extragalactic Database (NED) \(^2\) for possible counterparts of our γ-ray blazar candidates, selected with the WISE association method, to verify if additional information could confirm their blazar-like nature. For the radio counterparts we used the NRAO VLA Sky Survey [NVSS: Condon et al. 1998 - N], the VLA Faint Images of the Radio Sky at Twenty-Centimeters [FIRST; Becker et al. 1995, White et al. 1997 - F], the Sydney University Molonglo Sky Survey [SUMSS: Mauch et al. 2003 - S] and the Australia Telescope 20 GHz Survey [AT20G; Murphy et al. 2010 - A]; for the infrared we used the Two Micron All Sky Survey [2MASS; Skrutskie et al. 2006 - M] since each WISE source is already associated with the closest 2MASS source by the default catalog [see Cutri et al. 2012 for more details]. Then, we also searched for optical counterparts, with possible spectra available, in the Sloan Digital Sky Survey [SDSS; e.g. Adelman-McCarthy et al. 2008, Paris et al. 2012 - s], in the Six-degree-Field Galaxy Redshift Sur-

\(^1\)http://wise2.ipac.caltech.edu/docs/release/allsky/

\(^2\)http://ned.ipac.caltech.edu/
A significant fraction (i.e., \(\sim 36\%\)) of the WISE sources associated with our method with UGSs have a radio counterpart, more than 50% are also detected in the 2MASS catalog as generally occurs for blazars, and more than \(\sim 10\%\) appear to be variable according to the WISE analysis flags [Cutri et al. 2012]. Notably, more than 90% sources for which an optical spectrum was available in literature clearly show blazar-like features, being either featureless or having broad emission lines typical of quasars. As generally expected for \(\gamma\)-ray blazars a handful of the selected candidates are also detected in the X-rays. A deeper investigation of their X-ray counterparts will be addressed in a forthcoming paper [Paggi et al. 2013].

Our results are in good agreement with those based on different statistical approaches like the Classification Tree and the Logistic regression analyses [Ackermann et al. 2012]. In particular, 23 out of 28 UGSs that we associate to a \(\gamma\)-ray blazar candidate are also classified as active galaxies by the above methods at high level of confidence.

Finally, we emphasize that additional investigations of different samples of active galactic nuclei, such as Seyfert galaxies, are necessary to study the problem of the contamination of our association method by extragalactic sources with infrared colors similar to those of \(\gamma\)-ray blazars. Moreover extensive ground-based spectroscopic follow up observations in the optical and in the near IR would be ideal to verify the nature of the selected WISE sources and to estimate the fraction of non-blazar objects, similar to the recent studies performed for the unidentified INTEGRAL sources [e.g., Masetti et al. 2008, Masetti et al. 2009, Masetti et al. 2010, Masetti et al. 2012].

Acknowledgments

F. Massaro is grateful to S. Digel and D. Thompson for their helpful discussions and to M. Ajello, E. Ferrara and J. Ballet for their support. The work is supported by the NASA grants NNX12AO97G. R. D’Abrusco gratefully acknowledges the financial support of the US Virtual Astronomical Observatory, which is sponsored by the National Science Foundation and the National Aeronautics and Space Administration. The work by G. Tosti is supported by the ASI/INAF contract I/005/12/0. H. A. Smith acknowledges partial support from NASA/JPL grant RSA 1369566. TOPCAT\(^3\) [Taylor 2005] and SAOImage DS9 were used extensively in this work for the preparation and manipulation of the tabular data and the images. Part of this work is based on archival data, software or on-line services provided by the ASI Science Data Center. This research has made use of data obtained from the High Energy Astrophysics Science Archive Research Center (HEASARC) provided by NASA’s Goddard Space Flight Center; the SIMBAD database operated at CDS, Strasbourg, France; the NASA/IPAC Extragalactic Database (NED) operated by the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration. Part of this work is based on the NVSS (NRAO VLA Sky Survey); The National Radio Astronomy Observatory is operated by Associated Universities, Inc., under contract with the National Science Foundation. This publication makes use of data products from the Two Micron All Sky Survey, which is a joint project of the University of Massachusetts and the Infrared Processing and Analysis Center/California Institute of Technology, funded by the National Aeronautics and Space Administration and the National Science Foundation. This publication makes use of data products from the Wide-field Infrared Survey Explorer, which is a joint project of the University of California, Los Angeles, and the Jet Propulsion Laboratory/California Institute of Technology, funded by the National Aeronautics and Space Administration. Funding for the SDSS and SDSS-II has been provided by the Alfred P. Sloan Foundation, the Participating Institutions, the National Science Foundation, the U.S. Department of Energy, the National Aeronautics and Space Administration, the Japanese Monbukagakusho, the Max Planck Society, and the Higher Education Funding Council for England. The SDSS Web Site is http://www.sdss.org/. The SDSS is managed by the Astrophysical Research Consortium for the Participating Institutions. The Participating Institutions are the American Museum of Natural History, Astrophysical Institute Potsdam, University of Basel, University of Cambridge, Case Western Reserve University, University of Chicago, Drexel University, Fermilab, the Institute for Advanced Study, the Japan Participation Group, Johns Hopkins University, the Joint Institute for Nuclear Astrophysics, the Kavli Institute for Particle Astrophysics and Cosmology, the Korean Scientist Group, the Chinese Academy of Sciences (LAMOST), Los Alamos National Laboratory, the Max-Planck-Institute for Astronomy (MPIA), the Max-Planck-Institute for Astrophysics (MPA), New Mexico State University, Ohio State University, University of Pittsburgh, University of Portsmouth, Princeton Univer-

\(^3\)http://www.star.bris.ac.uk/~mbt/topcat/
sity, the United States Naval Observatory, and the University of Washington.

References


99