INTEGRAL observations of SN 1006

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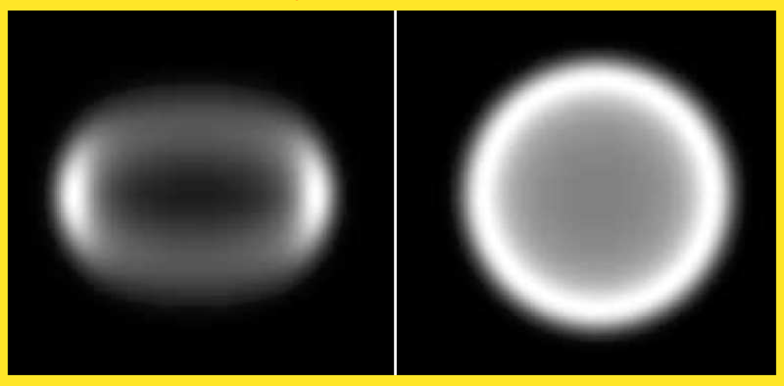
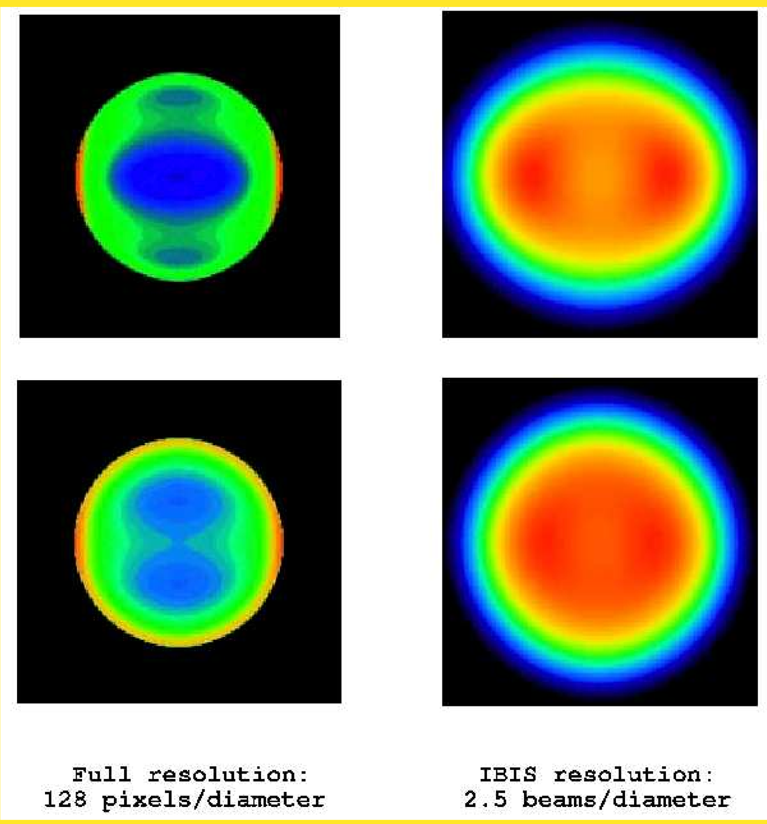
Abstract The remnant of the supernova of 1006AD, the remnant first showing evidence for the presence of X-ray synchrotron emission from shock-accelerated electrons, was observed for $\sim$1000 ksec with INTEGRAL for the study of electron acceleration to very high energies. In IBIS and JEM-X spectral bands, both synchrotron emission and bremsstrahlung are expected. The aim of the observations is to distinguish the morphology of synchrotron and bremsstrahlung regions using the combination of IBIS and JEM-X spatial and spectral coverage. Here, we report on our preliminary results from the analysis of the INTEGRAL data, concentrating on the JEM-X results.

INTRODUCTION

Synchrotron and bremsstrahlung model images of SN1006 at 30 keV, convolved to JEM-X resolution)



