Session 5

Overall population characteristics

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Hans-Jakob Grimm (right) and Laura Norci, overlooked by specimen of modern Irish art.

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The INTEGRAL Gamma-Ray Sky after 1000 days in orbit

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Abstract. This paper will review the main astrophysical results obtained in the field of high energy Galactic sources with the INTEGRAL/IBIS Gamma-ray Imager (Ubertini *et al.* 2003) on-board INTEGRAL (Winkler *et al.* 2003), the ESA space Observatory successfully launched the 17th October 2002 from Baikonur with a Proton vehicle. In view of the high sensitivity of the two gamma ray instruments IBIS and SPI and their capability to provide at the same time image, spectra and time profiles of all the sources in their wide field of view, a key project was approved as "Core Programme" to deeply observe the Galactic Centre (GCDE) and to exploit regular scans of the whole Galaxy Plane. The major results obtained in terms of classes of high energy emitters are shortly outlined.

Keywords. gamma rays: observations, telescopes, surveys

1. Introduction

After more than 1000 days in orbit one of the main INTEGRAL/IBIS achievement is the detection of more than 200 high energy sources for E > 20 keV. Out of this unprecedented sample, ∼30 are detected above 150 keV, showing for the first time a populated "non thermal" sky. A substantial fraction of the whole sample of sources has been so far identified with already known objects, typically at X and IR wavelengths. Nevertheless, a few tens are still of unknown origin. Among them, we have recently discovered two different classes of objects:

- The slow highly absorbed pulsars (period between ∼100 to ∼1000 s) in high mass systems, populated by a young system composed by an evolved magnetised neutron star orbiting in the faint stellar environment of a "giant star"

- The INTEGRAL/IBIS soft gamma ray counterpart of the newly discovered TeV emitting objects. In fact, the first IBIS survey indicates a clear association for a number of TeV detected objects: AX J1838.0-0655, SGR A*, MSH 15-52/PSR1509-58, and Crab

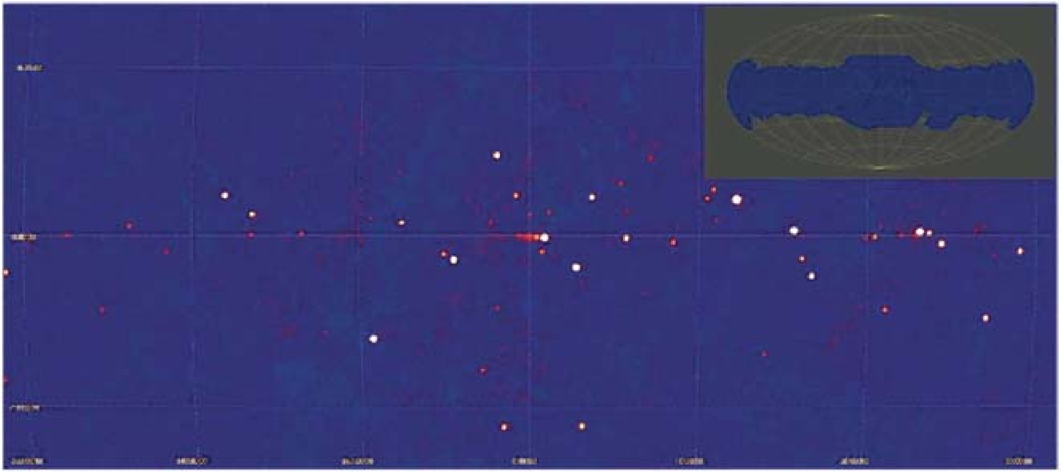

Figure 1. The 30-50 keV significance map for the 1st IBIS/ISGRI catalog

Nebula, while the second survey has discovered that IGR J18135-1751 is the soft gamma-ray counterpart of the TeV source HESS1813-178.

2. Surveys

From the outset, surveys were considered a key element of the INTEGRAL data results. The intention was to provide a temporally and spectrally resolved archival view of the gamma-ray sky, and this concept was included as part of the Core Programme for all instruments. Survey teams were established for each instrument, with the intention of providing *unbiased* surveys of the sky, while other teams were established to search for more specific source types.

