

Hard X-Ray sources observed by INTEGRAL/IBIS and their science

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ABSTRACT

After more than 5.5 years of in flight lifetime, the ESA space observatory INTEGRAL is depicting a new scenario in the soft gamma Ray domain. With the observation and discovery of more than 400 hard X-Ray sources has changed our view of a moderately crowded and dark sky basically populated by "peculiar" and erratic sources. The new high energy sky is also composed by a large variety of "normal" though very powerful objects, characterized by new accretion and acceleration processes. Among the 421 sources detected in the energy range 17-100 keV the 3rd INTEGRAL/IBIS catalogue includes 41% galactic accreting system, 29% extragalactic objects, 8% of other types, and 26% not classified i.e. of unknown origin. If compared to previous IBIS/ISGRI surveys it is clear that there is a continuous increase of the rate of discovery of HMXB, an increase in the number of AGN discovered, including a variety of distant QSOs, basically due to the increased exposure away from the Galaxy Plane, while the percentage of sources without an identification has remained constant. INTEGRAL, by the end of Y6, will complete the Core Programme observation due to provide an almost constant exposure of the whole Galaxy Plane and will be fully open to the scientific community for Open Time and Key Programme observations from the beginning of 2009. In this paper we shortly review the main outcome of the 3rd INTEGRAL/IBIS catalogue (cat3) including an excursus of the INTEGRAL high energy sky with particular regard to sources emitting at high energy, including Low and High Mass X-Ray Binaries (LMXB & HMXB), Supergiant Fast X-Ray Transients (SFXT), Pulsar Wind Nebulae (PWN) and Active Galactic Nuclei (AGN).

KEY WORDS: Subject headings: Gamma-rays, observations, surveys

1. INTRODUCTION

The INTEGRAL ESA gamma-ray observatory has already carried out more than 5 years of Core, Key and Guest Observer Programme observations in the energy range from 5 keV - 10 MeV (Winkler et al. 2003). The IBIS coded mask imager is optimised for scientific observations over a wide field of view (~ 1000 squared degree) with excellent imaging and spectroscopy capability (Ubertini et al. 2003), to provide survey type data, including detailed images of the whole sky, time profile and spectra of all the sources detected with a sensitivity better than 1 mCrab in the central radian.

2. The INTEGRAL Observatory

The ESA INTEGRAL (International Gamma-Ray Astrophysics Laboratory) observatory was selected in June 1993 as the next medium-size scientific mission within ESA Horizon 2000 programme. INTEGRAL (Winkler et al. 2003), shown in Figure 1, is dedicated to the fine spectroscopy (2.5 keV FWHM @ 1 MeV) and fine imaging (angular resolution: 12 arcmin FWHM) of celestial gamma-ray sources in the energy range 15 keV



Fig. 1. The INTEGRAL Observatory (ESA Courtesy).

to 10 MeV. While the imaging is carried out by the imager IBIS (Ubertini et al. 2003), the fine spectroscopy is performed by the spectrometer SPI (Vedrenne et al. 2003) and coaxial monitoring capability in the X-ray (3-35 keV) and optical (V-band, 550 nm) energy ranges is provided by the JEM X and OMC instruments (Lund et al. 2003; Mass-Hesse et al. 2003). SPI, IBIS and Jem-X, the spectrometer, imager and X-ray monitor are based on the use of coded aperture mask technique that is a key feature to prove images at energy above tens

of keV, where photons focusing become impossible using standard grazing technique. Moreover, coded mask feature the best background subtraction capability because of the possibility to observe at the same time the Source and the Off-Source sky. This is achieved at the same time for all the sources present in the telescope field of view. In fact, for any particular source direction, the detector pixels are split into two sets: those capable of viewing the source and those for which the flux is blocked by opaque tungsten mask elements. This very well established technique is discussed in detail by (Skinner & Connell 2004) and is extremely effective in controlling the systematic error in all the telescope observation, working remarkably well for weak extragalactic field as well for crowded galactic regions, such as our Galaxy Center. The mission was conceived since the beginning as an observatory led by ESA with contributions from Russia (PROTON launcher) and NASA (Deep Space Network ground station). INTEGRAL was launched from Baikonur on October 17th, 2002 and inserted into an highly eccentric orbit (characterized by 9000 km perigee and 154000 km apogee). The high perigee in order to provide long uninterrupted observations with nearly constant background and away from the electron and proton radiation belts. Scientific observations can then be carried out while the satellite being above a nominal altitude of 60000 km, while entering the radiation belts, and above 40000 km, while leaving them. This strategic choice ensure about 90% of the time is used for scientific observations with a data rate of realtime, 108 kbps science telemetry received from the ESA station of Redu and NASA station of Goldstone. The data are received by the INTEGRAL Mission Operation Centre (MOC) in Darmstadt (Germany) and relayed to the Science Data Center (Courvoisier et al. 2003) which provide the final consolidated data products to the observes and later archived for public use. The proprietary data become public one year after distribution to single observation PIs.

