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Unveiling the Nature of *INTEGRAL* Objects: a Review

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Abstract

Since its launch in October 2002, the *INTEGRAL* observatory has improved our knowledge of the hard X-ray sky above 20 keV, carrying out more than ten years of observations in the energy range from 5 keV to 8 MeV. The most recently published *INTEGRAL*/IBIS surveys listed more than seven hundred sources in the 20-100 keV band. Most of these objects are either Active Galaxies (AGNs) or X-ray binaries; a fraction of both classes is made of highly absorbed sources, often associated with dim optical counterparts. Despite the big effort in the identification process, a large part of these IBIS objects (∼25% of them) still remains unclassified. Cross-correlation with archival catalogues and/or multiwaveband follow-up observations are of invaluable help to identify and properly classify this unknown objects, but only optical or IR spectroscopy with ground based telescopes in the Northern and Southern Hemisphere can reveal the real nature of these objects. In this work we report on source types that we find among the unidentified objects in the most recent *INTEGRAL* surveys.

Keywords: galaxies: Seyfert - X-ray binaries - techniques: spectroscopic.

1 Introduction

One main objective of the *INTEGRAL* mission is a regular survey of the entire sky in the hard X-ray band. This makes use of the unique imaging capability of the IBIS instrument (Ubertini et al. 2003) which allows the detection of sources at the mCrab level with a typical localization accuracy of a few arcmin. During the first 5 years of its life, the observatory concentrated mainly on a deep exposure of the Galactic central radian, regular scans of the Galactic plane, pointed observations of the Vela region, and Target of Opportunity follow up observations. Through the IBIS imager, optimized for survey work with excellent imaging and spectroscopy capability, catalogs devoted either to the Galactic Plane Scan (GPS) or to the improvement of the extragalactic coverage were published. Up to now, IBIS detected more than 700 sources in the hard X-rays between 20 and 100 keV (Bird et al. 2010, Krivonos et al. 2010, 2012), and $\sim 30\%$ had no obvious counterpart at other wavelengths and therefore cannot yet be associated with any known class of high-energy emitting sources. Comparisons with catalogues or surveys at other frequencies (especially soft X-rays, optical, infrared and radio) are of invaluable help in reducing the localization uncertainty of these IBIS sources from arcminutes down to a few (< 10) arcseconds, thus making the search for their optical or IR counterparts much easier. Once this is done, then spectroscopic follow up observations provide a classification of the source, a confirmation of the proposed association and the study of that source individually or at population level.

Thanks to the above method, many new hard X-ray sources have been studied for the first time, including new classes of Galactic objects, such as absorbed High Mass X-ray Binaries (HMXB see Walter 2007), Supergiant Fast X-ray Transients (SFXT, e.g., Sguera et al. 2005, 2006; Leyder et al. 2007), magnetic cataclysmic variables (CVs; Barlow et al. 2006; Bonnet-Bidaud et al. 2007; Landi et al. 2008) and Symbiotic X-ray binaries (SyXBs); in the extragalactic sky, a higher percentage of absorbed Active Galactic Nuclei (AGNs) were reported compared to softer (2-10 keV) surveys, including a few new nearby Compton thick objects (Malizia et al. 2009), systematically pinpointing, for the first time, extragalactic sources in the so-called 'Zone of Avoidance', which hampers observations in soft X-rays and optical along the Galactic plane due to the presence of gas and dust. All of these objects were classified by means of intensive optical and IR spectroscopic campaigns at various telescopes located worldwide.

2 Surveys

Through hard X-ray surveys we can obtain all-sky maps of the celestial high-energy emission and study catalogues of sources unbiased in term of absorption and which are capable of producing non thermal emission processes, or being the site of the most extreme astrophysical phenomena observed in the Universe. The most recent *INTEGRAL*/IBIS surveys are that of Bird et al. (2010) and Krivonos et al. (2010, 2012):

- The 4th IBIS survey (Bird et al. 2010) collected data from November 2002 to October 2008 for ∼80 Ms of exposure in the 20-100 keV energy range and produced a catalogue of 723 sources (29% unidentified) ;

- The IBIS 7-years all-sky hard X-ray survey (Krivonos et al. 2010) collected data from December 2002 to July 2009 for ∼80 Ms of exposure in the 17-60 keV energy range and found 521 sources (12% unidentified);

- The 9-year Galactic hard X-ray survey (Krivonos et al. 2012) collected data from December 2002 to January 2011 for 132 Ms of exposure in the 17-60 keV energy range and reported 402 sources (9% unidentified).