2.1. *IBIS all-sky survey*

The *IBIS survey team* have so far conducted two surveys of the gamma-ray sky based on all available data. The 1^{st} IBIS/ISGRI soft gamma-ray galactic plane survey catalogue (Bird *et al.* 2004), hereafter *the first catalogue*, used all data from revolutions 46-120, a total of 2529 pointings. As the catalog name suggests, the 5Ms exposure of this survey was biased heavily towards the Galactic Plane and specifically the central ~40 degrees of the galactic sky covered by the Galactic Centre Deep Exposure. Construction of the first catalogue was optimised for the detection of weak, persistent sources, and followed this process:

- Image generation and cleaning for each pointing using the *OSA 3* software. This involved an iterative procedure to develop a catalogue of sources to be included for image cleaning.
- All-sky mosaic generation in two energy bands optimised for source detection: 30-50 keV and 20-40 keV. Figure 1 shows the 30-50 keV map.
- Determination of selection thresholds based on whole-image statistics to minimise false source detections. Conservative thresholds were chosen so as to limit the false detections to at most one source.
- Automatic source detection using the SExtractor software.
- Construction of final source list by visual inspection of each excess to remove systematic structures.

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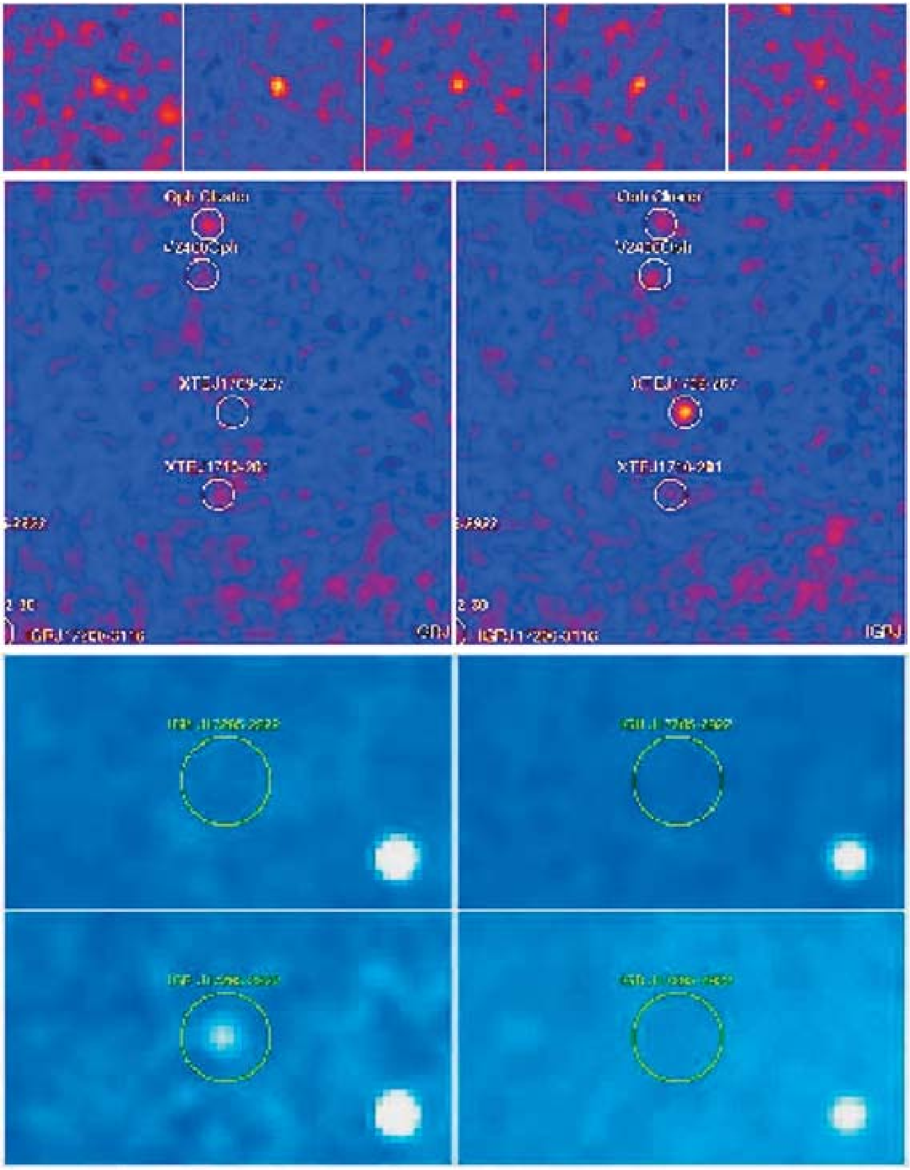

