Stars as Suns: Activity, Evolution, and Planets
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Stars at γ-ray Energies : the INTEGRAL Look at Stars

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Abstract. The European γ-ray satellite INTEGRAL, launched on October 17, 2002, is the successor to the highly successful American satellite Compton-GRO. Even though its main observational program focuses on "classical" high-energy sources like compact X-ray binaries or AGNs, some time is being devoted to γ-ray studies of massive stars and magnetically active late-type stars. We briefly describe here the four instruments of INTEGRAL, and summarize the ongoing stellar programs.

1. Astrophysical context : high-energy phenomena in stars

Although it is not common knowledge among astronomers, stars emit a fraction of their energy at high-energies, i.e., X-rays ($\sim 0.1 - 10$ keV), and even γ-rays ($\sim$ 100 keV - 10 GeV). The emission processes, however, vary with the stellar type.

- *Continuum emission.* This is the result of particle acceleration in the case of the strong stellar winds from OB and WR stars. In the presence of a magnetic field (which is now measured in a few O stars, see Donati et al. 2002), winds shocks can accelerate electrons up to $\sim$ MeV energies or more (by, e.g., the so-called "diffusive acceleration mechanism", see, e.g., Ellison, Berezhko, & Baring 2000). The electrons in turn radiate efficiently via the synchrotron mechanism in the radio range: there is indeed early evidence for the non-thermal radio emission of massive stars (Chen & White 1994). The electrons may also interact with the ambient UV photons via the inverse Compton effect, boosting them to γ-ray energies. This is the explanation proposed for the $\sim$ 1 GeV γ-ray emission detected from a few WR stars (see White & Chen 1992).

  Low-mass stars can also emit high-energy continuum radiation, at least as can be expected from the example of the Sun, in association with flares (see below). The hard X-ray continuum is emitted in the form of a non-thermal synchrotron tail, testifying to the prompt acceleration of electrons resulting from reconnection processes (e.g., White et al. 2003).

- *Line emission.* In addition to the usual emission-line spectrum from stellar coronae (low-mass stars) and winds (high-mass stars), a number of γ-ray lines may be emitted. Gamma-ray lines from the strongest solar

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flares (like that of Aug. 7, 1972) have been known from quite some time (e.g., Kozlovsky, Murphy, & Ramaty 2002). They result mostly from the deexcitation of various nuclei, as a result of spallation reactions between energetic protons and the ambient nuclei. Most of these γ-ray emissions take place on very short time scales. These phenomena are now being studied in detail with the RHESSI mission (see talk by G. Share, and Lin et al. 2003).

Entirely different is the emission of γ-ray lines of nucleosynthetic origin in massive stars. Of particular interest because of its lifetime is ^{26}Al. This radioactive isotope decays with a half-life $\tau_{1/2} = 0.7$ Myr after being produced in the core of massive stars and expelled by stellar winds (e.g., Diehl 2002). ^{26}Al decays into ^{26}Mg with the emission of 1.809 MeV photons. Therefore observing this emission traces "live" nucleosynthesis in massive stars, which typically have a lifetime of 1-2 Myr.