3 Identification Method

In the second semester of 2004 we started an optical spectroscopy campaign performed at ground based telescopes of the Northern and Southern hemisphere to identify unknown hard X-ray sources detected by INTEGRAL (Masetti et al. 2004, 2006a,b,c,d, 2007, 2008a,b, 2009, 2010, 2012, 2013), and we selected unidentified or unclassified hard X-ray sources that contain, within the IBIS 90% confidence level error box, a single bright X-ray object detected either in the ROSAT all-sky surveys (Voges et al. 1999, 2000), or in the Slew Survey (Saxton et al. 2008) and/or in the Serendipitous Source Catalog (Watson et al. 2009) of XMM-Netwon, or having pointed observations either from Chandra, Swift/XRT or XMM-Netwon satellites. This approach was proven by Stephen et al. (2006) to be very effective in associating, with a high degree of probability, IBIS sources with a softer X-ray counterpart, in turn drastically reducing the positional error circles to better than a few arcsec in radius, making the search area smaller by a factor of 10^4. Taking into account the hard X-ray characteristics and the global properties of the sources, such as the position in the sky, the 20-100 keV light curve and the broad band spectrum, we can have some clues about their nature. After this first selection, we chose among these objects those that had, within their refined 90% confidence level soft X-ray error boxes, a single possible optical counterpart with magnitude R < 20 in the DSS-II-Red survey, so that optical or IR spectroscopy could be obtained with reasonable signal-to-noise ratio using medium-sized telescopes (i.e. with diameter up to 4 meters; Masetti et al. 2004, 2006a,b,c,d, 2007, 2008a,b, 2009, 2010, 2012, 2013).

4 Galactic Sources

Many important results from the INTEGRAL mission have been obtained in the observations of the Galactic sources. Specifically, they have shown the existence of a new class of heavily absorbed X-ray binaries and of the SFXTs, doubling the number of known HMXBs and allowed the detection of a substantial number of new magnetic CVs.

4.1 CVs

CVs are close binary systems consisting of a late-type (i.e. red dwarf) star trasferring material onto a white dwarf (WD) via Roche lobe overflow. Those which have a magnetic field are called magnetic CVs and fall into two categories:

- Polar CVs have a strong magnetic field (B > 10^7 G); their accretion does not occur via accretion disc and the accreting material is channeled by the magnetic field along its lines and falls on the magnetic poles of the WD;

- Intermediate polars (Warner 1995), instead, have a weaker magnetic field (B $\sim 10^6 - 10^7$ G) that truncates the accretion disc in the inner region close to the magnetosphere, resulting in an accretion curtain, where the accreting material follows the magnetic field lines down to the WD poles.

If the WD is not magnetic the accreting material flows towards the WD through an accretion disc.

Up to now the CVs detected by *INTEGRAL* are 35 (∼ 80% are magnetic, mostly Intermediate Polars), and 29 of these have been identified through optical or NIR spectroscopy. This is an important result, if we consider that before *INTEGRAL* very few CVs have been detected at high energies. Fig. 1 shows the CVs distribution in the sky (white filled circles superimposed on an IBIS 20-100 keV image).

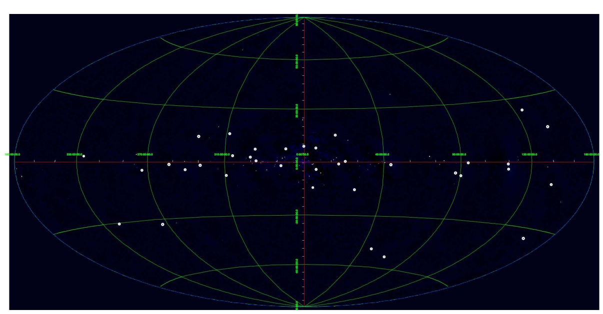

Figure 1: Distribution of CVs (white filled circles) in the 20-100 keV sky imaged by IBIS.

4.2 Low Mass X-ray Binaries

Low Mass X-ray Binaries (LMXBs) are systems consisting of an accreting compact object (neutron star or black hole) and a low-mass (< 1 $M_{\odot}$) main-sequence or slightly evolved late-type star. The low mass companion fills and overflows its Roche lobe, therefore accretion of matter always occurs through the formation of an accretion disc. Up to now $\sim$ 100 LMXBs have been detected by *INTEGRAL*, and only 15 have been classified through optical or NIR spectroscopy, this means that almost all the LMXBs have been detected and very few are found among unidentified INTEGRAL sources. In Fig. 2 we report the LMXBs distribution (white filled circles superimposed on an IBIS 20-100 keV image): it is clear that they lie in the Galaxy bulge or in globular clusters, where we the majority of old stellar populations are located.