Figure 2. Examples of transient source detection on different timescales: (top) Short flare from XTE J1858+034 in March 2004 visible in a few science windows with duration ~10000s; (middle) XTE J1709-267 visible during revolution 171; (lower) IGR J17285-2922 visible only during the Sept/Oct GCDE observation period (Sguera *et al.* 2005).

The first catalogue contained 123 sources dominated by galactic binary systems, at least partly because of the exposure bias. The detailed breakdown of this first catalog was 53 LMXB, 23 HMXB, 7 supernova products, 5 CVs, 5 AGN, 1 SGR, 1 galaxy cluster and 28 sources of unknown nature. Of these 28 sources, exactly half had been previously observed by previous missions, while for 14 sources, the INTEGRAL detection represented the first discovery. Each source in the first catalogue was localised with an accuracy of between $1'$ and $3'$ depending on source brightness, and the quoted sensitivity limit was ~1mCrab in the regions of highest exposure. The fact that nearly a quarter of the first

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catalog consisted of sources of unknown origin has led to a large campaign of follow-up observations and detailed studies which have revealed the nature of several of these sources. Of the '28 unknown' sources, only 9 remain with no clue to their nature. The other 19 have some, at least tentative identification, including:

• IGR J16318-4848, in the Norma arm of the galaxy, was the first INTEGRAL-detected source to be identified by optical/NIR spectroscopy. It was found to be a supergiant B[e] star, and the spectra showed a very high level of line-of-sight obscuration ($N_H > 2 \times 10^{24}$). High levels of obscuration have been observed in many of the new IGR sources, interpreted as binary systems within a Compton-thick envelope (Walter *et al.* 2003).

• IGR J18027-2016 was identified, by a combination of XMM, SAX and IBIS data, to be an eclipsing HMXB (Hill *et al.* 2005) comprising a neutron star emitting X-rays through wind-fed accretion from an OB-supergiant. Again, a high hydrogen column density is observed in this source.

• IGR J16479-4514 has been identified as a fast transient system (Sguera *et al.* 2005), possibly in a LMXB system.

• IGR J18027-1455 and IGR J20247+5058 have been optically identified as Sy1 galaxies at redshifts of z = 0.035 and z = 0.02 respectively (Masetti *et al.* 2004). IGR J20247+5058 is also a radio galaxy, with an interesting core-jet morphology (Mantovani *et al.* 1982).

