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Main results from the INTEGRAL mission

N. Produit[a] on behalf of the INTEGRAL science working team
(a) ISDC, Université de Genève, Switzerland
Presenter: N. Produit (Nicolas.Produit@obs.unige.ch), swi-produit-N-abs1-og22-oral

INTEGRAL is an European Space Agency (ESA) astronomical satellite for observing the gamma-ray sky in the keV to MeV energy range. Highlights of the main results obtained since the start of the mission are presented.

1. Introduction

INTEGRAL[1], the ESA gamma-ray observatory, was launched on October 17, 2002. Since this date, it took data of excellent quality while experiencing no major flaw.
The instruments on board INTEGRAL are sensitive to γ-rays from 2 keV to 1 MeV. They can all provide images and spectra but some of them are specialized in just one of these two tasks. The imager IBIS[2] has a field of view of 19° by 19° for a point source location accuracy of 1-2 arcmin. The spectrometer SPI[3] has a sensitivity for narrow lines of 2.5 10^{-5} ph cm^{-2} s^{-1} and a spectral resolution of 3 keV. The two JEMX monitors[4] are specialized for photons in the X-ray domain and cover an energy range from 2 to 20 keV.
INTEGRAL is an observatory-type mission. Most of the total observing time (70%) is awarded as the General Program to the scientific community at large. The rest of the time (Core Program) is devoted to periodic Galactic surveys, deep Galactic center exposures, and targets of opportunities. All the data become public after one year. More then one year of data is already publicly available for download on the INTEGRAL science data center (ISDC) web site[5].

2. Catalogs

One year's worth of all Core Program exposures (5 Msec) were mosaicked to produce a deep all-sky map. This map was searched for known and new sources and a catalog was published[6]. The maps are not homogeneous in depth everywhere (see figure 1), as most of the Core Program time is devoted to the Galactic disk and center. Yet, a typical position accuracy of 0.72 arcmin and a sensitivity of 1 mCrab are achieved almost everywhere.
On hundred and twenty-three sources are found in this catalog: 5 Active galactic Nuclei (AGN), 5 white dwarfs, 4 radio pulsars, 3 supernova remnants (SNR), 54 low mass X-ray binaries (LMXB), 24 high mass X-ray binaries (HMXB), and 28 unidentified sources.
This catalog activity will continue and eventually use all the public data. The map will become deeper and more complete, and as the γ-ray sky is highly variable, we will continue to serendipitously discover more sources. Follow-up observations in other wavelengths are needed to understand the nature of the unidentified sources.

3. Compact sources account for all the soft γ-ray emission of the Galaxy

Thanks to the high spatial resolution of the imager, most of the total emission of the Galaxy from 2 keV to 120 keV can be assigned to visible point sources[7]. In fact, in the band 40 keV to 120 keV, there is no indication of an interstellar emission. In the 20 keV to 40 keV band, a Galactic diffuse component can contribute at most 13% of the total emission.
This means that the situation in the soft γ-ray domain is very different than in the X-ray domain ($<$10 keV)

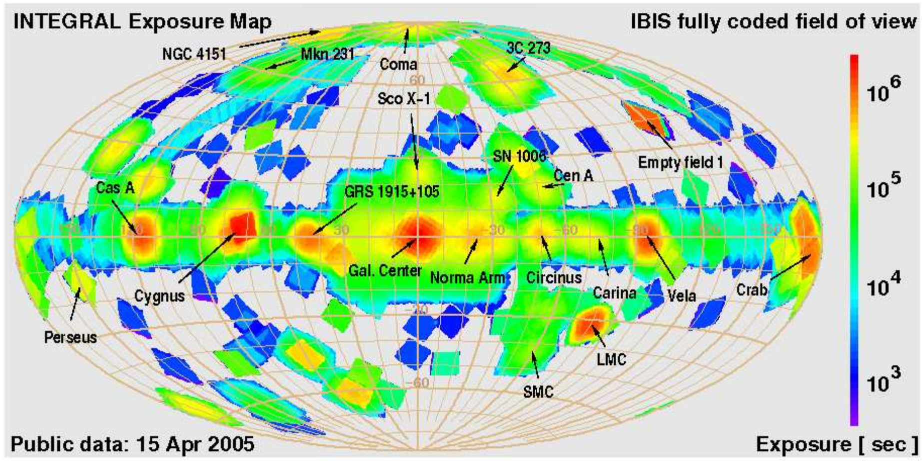

Figure 1. INTEGRAL exposure map of all public data on 15 April 2005

where a diffuse component dominate. This also means that the emission mechanism changes drastically between 10 and 20 keV.
This measurement places strong constraints on the population of GeV cosmic-ray electrons that would contribute to the diffuse background by inverse Compton scattering, and on the population of lower energy electrons that would radiate through bremsstrahlung on interstellar gas.

4. IGR sources

On January 29, 2003, only three months after the launch, INTEGRAL found its first new uncatalogued high-energy source IGR J16318-4848[8]. Today (June 2005), the number of IGR sources amounts to 55 (for an up to date list see [5]). Follow-up observations of IGR J16318-4848 at other wavelengths have shown that this source is likely to be a high mass X-ray binary (HMXB).
All the new sources are located very near to the Galactic disk and predominantly in regions with high OB star formation rate. It is therefore likely that most of them are HMXB. The sources that have been followed with the Chandra and XMM satellites show strong absorption, explaining why they were discovered first in γ-rays rather then in X-rays. All sources are strongly variables.
It seems that all these new sources constitute a new population of HMXB[9].