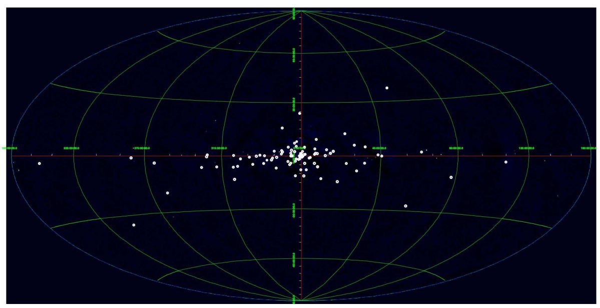

Figure 2: Distribution of LMXBs (white filled circles) in the 20-100 keV sky imaged by IBIS. They are segregated in the Galactic bulge and in Globular Clusters.

4.2.1 Symbiotic X-ray binaries

Three of the LMXBs spectroscopically identified among unidentified objects are Symbiotic X-ray stars (SyXBs). They are part of a small subclass of LMXBs in which the compact object (generally a neutron star), receives matter from a red giant rather than from a late-type companion star on the main sequence. Compared to LMXBs they show an optical continuum typical of a red giant of M spectral type, with Balmer series generally in absorption (of the 7 SyXBs known only one, GX 1+4, shows H_{α} in emission, because the donor star is a red supergiant star that fills its Roche lobe, accreting matter via accretion disc) and with the presence of absorption bands, and matter is accreted via stellar wind from the donor star.

4.3 HMXBs

The Galactic Plane scans performed with *INTEGRAL* revealed a wealth of new HMXBs. These binary systems are composed of a compact object (neutron star or black hole) orbiting and accreting matter from a luminous early spectral type OB high mass (> 10 $M_{\odot}$) companion star. HMXBs have different ways to accrete matter:

- Via Roche lobe overflow, but we know only very few cases of this type;
- Star with a circumstellar disc: the compact objects with a wide eccentric orbit crosses the decretion disc produced by a rapidly rotating Be III/IV/V star, producing accretion through stellar wind;
- A massive star (supergiant I/II star) ejects a fast and dense radially outflowing wind, and the compact object directly accretes from it.

Up to now $\sim$ 90 HMXBs have been detected by *INTEGRAL*; of these, 45 were identified through optical or NIR spectroscopy. This class of objects is distributed along the galactic plane (see Fig.3). If we also consider the HMXBs distances, we note that they closely trace the underlying distribution of the massive star-forming regions that are expected to produce the progenitor stars of HMXBs (Bodaghee et al. 2012).

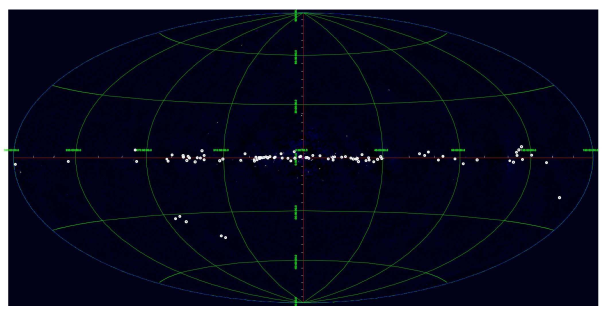

Figure 3: Distribution of HMXBs (white filled circles) in the 20-100 keV sky imaged by IBIS. They lie along the Galactic plane.

4.3.1 SFXTs

This is a new class of transient HMXBs discovered by *INTEGRAL*. The SFXTs host a massive blue supergiant star (OB) and a compact object, mainly a neutron star. They have fast X-ray flares, from few hours to few days duration, with luminosity of $\sim 10^{36}$-10^{37} erg s^{-1}; they also have short duty cycles ($T_{inflare}/T_{total}$=0.05% - 3%) The accretion mechanism is not clear yet. There are different scenarios, such as the clumpy wind (Negueruela et al. 2008, Ducci et al. 2009) or the centrifugal/magnetic barrier (Bozzo et al. 2008). The clumpy wind scenario has two possible configurations: a neutron star orbiting a supergiant star on a circular orbit, or on an eccentric orbit, accreting from the clumpy stellar wind of the supergiant. In the centrifugal/magnetic barrier scenario, a magnetic barrier or a centrifugal barrier can sets in, and according to the spin period and the strength of the magnetic field of the neutron star, it can cause or not the inhibition of accretion. Up to now the SFXTs optically or NIR identified are ∼10 and other ∼10 are candidates.