Analysis of the global properties of the first survey sources (Dean *et al.* 2005) concluded that INTEGRAL is detecting a previously un-noticed population of highly absorbed sources, probably binary systems with massive stars and a neutron star companion. Many of the IGR sources may fall into this class of object. A systematic correlation was carried out of the sources in the first catalog with those in the ROSAT bright source catalogue, a previous all-sky soft X-ray survey. This revealed a total of 75 IGR-ROSAT associations within a $3'$ error circle (Stephen *et al.* 2005a), while it was also shown that, on a statistical basis, less than 1 of these should be a random association. This study has paved the way for follow-ups of many IGR sources at optical and IR wavelengths, since the ROSAT association provides us with a much better source location for 10 of the IGR sources. The 2^{2nd} IBIS/ISGRI catalog (Bird *et al.* 2005) significantly increases both the breadth and depth of exposure, and is constructed from all data from revolutions 46-96, and all Core Programme data from revolutions 96-210, a total of more than 6500 individual pointings, more than doubling the exposure of the 1st catalog. In addition, several technical improvements were made over the first survey, both in terms of the core *OSA 4* software used and the survey-specific tools used for source detection and location. In particular, emphasis has been placed on the filtering of science window data to remove those pointings with poor image quality, usually due to inadequate background subtraction following bad 'space weather' such as solar flares. With the rapidly increasing overall exposure, one other significant change implemented for the second catalog has been the search for sources on different timescales. We cannot expect to detect a short-lived transient in a mosaic of many Ms of data, since detection is based on the average flux throughout the exposure on any given source. In order to counter this problem, detection is now carried out on: science window (typically 2000s) timescales; revolution (typically 200ks) timescales; revolution groups, typically encompassing one long exposure campaign such as a Galactic Centre Deep Exposure period; whole-exposure mosaics, as used for the first catalogue, covering a varying exposure depending on the location in the sky. Figure 2 illustrates sources becoming visible on several of these timescales (Sguera *et al.* 2005). The multi-timescale approach will become more important as the accumulated exposures become more incompatible with the detection of transient activity. The resulting second

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catalogue contains 209 sources, with a significantly different distribution of source types due to a reduction in the exposure bias towards the Galactic Centre. Significant parts of the extragalactic sky have now been viewed by INTEGRAL, and so the contribution of AGN towards the overall source population (∼20%) is increasing dramatically. As in the first catalogue, a large fraction (∼25%) of these sources are of unknown nature. A vigorous follow-up campaign is already underway to understand the detailed characteristics, and hence nature, of these sources. Again, correlation with the ROSAT Bright Source catalog has been fruitful (Stephen *et al.* 2005b), providing improved locations for a further nine sources. The IBIS survey team continues to enhance their techniques for detection of both persistent and transient sources.

2.2. *Other surveys*

Other surveys (of smaller fields) have been constructed. Revnivtsev *et al.* 2004 detected 60 sources in a 2 Ms private observation of the Galactic centre in Aug-Sept 2003, down to a sensitivity limit of ∼2mCrab. The spiral arm tangents have also been the subject of detailed study: Molkov *et al.* 2004 report 28 sources in a 0.8 Ms exposure of the Sagittarius Arm, while a more recent 2Ms exposure of the Crux arm tangent (Revnivtsev *et al.* 2005) has detected 46 sources down to a sensitivity limit of ∼1mCrab. Surveys of specific sources types are now beginning to be practical, an example of this being a survey of AGN detected (Bassani *et al.*, 2005, submitted) using similar techniques to *the IBIS survey.* This has detected 48 AGN, and a further 19 candidate AGN emitting in the 20-100 keV band. Work is also underway to compile a catalogue of sources visible at higher energies, above 100keV.

3. New absorbed persistent super-giant HMXB

The detection of new bright (>10 mCrab) persistent hard X-ray sources by INTEGRAL has been a surprise as those have remained almost unnoticed in previous X-ray galactic surveys. XMM-Newton follow-up observations have been collected for seven of those sources. The X-ray counterparts (Figure 3) feature strong absorption ($>10^{23}$cm^{-2}), intense fluorescence lines and soft X-ray excesses. Five of those sources appeared to be long spin period pulsars (>139 s) and a short orbital period (<10 days) was detected in two of them, thanks to eclipses (Figure 3). Long spin periods and persistency are characteristics of super-giant HMXB systems. A picture confirmed by the short orbital periods, the fraction of eclipsing systems and the early type near infrared counterparts. The 2MASS counterparts are not strongly reddened indicating that the X-ray absorption is indeed local to the sources. A persistent strong absorption is unusual among super-giant HMXB and may point out a peculiar stellar wind configuration. A number of the new, yet unidentified, galactic sources discovered by INTEGRAL could be new heavily absorbed HMXB. INTEGRAL therefore increases the number of know super-giant HMXB systems very significantly.