3. The INTEGRAL/IBIS sky

3.1. The Catalogue

In order to give maximum access to the whole scientific INTEGRAL/IBIS data set a catalogue, comprising all the detected high energy sources is generated roughly on an annual basis (Bird et al, 2004, 2006, 2007). The last of them (the 3rd, namely THE 3rd IBIS/ISGRI SOFT GAMMA-RAY SURVEY CATALOG) has been produced using all the IBIS data available up the end of May 2006 (40 Ms exposure time). It contains 421 sources, detected above 4.5σ in the energy range 18-100 keV; in Figure 2 is shown the distribution of the sources (top panel) and the INTEGRAL/IBIS Sky coverage evolution as per cat 1, 2 and 3; the bottom panel on the right is the coverage at the end of Y5. As expected the

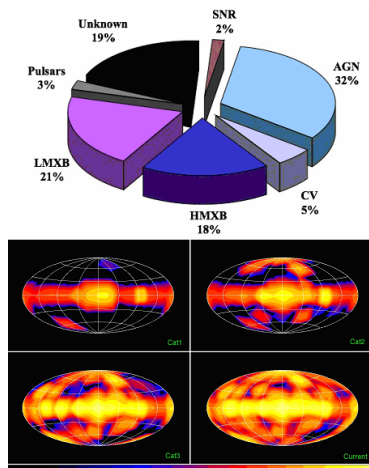


Fig. 2. Top: distribution of the high energy sources of the 3rd IBIS Catalogue: for each source is also produced the spectrum and the light curve. Bottom: IBIS Sky coverage evolution vs time.

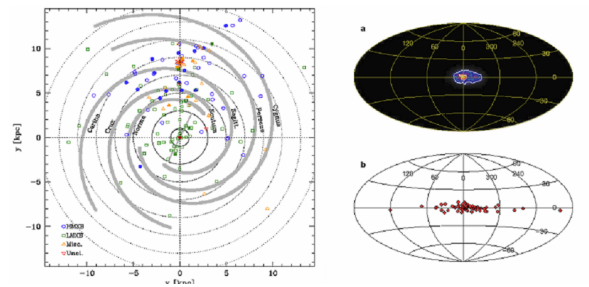


Fig. 3. Left: distribution of IBIS sources in the Galaxy. Right-top: discovery of asymmetric distribution of positron 511 keV annihilation in the Galactic disk. Right-bottom: IBIS LMXB distribution.

majority of the IBIS sources are located at low galactic latitudes, due to the basic fact that INTEGRAL is frequently observing in the Galactic Plane and the sky coverage is far for uniform, as shown in Figure 2. The source identification process is based on a multi wavelength approach, taking into consideration the Radio, IR, X-ray and higher energy archival data. A robust programme of optical and IR observation campaigns has been activated just after the INTEGRAL launch and had been very successful (Masetti et al. 2006a,b,c,d and 2008). Among the sources that have been firmly identified are 171 associated with galactic binary accreting systems (41%), 122 are extragalactic sources (29%), 15 belong to different classes of high energy emitters. As many as 113 (26%) are still not identified. The sources belonging to our Galaxy are sub-divided into 21 CV systems (9 of which are new detections with emission extending up to 100keV), 65 high-mass X-ray binaries (HMXB) and 78 low-mass X-ray binaries (LMHB). IBIS continues to detect Low Mass systems X-Ray Binaries even if the rate of discovery is much lower than for the high mass systems.