5 Extragalactic Objects

The *INTEGRAL* satellite has been able to obtain also important results in the field of extragalactic objects. Observations are giving fundamental insights into the study of AGNs located in the Zone of Avoidance along the Galactic Plane (see Fig. 4 for the AGNs distribution in the sky) but also positioned across the whole sky.

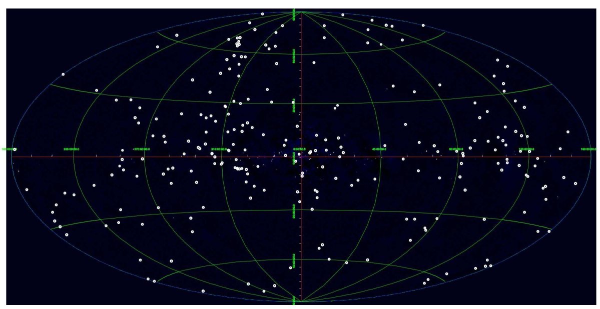

Figure 4: Distribution of AGNs (white filled circles) in the 20-100 keV sky imaged by IBIS. This is an IBIS 20-100 keV image.

5.1 Seyfert galaxies

The most common extragalactic objects detected by *INTEGRAL* are Seyfert galaxies; their luminosity ranges from 10^{42} to 10^{45} erg s^{-1}, they are located in the nearby universe (z < 0.5) and have an optical spectrum characterized by emission lines. All the Seyferts show narrow high ionization emission lines, such as [OIII] or [NII] forbidden emission lines. Some show broad permitted lines in emission (generally Balmer series), suggesting the presence of a dense and fast moving gas: we call these Seyfert 1 galaxies. In these objects, according to the Unified Model, our line of sight intercepts both broad line regions and narrow line regions. Those AGNs with only narrow emission lines are instead named Seyfert 2 galaxies. According to the Unified model, in these sources our line of sight intercepts only the narrow line region due to the presence of a torus which hides the broad line region. These gas and dusty regions are photoionized by the central engine; BLRs are confined to sub-pc scales around an accretion disk, producing kinematically broadened emission lines with typical velocities of 10^3–10^4 km s^{-1}, NLRs are characterized by narrow-lines with typical velocities of 10^2–10^3 km s^{-1} and can span over kpc scales, which are comparable to the size of the bulge or even the entire galaxy. Up to now 148 AGNs detected by *INTEGRAL* have been identified through optical and NIR spectroscopy. In particular, 68 AGNs are Seyfert 1, while 55 are Seyfert 2 galaxies.

5.1.1 Narrow-line Seyfert 1

These galaxies are peculiar Seyfert 1 AGNs (Osterbrock & Pogge 1985) with a full width at half maximum (FWHM) of the H_β emission line smaller than 2000 km s^{-1}, with permitted lines which are only slightly broader than the forbidden ones, with a $[OIII]_{5007}/H_\beta$ ratio < 3, and finally with evident FeII and other high-ionization emission-line complexes (e.g. see Fig. 5). A few NLS1 galaxies have been discovered so far by INTEGRAL and recognized as such by optical spectroscopy.

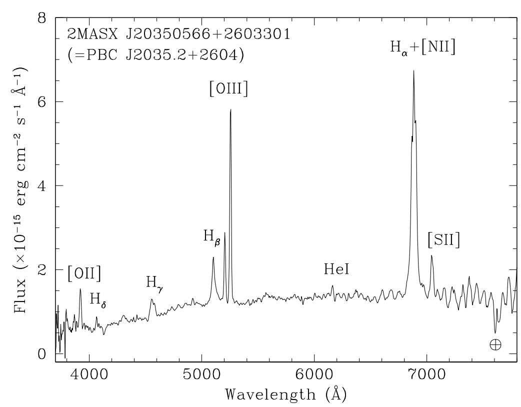

Figure 5: Optical spectrum (not corrected for the intervening Galactic absorption) of a typical Narrow-line Seyfert 1. The main spectral features are labeled.

5.2 Low ionization nuclear emission-line regions

Low ionization nuclear emission-line regions (LINERs; Heckman 1980) are peculiar AGNs with a level of activity much smaller than that in classical AGNs and in which some low-ionization lines ($[OII]_{3723}$, $[OI]_{6300}$, and $[NII]_{6584}$) are stronger than in typical Seyfert 2 galaxies; the permitted emission-line luminosities are weak; and the emission-line widths are comparable with those of type 2 AGNs (see Fig. 6). According to Heckman (1980), LINERs have $[OII]_{3723} > [OIII]_{5007}$ and $[OI]_{6300} > 1/3\ [OIII]_{5007}$, and often $[NII]_{6584}/H_\alpha > 0.6$.