4. Active Galactic Nuclei Results

The extragalactic gamma-ray sky is still poorly explored with only two surveys performed above 10 keV in the past: the historical all-sky survey conducted in the 1980's (Levine *et al.* 1984) by the HEAO/A4 instrument in the 13-80 keV band and the more recent RXTE/PCA one made in the 8-20 keV band using slew observations (Revnivtsev *et al.* 2004, Sazanov and Revnivtsev, 2004). Both surveys lacked imaging capability, so that the association with an active galaxy was sometimes tentative. Despite being so rare, gamma-ray surveys are an efficient way to find AGN as they probe

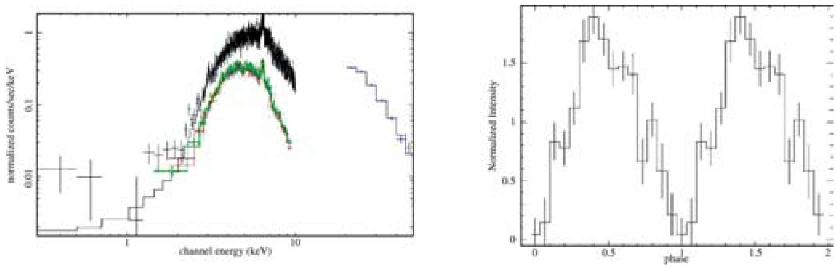

Figure 3. Left: XMM-Newton/INTEGRAL combined spectrum of IGR J17252-3616. The soft excess has not been modelled. Right: INTEGRAL orbital folded lightcurve of IGR J17252-3616. Phase 0 indicates the time of the eclipse.

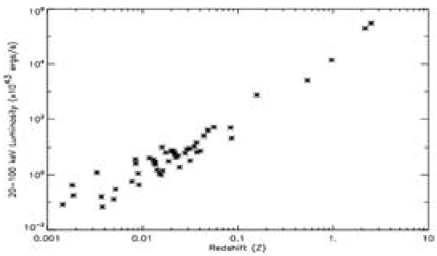

Figure 4. Redshift vs 20-100 keV luminosity for the INTEGRAL AGN sample.

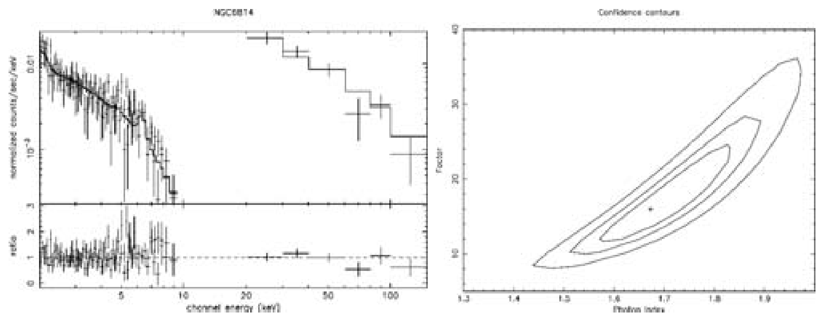

Figure 5. Left: ASCA/INTEGRAL combined spectrum of NGC6814. Right: Confidence levels of the cross-calibration constant $\frac{INT}{ASCA}$ vs photon index for NGC6814

heavily obscured regions/objects, i.e. those that could be missed in optical, UV, and even X-ray surveys. That absorbed AGN are common in the local Universe (Risaliti *et al.* 1999) is obvious from the fact that the 3 nearest (within 4 Mpc) active galaxies (NGC 4945, Centaurus A and Circinus galaxy) are all highly obscured with $N_H \geqslant 10^{23}$ atoms cm^{-2} (Matt *et al.* 2000). This situation has only recently been appreciated, perhaps due to all 3 objects lying close to the Galactic plane. The absorbing matter is often thick, since more than half of the Seyfert 2s in the local Universe have column densities in excess of, or equal, to 1.5×10^{24} atoms cm^{-2} (Risaliti *et al.* 1999). This result, coupled with the fact that type 2 objects are probably more numerous than type 1 sources, indicates the need for surveys free from biases against the Compton thick regime, i.e. above the 10-20 keV band. Quantifying the fraction of AGN missed by current surveys which are affected by selection due to absorption is necessary if we want to understand the accretion history of the Universe and study a population of objects so far poorly understood. Furthermore,