In particular, the High Mass Binary includes 19 new IBIS sources which have been identified with Be systems on the basis of their spectral characteristic and/or transient behavior. A distinct type of new objects, increasing regularly in the INTEGRAL/IBIS sample are the Super Giant fast X-ray transient (SFXT). Apart from the detailed and unbiased study related to the IBIS/ISGRI catalogue production several outstanding studies and results of wide astrophysical interest have been carried out with INTEGRAL/IBIS. An overview, even if superficial, is behind the scope of this short overview. Just as an example in Figure 3 (left panel) is shown the distribution of the IBIS sources in the Galaxy: circles are HMXB, squares are LMXB, triangles are Miscellaneous and inverted triangles are unclassified sources (Bodaghee et al., 2007). Of complete different nature the discovery of asymmetric distribution of positron annihilation in the Galactic disk based on the SPI outstanding spectroscopic capability and IBIS high angular resolution (Weidenspointner et al., 2008) as shown in Figure 3 (left panel): the IBIS LMXB distribution; (right panel) the SPI 511 keV emission. This result clearly demonstrate the SPI-IBIS complementarity.

3.2. The IBIS sky: $E > 100$ keV

The data accumulated with INTEGRAL/IBIS at energies above 100 keV in the first 3.5 years of operative life, have been discussed in Bazzano et al. (2006). This data set provided the first IBIS sources catalog characterised by very hard spectral components, listing 49 sources detected with a significance above 4 in the 100-150 keV energy range of which only 14 seen above 150 keV. Black Holes and accreting Neutron Stars systems mainly populate the high energy sky but extragalactic source are also contributing with 20% of the sample. In the higher energy range (>150 keV) the main emitting sources are Black Hole candidates/microQSOs. A larger sample is due to be finalized and the sample consist now of about 100 sources. All classes are included with the majority being galactic sources. The IBIS sample is consistent with the SPI resolved point sources in the 100-200 keV band (Bouchet et al., 2008). Also, an indication of the possible association between the the observed asymmetry in the 511 keV line emission from the galactic disk with X-ray Binary, mainly LMXB, has been suggested by Weidenspointner et al., 2008 (cfr paragraph 3.1). It was also noticed by the same author that similar asymmetry is derived when taking into account the LMXB distribution as from the 3rd IBIS catalog above 20 keV (Bird et al., 2007) and even more evident when using the sources above 100 keV. Finally, in Figure 4 is shown the AGILE High Energy Sky for $E > 100$ MeV (Tavani et al. 2008), dominated by the Disk diffuse emission (left) and the IBIS soft gamma Ray sky, $E > 20$ keV, dominated by discrete sources (right).

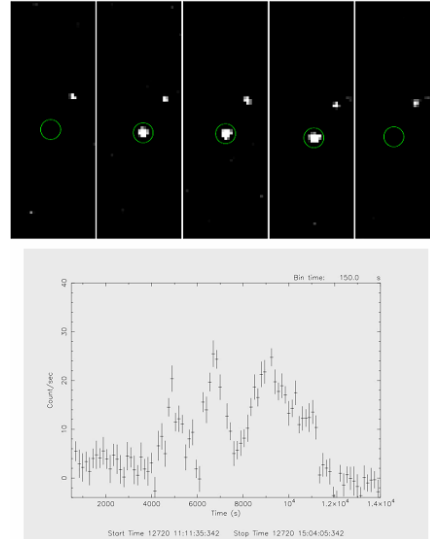


Fig. 5. Short time variability of XTE J1739-302.

3.3. The keV to TeV connection

Another significant class of sources strongly emitting in the soft gamma-ray range as well as at very high energies ($> \text{TeV}$) are the Pulsar and Pulsar Wind Nebulae (PWN). While there is no room in this short paper to properly address this topic, it is worth to mention that IBIS has detected more than 10 of those high energy sources, most of them associated with HESS/MAGIC high energy gamma ray emission (For a comprehensive review see Aharonian et al. 2005, Albert et al., 2007, Malizia et al. 2005, Ubertini et al. 2005, Dean et al. 2008, Ubertini et al., 2008 and references therein).