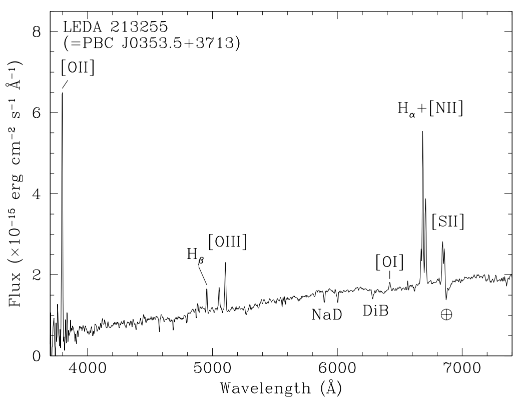

Figure 6: Optical spectrum (not corrected for the intervening Galactic absorption) of a typical LINER. The main spectral features are labeled.

5.3 X-ray bright optically normal galaxies

Some *INTEGRAL* objects show a continuum typical of a normal galaxy, dominated by absorption lines due to star forming regions, they are X-ray bright, optically normal galaxies (XBONGs; Comastri et al. 2002), that is, X-ray bright galactic nuclei with no emission lines in their optical spectra (e.g. Fig. 7).

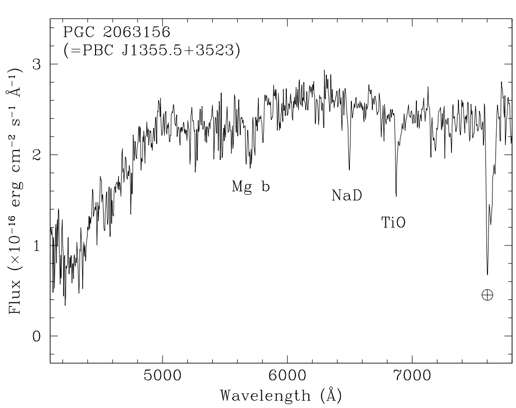

Figure 7: Optical spectrum (not corrected for the intervening Galactic absorption) of a typical XBONG. The main spectral features are labeled.

5.4 Blazars

Using medium-sized telescopes (i.e. TNG, ESO), we are also able to identify and classify sources at high redshifts (> 0.6) detected by *INTEGRAL*. They are Blazars, distant and powerful AGNs which are oriented in such a way that a jet expelled from the central black hole is directed at small angles with respect to the observers line of sight.

An example is IGR J12319-0749 a powerful blazar at z = 3.12 (Masetti et al. 2012), the farthest optically-identified object of any *INTEGRAL* survey and the second furthest of all objects detected by *INTEGRAL*.

6 Summary and Conclusions

Up to now 273 *INTEGRAL* objects have been identified and classified through optical and NIR spectroscopy using ground-based telescopes of the Northern and Southern Hemisphere. Of these objects, 62% are AGNs, 36% are X-ray Binaries and the remaining 2% are chromospherically active stars. Going into details, of the 62% AGNs, 27.8% are Seyfert 1 galaxies, 22% are Seyfert 2 AGNs, 8.5% QSOs, 2.9% XBONGs and 1.1% are other sources. Among the Galactic sources (36%), we found that 18% are HMXBs, 12.5% are CVs and 5.5% are LMXBs.

The IBIS surveys secured the detection of extragalactic sources in the so-called Zone of Avoidance, which hampers observations in soft X-rays along the Galactic Plane due to the presence of gas and dust. Moreover, these surveys are expanding our knowledge about Galactic X-ray binaries, by showing the existence of a new class of heavily absorbed supergiant massive X-ray binaries (first suggested by Revnivtsev et al. 2003), by allowing the discovery and the study of supergiant fast X-ray transients (e.g., Sguera et al. 2005, 2006; Leyder et al. 2007), by doubling the number of known HMXBs (see Walter 2007), and by detecting a substantial number of new magnetic CVs. Indeed, the new IBIS catalogue (in progress) will offer new spectral and timing information on newly detected sources and an insight on peculiar ones, giving us the unique opportunity to discover new HMXBs and understand the differences among them.

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DISCUSSION

PIETER MEINTJES: The novalike cataclysmic variable AE Aquarii has been detected by Suzaku above 10 keV, showing evidence of non-thermal emission. Has it been detected by Integral as well?

PIETRO PARISI: The cataclysmic variable AE Aquarii has not been observed by *INTEGRAL*.