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the distribution of column densities is a key parameter for estimating the contribution of AGN to the X-ray cosmic diffuse background and for testing current unified theories. A step forward in this field is now provided by SWIFT/BAT and INTEGRAL/IBIS which are surveying a great fraction of the sky above 20 keV with a sensitivity better than a few mCrab and a point source location accuracy of the order of 1-3 arcminutes depending on the source strength. These two surveys are complementary to each other, as the first covers the high galactic latitude sky, while the second one concentrates on mapping mostly the galactic plane so that together they will provide the best yet sample of AGN selected in the gamma-ray band. The first sample of AGN detected by SWIFT/BAT lists 45 objects (Markwardt *et al.* 2005), all but 5 of which have archival X-ray spectra, enabling the estimation of the column density and other spectral properties. The column density distribution of these AGN is bimodal with 64% of the non blazar sources having absorption in excess of 10^{22} atoms cm^{-2}. None of the sources brighter than 3×10^{43} erg s^{-1} in the 14-195 keV band shows high column densities, while almost all those below this value are absorbed. The INTEGRAL/IBIS catalogue comprises 54 confirmed AGN and 13 candidates. Figure 1 shows a plot of the 20-100 keV luminosity (assuming H_0 = 75 Km/sec Mpc and $q_0 = 0$) against redshift when available for the INTEGRAL AGN sample. The complementarity of the SWIFT and INTEGRAL surveys is confirmed by the little overlap between the two, since only 9 objects are present in both catalogues. Within the sample of INTEGRAL AGN, 37 objects have an estimate of the intrinsic absorption. Within this subsample the fraction of absorbed $N_H \geqslant 10^{22}$ atoms cm^{-2} objects is 62%, much in agreement with the SWIFT result and also with the expectations of population synthesis models when Compton thick sources are taken into consideration (Comastri 2004). We also find that the ratio of Seyfert 1-1.5 to Seyfert 2 is ~1:1, considerably different than the ratio found in optical or line selected surveys where the same ratio is 1:3 (Maiolino and Rieke, 1995, Ho, Filippenko and Sargent, 1999). We also find 6 Blazar type objects. Interestingly, in the sample of 17 Seyfert 2 with absorption measured, 75% are heavily absorbed ($N_H \geqslant 10^{23}$atoms cm^{-2}) with almost half of these being Compton thick. The fraction of Compton thick objects over the whole sample of INTEGRAL AGN having a measured column density is at the moment ~30%, stressing again the need for considering Compton thick absorption in synthesis models of the X-ray background. A very preliminary LogN LogS distribution of our sample indicates substantial agreement with the HEAO/A4 and PDS fluxtuations analysis result (Fiore 1999, private communication), with typically 0.02 sources per square degrees above our sensitivity limit. It is important to note that IBIS can also provide detailed spectral information particularly if combined with lower energy data as obtained by past and current X-ray instruments also in view of the good cross calibration obtained between the various instruments. For example in the particular case of NGC6814, a source poorly studied in the past due to confusion with a nearby galactic source, IBIS in combination with ASCA has provided for the first time a broad band spectrum (Figure 5) as well as information on the extreme flux variability behaviour: a huge change in the cross calibration constant between the two instruments is required by the data, Figure 5 implying a flux change of a factor of 16 over a 10 year period (Molina *et al.* 2005). Source behaviour over time can also be checked through the light curves covering the entire INTEGRAL lifetime: while mainly developed for galactic objects this standardized analysis can also be used for extragalactic objects. Finally much is expected by IBIS on the study of absorbed objects. In Figure 6 we show the combined spectra (in the form of νF_ν) of IGR J07565-4139 (left panel) and NGC788 (right panel), observed respectively by INTEGRAL & Chandra and INTEGRAL & ASCA. IGR J07565-4139 has a Compton thick reflection dominated spectrum, with $N_H > 1.5 \times 10^{24}$ cm^{-2} but the pile-up fraction in Chandra data did not

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allow us to observe the expected (huge) iron line. NGC788 is characterized by a Compton thin model with $N_H \sim few 10^{23}$ cm^{-2}, and the ASCA data show the presence of the Kα iron line with EW = 600 eV, as expected with such strong absorption fraction.