5. Center of the Galaxy

Using a 1 Msec observation of the Galactic center[10], a deep map of the vicinity of Sgr A* was produced. In the central 2°x2° field, 5 known sources are clearly seen: 1E 1740.9-2942.7, KS 1741-293, A 1742-294, 1E 1743.1-2843, SLX 1744-299/300 and a new uncatalogued source IGR J1745.6-2901. The flux of this new source varies with time. The position is compatible with the Sgr A* radio position and incompatible with the the position of GRS 1741.9-2853 which is not detected in this sample. All these hints seem to indicate that IGR J1745.6-2901 is the γ-ray counterpart of the Galactic nucleus. The flux in the 20 to 40 keV band is $1.92\pm0.36\ 10^{-11}$ erg cm^{-2} s^{-1}, and $1.86\pm0.40\ 10^{-11}$ erg cm^{-2} s^{-1} in the 40 to 100 keV band, making it a

faint, but by far not the faintest, source discovered by INTEGRAL.
If our super massive black hole seems to be very quiet right now, it was perhaps not the case in the past. We have now the intriguing possibility to prove this. The radiation emitted in the past by Sgr A* could be Compton scattered and reprocessed by giant molecular clouds and delayed by the light travel time. In that case, the source must be weak in X-rays but strong above 15 keV making it ideal for INTEGRAL. Revnivtsev et al[11] have shown that we are seeing a 300-year delayed signal of Sgr A* as a reflection on the giant molecular cloud Sgr B2. This analysis shows that, 300 years ago, Sgr A* was a few 10^5 times more luminous in γ-rays than it is now. This high luminosity of Sgr A* must have lasted for at least 10 years as proven by historical data of the luminosity of Sgr B2. Models based on cosmic-ray heating of Sgr B2 are rebuked as they cannot explain at the same time the X-ray and the γ-ray spectra of Sgr B2.

6. Emission lines

The center of our Galaxy is a known strong source of electron-positron 511 keV annihilation radiation.
Knödlseder et al[12] have shown that the annihilation signal is coming from the bulge. The source shape is incompatible with a single point source. There seems to be no disk component[13].
Aluminum-26 nucleosynthesis is common throughout the Galaxy. There are suggestions that it is primarily created by massive stars. This isotope β^+-decays with a half-life of 1.04 10^6years and emits a 1808.7 keV photon. Using data of the first year, R. Diehl et al[14] have clearly detected the signal of ^{26}Al but more data is still needed to compete with previous results of COMPTEL.

7. Anomalous X-ray Pulsars (AXP)

AXP are isolated neutron stars with very high magnetic fields 10^{14} to 10^{15} G. Their rotation period is around 10 s. The derivative of their period is large (10^{-11} s/s) and steady. Their X-ray luminosity cannot be explained just by their rotational energy loss.
Out of 6 known AXP in the Galaxy, INTEGRAL has found hard spectral tails in 4 of them (1E1841-045[15]; 1RXS J1708-4009; 4U0142+614; 1E2259+586). The tails are pulsed and no spectral break is seen up to the highest reachable energy. This comes as a surprise as it was not predicted by current AXP models that consider them as soft spectrum objects.

8. HESS counterparts

Very early in the mission, 4 HESS/IBIS associations (Crab, Sgr A*, PSR B1509-58 and AX J1838.0-0655) were already observed.
The HESS collaboration recently published[17] the discovery of 8 new sources seen in γ-rays $>$200GeV.
INTEGRAL has discovered 2 new HESS/IBIS associations among the 8 new sources:

- The new INTEGRAL point-like source IGR J18135-1751[16] has a powerlaw emission from 1 to 100 keV and is spatially compatible with HESS J1813-178. Its radio counterpart is a shell type supernova remnant.

- AX J1838.0-0655, one of the unidentified objects listed in the first IBIS/ISGRI survey catalog, located in the Scutum arm region is the likely counterpart of the TeV source HESS J1837-069. In the INTEGRAL data, this source is persistent, has a powerlaw (Γ=1.66$\pm$0.23) spectrum and a 20-100 keV flux of 4.2 10^{-11} erg cm^{-2} s^{-1} [18]. X-ray data show an absorption which is a factor of 2 to 3 in excess of the Galactic value and they show a point-like morphology. The source is probably a shell type or a plerionic supernova remnant.

More data is being collected to follow-up the other 6 HESS sources.

9. Conclusions

We were not able to speak about many other very interesting science done with INTEGRAL such as the discovery of the fastest spinning accreting neutron star[19], GRBs, High mass X-ray binaries, micro-quasars or AGN.
INTEGRAL has already been a very fruitful mission. It discovered a new class of sources and it advanced our knowledge of the γ-ray sky. We know now that the super massive black hole at the center of our Galaxy was not always as quiet as we see it today.
Most of the published results make use of just the first year of data. As more data are becoming publicly available every month, and as the analysis software released by ISDC (version 5 in August, 2005) is improving, we expect more exiting results from INTEGRAL in the near future.

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