3.4. FXT sources and Supergiant HMXB

One of the two new class of high energy emitters discovered by INTEGRAL belong to the category of Fast Transient X-Ray sources (FXT), the other one correlated with strongly absorbed binary NS of which J16318-4848 is the archetype (Walter et al., 2006). Even if one of the most common characteristics of the high energy sky is the source variability (from ms to Ms), very little was known before the INTEGRAL launch on the class of sources that were identified as FXT. The basic information available were correlated with their location, off the Galaxy plane, and their seldom large outbursts lasting less than a day. The only un-biased survey of those class of objects was performed by BeppoSAX with the Wide Field Camera detectors, taking advantage of their large field of view ($2 \times 40 \times 40$ squared degree looking at 180 degree each other) and the total mission span along more than 6 years. BeppoSAX detected almost 50 different objects that exhibited a bimodal distribution in their duration. The first type is now known to be associated with the so-called X-Ray flashes, connected with

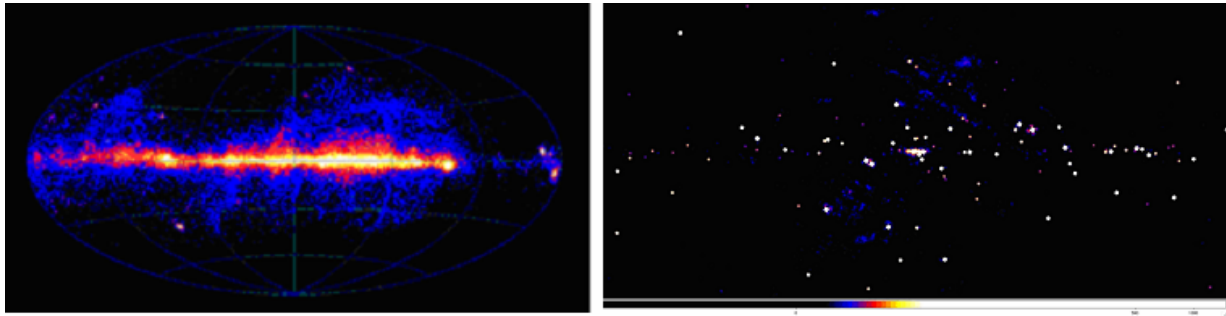


Fig. 4. The AGILE, $E > 100$ MeV, High Energy Sky, dominated by the Disk diffuse emission (left) and the IBIS soft gamma Ray sky, $E > 20$ keV, dominated by discrete sources.

Gamma-ray bursts type event (D’Alessio et al., 2006) and the second one, connected with active coronal star. More recently, INTEGRAL has changed the BeppoSAX scenario, thanks to the extended high energy response of the IBIS telescope, via the discovery of the so-called Supergiant Fast X-Ray Transient (Sguera et al., 2005, 2006, 2007, 2008; Neguerela et al., 2006). This new class of high energy emitters, SFXTs, has been optically identified with HMXB hosting an early type supergiant star. The surprise was that this kind of classical Supergiant HMXB (called SGXBs), discovered more than 40 years ago, were known to be persistent X-ray emitters with an emission ranging from $10^{36} - 10^{38} \text{ erg s}^{-1}$. In fact, the SFXTs have a quiescent luminosity from 1000 to 1000,000 times smaller and therefore undetectable most of the time with current X-Ray monitoring experiment. Conversely, they occasionally have fast X-ray activity lasting from hours to a day (or more) with peak luminosity of the order of $10^{36} - 10^{37} \text{ erg s}^{-1}$. INTEGRAL revealed flares characterized by short duration peaks (ten of minutes) and steep spectra above 20 keV, with photon power law index between 2-3. Alternatively, the spectra can be fitted with thermal bremsstrahlung models (kT comprised between 10 and 35 keV). In Figure 5 (top panel) is shown a ”classical” detection of the IBIS telescope: the images are related to the detection of a fast X-ray outburst of XTE J1739–302 in the energy range from 20 to 30 keV. Each panel has a duration of about 2000s and the source is visible only in the 3 central panel, for a total flare duration of less than one hour. In the first and last half hour observation is well below the flux at the peak and was not detected at all. The stable serendipity source in the top part of the image is the BHC 1E 1740.7-2942. In the right panel is shown the IBIS/ISGRI light curve integrated over the energy range from 20 to 60 keV (Sguera et al., 2005). The emission processes responsible for the very low stable emission from SFXTs and the short hysteric flares are probably explained by very wide