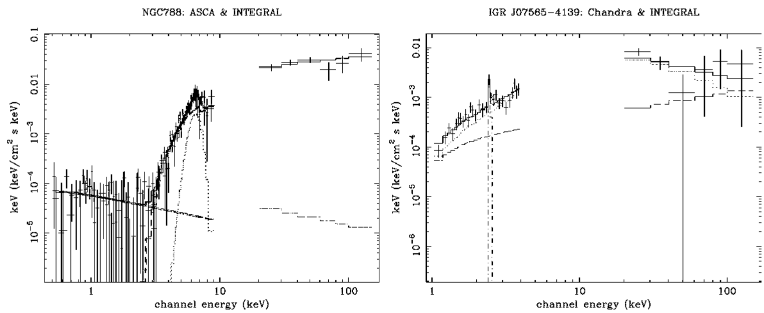

Figure 6. Left: ASCA/INTEGRAL combined spectrum of the Compton thin source NGC788. Right: Chandra/INTEGRAL combined spectrum of the Compton thick source IGRJ07565-4139.

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References

Bassani, L. *et al.* 2005, *ApJ Letters*, submitted
Bird, A.J., Barlow, E.J., Bassani, L., *et al.* 2004, *ApJ*, 607, L33
Bird, A.J., Barlow, E.J., Bassani, L., *et al.* 2005, *ApJ*, in press
Comastri, A. 2004, *Supermassive Black Holes in the Distant Universe*, 245
Dean, A.J., Bazzano, A., Hill, A.B., *et al.* 2005, *A&A*, in press
Hill, A.B., Walter, R., Knigge, C., *et al.* 2005, *A&A*, 439, 255
Ho, L.C., Filippenko, A.V., Sargent, W.L.W. 1997, *ApJ Suppl.*, 112, 315
Levine, A., Lang, F., Lewin, W. *et al.* 1984, *ApJS*, 54, 581
Maiolino, R. & Rieke G.H. 1995, *ApJ*, 454, 95
Mantovani, F., Nanni, M., Salter, J.C., *et al.* 1982, *A&A*, 105, 176
Markwardt, C. B. *et al.* 2005, *ApJ Letters*, submitted, astro-ph. 05099860
Masetti, N., Palazzi, E., Bassani, L., *et al.* 2004, *A&A*, 426, 41
Matt G. *et al.* 2000, *MNRAS*, 318, 173
Molkov, S.V., *et al.* 2004, *Astron. Lett.*, 30, 534
Molina M. *et al.* 2005, *in preparation*
Revnivtsev, M.G., *et al.* 2004, *Astron. Lett.*, 30, 382
Revnivtsev, M.G., *et al.* 2004, *A&A*, 418, 927
Revnivtsev, M.G., *et al.* 2005, *Astron. Lett.*, in press
Risaliti, G., Maiolino, R. & Salvati, M. 1999, *Apj*, 522, 157
Sazanov and Revnivtsev 2004, *A&A*, 423, 469
Sguera, V., *et al.* 2005, *A&A*, in press
Stephen, J.B., Bassani, L., Molina, M., *et al.* 2005a, *A&A*, 432, L49
Stephen, J.B., Bassani, L., Malizia, A., *et al.* 2005b, *A&A*, in press
Ubertini, P., *et al.* 2003, *A&A*, 411, L131
Walter, R., *et al.* 2003, *A&A*, 411, L427
Winkler C., *et al.* 2003, *A&A*, 411, L1

Discussion

MACCARONE: Do you think that a large fraction of the X-ray background above 20 KeV is truly diffuse, and if so, what emission mechanism do you think causes this?

UBERTINI: Down to about 10^{-11} ergs/sec/cm^2, we certainly don't resolve much of it. With future work on the log N-logS distributions, we will be able to make better extrapolations of the effects of fainter sources, but it seems right now that a lot of the emission is truly diffuse. I don't want to speculate about what would cause this diffuse emission.