2. The tool: *INTEGRAL*

Gamma-ray astronomy has been dominated, in the years 1991-2000, by the "Compton Gamma-ray Observatory" (CGRO). This highly successful mission surveyed the whole sky, and revealed for the first time the "radioactive Milky Way", i.e., our galaxy seen in the light of the ^{26}Al line at 1.8 MeV. The corresponding all-sky map is shown in Fig. 1. The central part of the galactic plane ($l = \pm 60°$) is conspicuous. It is highly correlated with the (unresolved) distribution of massive stars (O and WR stars), and to a lesser extent, with the distribution of novae inferred from observed events (Oberlack et al. 1996). Farther apart, two other regions are visible: the bright region around Cygnus (near $l \sim 90°$, $b \sim 0°$), and the fainter region near Orion ($l \sim 100°, b \sim -20 - 30°$). Cygnus contains among the most massive stars in the Galaxy (type O3), in large numbers (Knödelseder et al. 1999), and was expected from the outset to be a strong source of ^{26}Al. Less obvious is the emission associated with Orion, which hosts less massive stars (O7). The detected flux is weak ($\Phi_\gamma \sim 10^{-4}$ ph cm^{-2} s^{-1}, see Diehl 2002); the position of the maximum emission is in fact located near the tip of the Orion molecular cloud. The interpretation is that it has been produced by the present generation of massive stars (age about 1 Myr), and is currently flowing into the less dense medium created by past SN explosions forming the so-called Orion-Eridanus "superbubble" (see Parizot 2000). Knowing the population of massive stars in both cases, and the γ-ray line fluxes, one obtains a direct test of nucleosynthesis models.

The new generation of γ-ray satellites is now represented by INTEGRAL (which stands for INTernational Gamma-RAy Laboratory), a heavy (4 tons) satellite launched by ESA on October 17, 2002 from Baikonur, Kazakhstan. The four instruments aboard INTEGRAL (described below; for details, see Winkler et al. 2003 and references therein) are supplemented by a so-called "fifth" instrument, namely the INTEGRAL Science Data Center (ISDC), located in Versoix, near Geneva, an international facility created to help observers find their way into the complex data reduction process (see the web page http://isdc.unige.ch/, and Courvoisier et al. 2003).

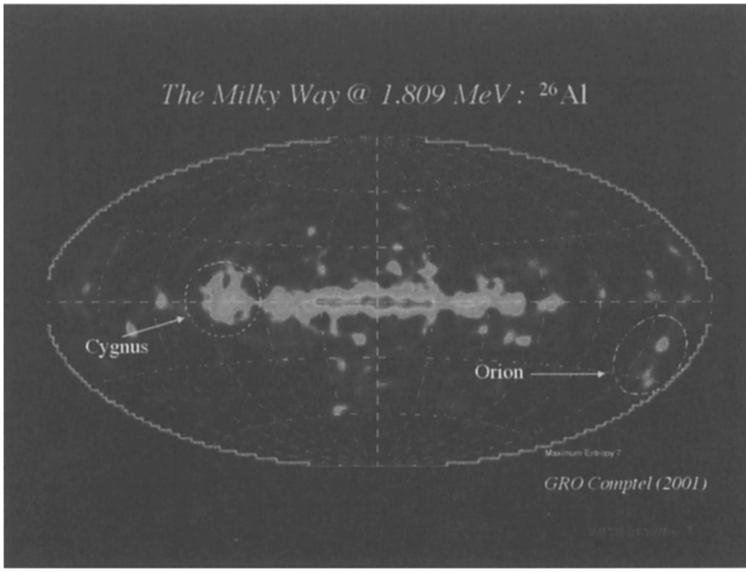

Figure 1. All-sky map in the 1.809 MeV line of ^{26}Al, as seen by Compton GRO.

The orbit of INTEGRAL has an apogee of 155 000 km, with a period of 72 h. It is thus away from the Van Allen belts most of the time, except for a ~ 1 hr segment at perigee. Such an orbit allows for long uninterrupted observations, which is mandatory in view of the fact that, because of the weakness of γ-ray fluxes, typical exposures run from 10^5 to 10^6 sec. INTEGRAL includes four instruments, spanning an unusually wide range of the electromagnetic stectrum, from the visible to medium-energy γ-rays. We briefly summarize their main characteristics. [FIG]

- *OMC : the Optical Monitor Camera.* This is a 50-mm aperture lens equipped with a CCD camera. It operates in the V-band, down to V= 18 mag. It can be used in various modes, depending on the expected telemetry rate. Its main purpose is to help identify in real time the optical counterpart of point sources, which may be particularly helpful in the case of γ-ray bursts (more on this below).