eccentric orbit (with a much longer period than classical SGXBs ~ 15 days) and in turn, with a low amount of wind material available to accretion onto the compact companion. When the collapsed star is closer to the supergiant donor star, highly inhomogeneous, structured, wind clumps accretion can become efficient and hence flares detectable by INTEGRAL in the soft gamma ray range (Negueruela et al., 2005, In’t Zand 2005). This scenario implies a periodicity of the fast outbursts as they should occur always relatively close to the periastron passage, but to date periodicity has been observed only from one source: IGR J11215–5952, with a period of ~ 330 days (Sidoli et al., 2006, Romano et al., 2007). In the light of these new and exciting INTEGRAL results, the size of the population of SGXBs in our Galaxy could have been severely underestimated. An entire population of still undetected SFXTs could be hidden in our Galaxy, on top the 8 firm source already discovered. Ongoing observations with INTEGRAL are expected to provide new SFXTs discovery and permit a breakthrough in our understanding of the physical processes behind their fast X-ray transient behavior.

3.5. The extragalactic IBIS sky

The INTEGRAL observing programme has been initially focused on the Galaxy plane scanning and deep observation of the Galaxy center. In recent years more attention has been dedicated to the observation of the extragalactic sky, with particular attention to obtain a substantial number of deep extragalactic field via the so-called Key Programmes. The result is that from the third IBIS survey (Bird et al. 2007) has provided a significant improvement in the detection of extragalactic objects due to the larger sky coverage available and deep observations ($> 2-5$ Ms). One of the main task was to have a better high energy picture of the close Universe, i.e. the one amenable for a ”complete sample” observation with IBIS. In fact, quantifying the AGNs missing fraction

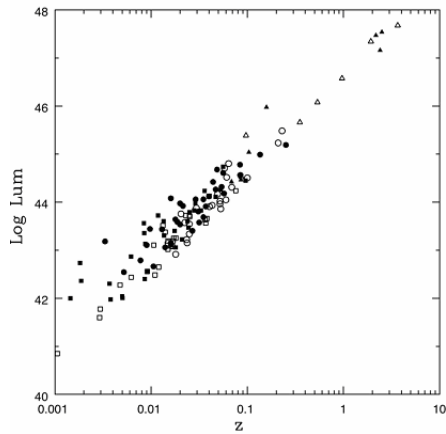


Fig. 6. Lum vs z for the IBIS AGN sample.

due to absorption (especially in the classical X-Ray band Surveys) is necessary to fully understand the accretion evolution of the Universe (Bassani et al., 2007a). This is also a fundamental issue to understand the contribution of AGNs to the X-ray cosmic diffuse background (Churazov et al., 2008) and in order to test the current unified theories. This is only possible with a good knowledge of the spectral shape and column density distribution of the detected AGNs. Clearly, high energy observations, above 10 keV, are necessary to obtain an unbiased measurement of the column densities and of the high energy cut-off distributions of AGNs in the local Universe. Recently, this has been possible thanks to the extragalactic INTEGRAL/IBIS deep exposure and by the All Sky monitoring from SWIFT/BAT (Gehrels et al., 2004) providing new complementary information on hard X-Ray emitting AGNs. The list of cat3 AGNs has been obtained by the use of a large number of identification and classification being provided through optical spectroscopy and catalogue searches. Within the sample of optically classified objects (Masetti et al., 2006 a,b,c,d, 2008) about 120 are Seyfert galaxies and 13 are blazars; within the Seyfert sample 58 objects are AGN of type 1-1.5 (circles in Figure 6) while are 60 type 2 (squares), i.e. a ratio 1:1, which illustrates the power of gamma-ray surveys to find narrow line AGN and 13 are blazars (triangles), with about 10% of the sample being radio loud objects. The range of redshift probed by our sample is 0.001-3.668 while the 20-100 keV luminosities span from 10^{41} to 10^{48} erg s^{-1} . This, in turn, establish the limit sensitivity of the cat3 Survey, i.e. about 1.5×10^{-11} $\text{erg cm}^2 \text{ s}^{-1}$. This limit is improving with time in view of the largest exposure for extragalactic fields and the basic insensitivity of the IBIS observation to systematic error. The closest object detected is the Seyfert 1.8 galaxy NGC4395 with a $z=0.001$ (Panessa et al. 2006) and IGR J22517+2218