IBIS model image at 30 keV and 60 keV



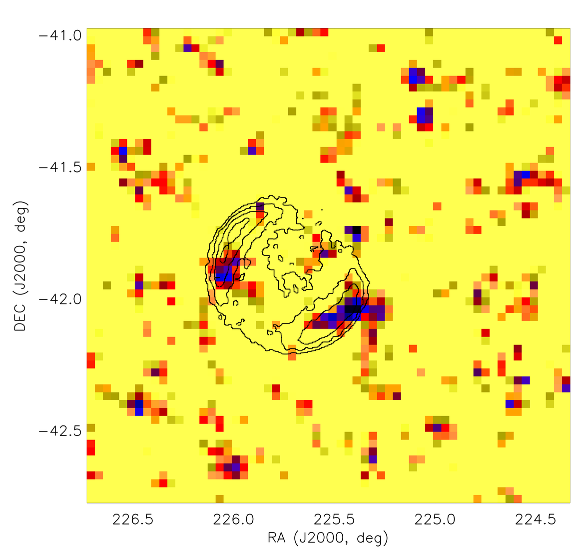
Our group has observed SN 1006 for $\sim$1000 ks with the INTEGRAL Observatory with the main aim of detecting, and distinguishing, synchrotron and non-thermal bremsstrahlung emission. Both are expected in lower-energy INTEGRAL bands, and can be distinguished by different predicted morphology. **The synchrotron emission should be concentrated in two bright opposing limbs like radio emission (Reynolds, 1998, 1999, see figure) while non-thermal bremsstrahlung, resulting from slightly supra-thermal shock-accelerated electrons interacting with thermal ions, should be more symmetrically distributed.** The figures show predictions for a particular model (Reynolds, 1998; Dyer et al., 2001) convolved to JEM-X and IBIS angular resolutions. Here the azimuthal modulation of synchrotron emission is due to more rapid electron acceleration where the magnetic field is perpendicular to the shock normal, suggesting that the ambient magnetic field lies in the SE-NW direction.

The synchrotron emission is expected to be falling off rapidly with energy, while the bremsstrahlung should have a much harder spectrum. The quantitative flux of synchrotron emission can help distinguish between models in which the maximum electron energy is limited by radiative losses, and those in which electron escape dominates. The former require very high magnetic fields, of order 10^{-4} Gauss, demanding magnetic-field amplification in the shock, and predict higher synchrotron fluxes above 10 keV. **The flux of bremsstrahlung emission, along with thermal X-ray modeling, gives the efficiency of electron acceleration at low energies, not yet observationally determined in any remnant.** It is possible that even low-energy suprathermal electrons are preferentially accelerated where the magnetic field is parallel to the shock normal; this effect might cause some modulation of the bremsstrahlung emission as well and would be an important step forward in our understanding of the "injection" process by which electrons get their initial acceleration.