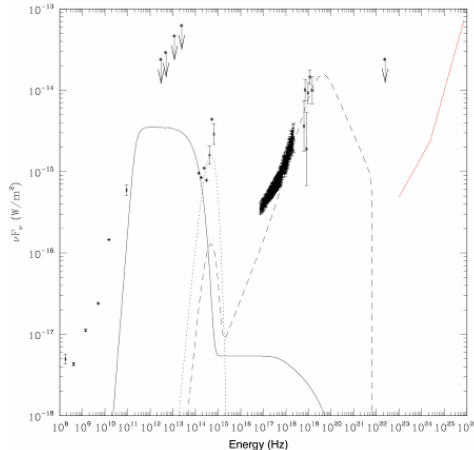


Fig. 7. SED of the QSO 4c04.42 ($z=0.965$) suggestive of Bulk Comptonisation.

with a $z=3.668$ (Bassani et al., 2007b). The IBIS sensitivity to faint extragalactic objects is increasing with time providing, for the first time, the detection of the brightest Blazars, the most powerful objects in the observable Universe emitting from radio up to very high energy gamma-ray. In the X/gamma-ray range, hard spectra are shown by the highest luminosity objects (Fossati et al. 1998), and Flat Spectrum Radio Quasars (FSRQ) are the most luminous class of Blazars. The Spectral Energy Distribution (SED) of FSRQ exhibits two main peaks (one between the IR and soft X-ray frequencies and the other in the gamma-ray regime), disclosing the presence of two main components: it is widely believed that the low energy one is due to the Synchrotron radiation of relativistic electrons in a jet, while the high energy one is due to Inverse Compton scattering (IC) of the same electrons with a photon field (Ghisellini et al. 1998). IBIS is becoming sensitive to bright distant AGNs, and several of them are now becoming visible and amenable to spectral studies (Table I). As an example, in Figure 7 is shown the SED of the luminous QSO 4c04.42 at $z=0.965$ for which has been observed and excess of emission below 2 keV (in the observer frame) suggesting Bulk Compton motion (De Rosa et al., 2008).

Conclusion

After more than 5.5 years of observations, INTEGRAL is still performing a survey of the all sky and the deep monitoring of the Galactic Plane, monitoring more than 420 sources and spending several Ms observations in selected deep fields; this is giving us exciting results about new high energy emitters and discovering new dozen of variable sources. The large field of view, the good angular resolution and the deep observations provide all

together a powerful tool to discovery highly variable sources, like new SFXTs, distant AGN flares, Blazar like IGR J22517+2218, the second most distant one detected above 20 keV. The main conclusions are: i) the number of INTEGRAL sources continue to increase dramatically (> 200 sources in cat 4), ii) the HMXB numbers increasing faster than LMXB after initial GCDE campaign, iii) AGN numbers increased to ~ 130 in cat3 and are almost doubled today, boosted by exposure and follow-up campaigns, iv) the SFXT have emerged as a new class: 14 (including candidates) have been observed when not in outburst, v) a significant numbers of CVs are now detected: almost exclusively IP sub-class, vi) PWN are now a distinct class of soft gamma ray emitters. The Sky above 100 keV is becoming more and more populated. Finally, a great expectation is due to the launch of the GLAST high energy observatory just placed in orbit the 11 June, 2008, during the MAXI Workshop. We have clearly entered a "golden age" for high energy astrophysics with contemporaneous in-flight operation of CHANDRA, XMM/Newton, INTEGRAL, SWIFT, SUZAKU, AGILE, now GLAST and MAXI hopefully to arrive soon.

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 Masetti, N., et al. 2006a, A&A, 448, 547 (Paper II)

Table 1. High-z INTEGRAL QSOs: the sample

Source	z	Reference
PKS1830-211	2.507	De Rosa et al. 2005, Zhang et al. 2008
Swift J1656.3-3302	2.4	Masetti et al. 2008
IGR J22517-2218	3.668	Bassani et al. 2007
QSO B0836-710	2.172	Bird et al. 2007
4C04.42	0.965	De Rosa et al. 2008
1RXS J19245	0.352	Bird et al. 2007
IGR J03184-0014	1.93	Bird et al. 2007
QSO B0212+735	2.367	Bird et al. 2007
PKS 2149-307	2.345	Bird et al. 2007
PKS 0537-286	3.104	Possibly detected in 20-200 keV
QSO 0723+679	0.884	Possibly detected in 20-200 keV

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 Masetti, N., et al. 2006c, A&A, 455, 11 (Paper IV)
 Masetti, N., et al. 2006d, A&A, 459, 21 (Paper V)
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 Mass-Hesse M. et al. 2003, A&A, 411 L261
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