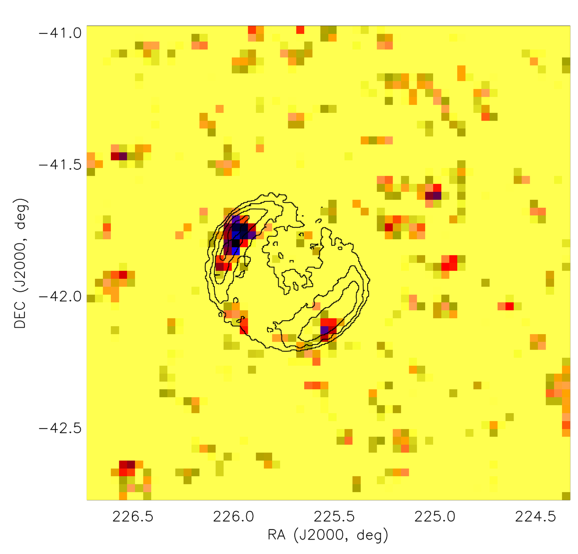
JEM-X Results

fubar

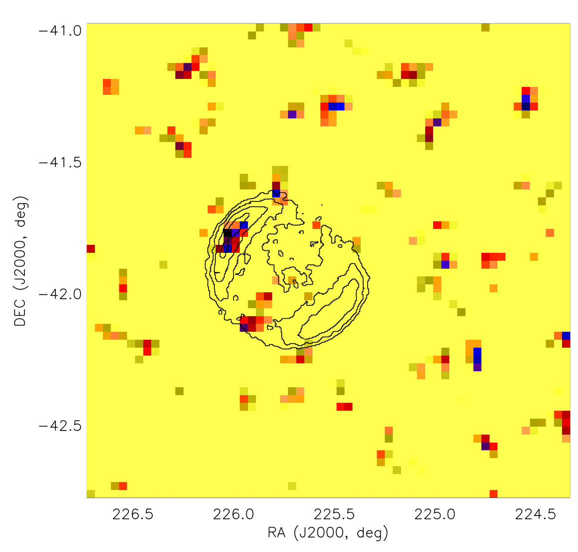
3 – 4.2 keV band



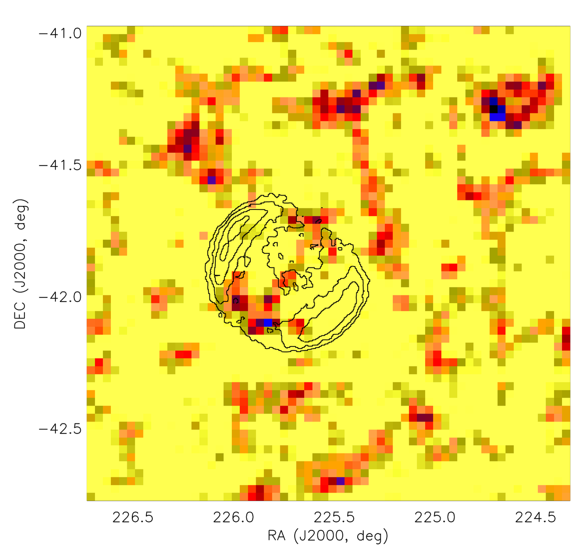
4.2 – 8.4 keV band



8.4 – 14 keV band



14 – 35 keV band



The INTEGRAL observations took place in two parts, the first part had approximately 250 ks exposure time, and conducted during revolutions 30 and 32. The second part had $\sim$ 755 ks exposure time, and conducted during revolutions 155, 156, 157 and 158. The first part was before the new background rejection criteria were implemented in JEM-X, and therefore was not included in this analysis. The results are from the second part of observations. We note that, although the total exposure time is 750 ks, due to the vignetting of JEM-X instrument during the 25 point dither, the effective exposure time of the central object is approximately 250 ks.

We have obtained JEM-X images in 4 energy bands using the "JEM-X Midisky" offline software package available from the DSRI (Lund et al., 2004). These energy bands are 3–4.2 keV, 4.2–8.4 keV, 8.4–14 keV, and 14–35 keV. The images from each pointing then mosaicked using the "mosaic-weight" program (Chenevez et al., 2004) to create the final images shown here. The contour plot of an *ASCA* image (0.4 – 8 keV band) of the source is overplotted to guide the eye. The two synchrotron emission dominated limbs are apparent in the contour plot.

The source is definitely detected at the limbs for 3–4.2 keV and 4.2–8.4 keV bands (see Table.1 below). This is the first time that the structure in an extended source is imaged with JEM-X. It appears that the South-West limb (right, bottom side of the image) is stronger in 3–4.2 keV band, but the trend is reversed at higher energies. At 4.2–8.4 keV, the North-East limb is stronger. An excess at the position of the NE limb is present in the 8.4–14 keV band (1.7 σ, no excess is seen in the SW limb). **If this excess represent the NE limb (both the position and the flux is consistent), then the source is imaged for the first time in an energy band beyond the energy range of the soft X-ray instruments (*ASCA*, *XMM-Newton*, and *Chandra*).** At the highest energy band, the source was not detected.

Table 1. Fluxes and signal to noise ratios

North-East limb

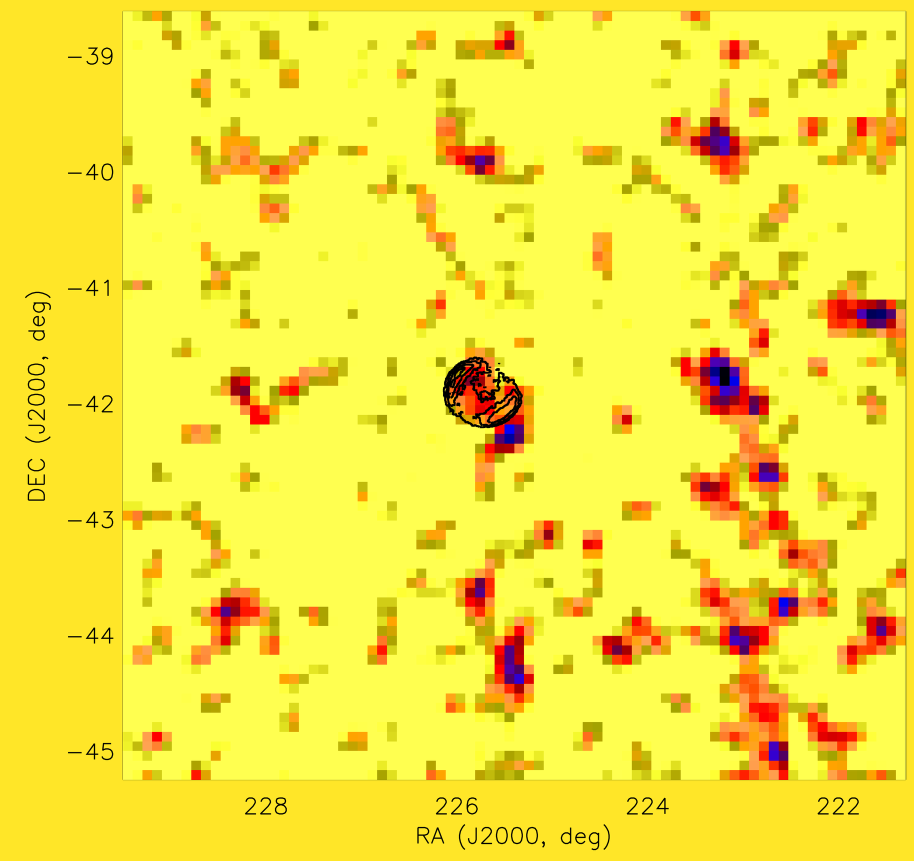
Energy Band (keV)	JEM-X flux (mCrab)	S/N ratio	ASCA flux (mCrab)
2.4 -- 4.2	0.64	2.6	0.8
4.2 -- 8.4	1.11	5.0	0.8
8.4 -- 14	0.86	1.7	0.5
14 -- 35 keV	-	-	-

South-West Limb

Energy Band (keV)	JEM-X flux (mCrab)	S/N ratio	ASCA flux (mCrab)
2.4 -- 4.2	0.92	4.0	-
4.2 -- 8.4	0.34	1.6	-
8.4 -- 14	-	-	-
14 -- 35 keV	-	-	-

The *ASCA* fluxes were calculated using the spectral information given in Dyer et al. (2001). The actual lower limit of the first enrgy bin is around 3 keV set by the lower energy threshold.

ISGRI Results



We also worked on the data from the IBIS/ISGRI instrument to detect the bremsstrahlung emission, which would allow direct inference of the efficiency of acceleration of cosmic-ray electrons. However, we hit technical difficulties in imaging and obtaining fluxes from ISGRI. The figure above shows mosaicked variance map of SN1006 obtained using OSA 4.0 in 20-40 keV band for revolution 155 only. Although the source is on top of an "excess" in the image, one can easily see that the excess is part of an artificial periodic structure. This structure is also present in the mosaicked images of other revolutions. 155 is the only revolution that the source is on top of an excess, and work is underway to understand and to remove the effects of the structure to obtain a detection or meaningful upper limits.

Summary and Discussion

We analyzed the data from the supernova remnant SN1006 using the JEM-X and IBIS instruments on *INTEGRAL* observatory. We detected the limbs in . – 4.2 keV band and 4.2 – 8.4 keV bands with JEM-X, and also observe an excess from the position of the NE limb in 8.4 – 14 keV bands. The analysis of the ISGRI data is in progress, and will not be discussed here.

The JEM-X detections occurred for the two bright limbs, consistent with the *ASCA* results and the expectations of synchrotron model at low energies. The JEM-X images indicate that the SW limb is stronger in 3. – 4.2 keV band, and, the NE limb is stronger in the 4.2 – 8.4 keV. And there is also an excess in 8.4 – 14 keV at the position of the NE limb. The asymmetry in the flux levels from the limbs was observed with *ASCA* (and somewhat with the PCA on *RXTE*), but the ratio is $\sim$ 55%/45% above 2 keV (Ozaki & Koyama, 1998), not 75%/25% observed for the 4.2 – 8.4 keV band of JEM-X. It is possible that the level of asymmetry increases with energy. We would like to remind that the *Cangoroo* experiment detected the source only in the NE limb.

The JEM-X fluxes we obtained and the *ASCA* fluxes differ as much as 30%. The JEM-X fluxes were obtained by comparing the number of counts in a group of pixels at each limb to the number of counts in an observation of Crab. These results are preliminary, and we are working on a more robust way to obtain flux levels. We also note that, because of the uncertainty in the lower energy threshold, the lowest energy band flux probably have higher uncertainty than the higher energy bands.

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The authors thank Dr. Allan Hornstrup for setting up a collaboration with the DSRI, and Peter Kretschmar for his helps in JEM-X analysis. This work is suppprted by NASA Grant NAG5-13142.