- *JEM-X: the Joint European Monitor.* This instrument consists in a pair of imaging hard X-ray detectors, sensitive in the range 3-35 keV. Much like the OMC, their main role is to identify the X-ray counterparts to point γ-ray sources (spatial resolution $\sim 1''$), and provide a spectrum in continuation with the higher-energy instruments. The energy resolution is $\Delta E/E \simeq 0.40[E(\text{keV})]^{-1/2}$. They are however restricted to rather bright sources (5σ sensitivity of 5 mCrab in 2 ksec).

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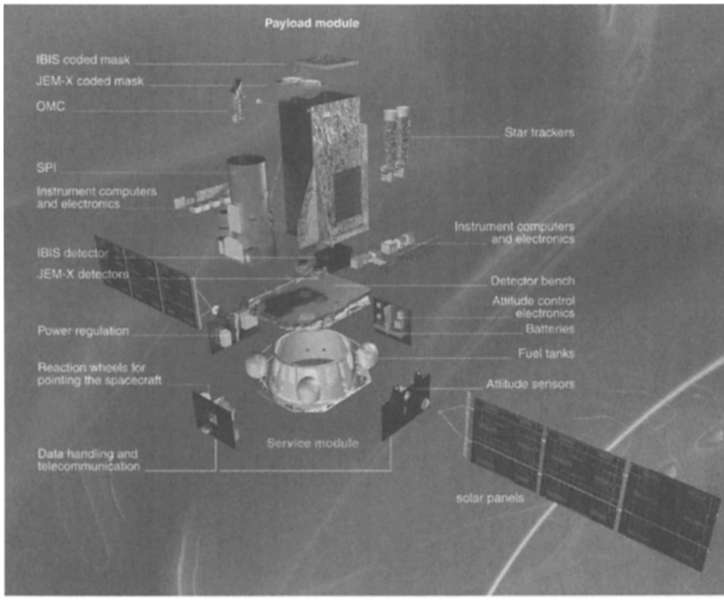

Figure 2. Exploded view: the four instruments of INTEGRAL.

- *IBIS: the INTEGRAL Bologna Imaging Spectrometer.* This is actually a combination of two detectors, one sensitive to X-rays down to 10 keV (ISGRI), the other up to 10 MeV (PiCSiT). Together they provide good spectral resolution ($\Delta E/E \simeq 10\%$) down to the JEM-X range, as well as imaging with a spatial resolution of a few arcmin (depending on energy). The focus of this instrument is on imaging.

- *SPI: the SPectrometer for INTEGRAL.* This is also a spectro-imager, but this time focusing on spectroscopy, with an energy range 20 keV-8 MeV and a resolution $\Delta E \sim 2.5$ keV at 1.3 MeV. Thus γ-ray lines can be detected (one of its main goals), although the line profiles cannot be resolved, except if the lines are unusually broad. Its wide field of view (16° diameter) allows to study extended diffuse emission, in particular for γ-ray lines like the 1.8 MeV line of ^{26}Al. This instrument is the closest to its GRO predecessor, and as such will play an important role in the analysis of galactic diffuse emission, in particular from star-forming regions.

Except for the OMC, the imaging on all instruments is based on the "coded mask" technique. In brief, this technique is based on the pinhole principle: the light from a distant object passing through a hole produces an image on an appropriate screen. Thus it is not a focusing system, which is very difficult to

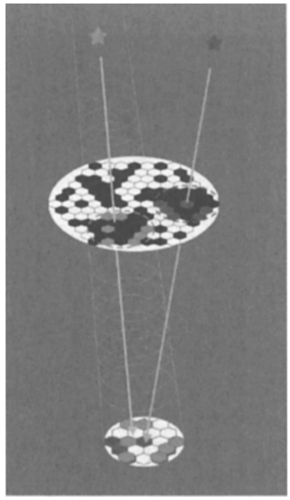

Figure 3. The coded-mask technique: a multiple pinhole γ-ray camera

obtain at these photon energies.[1] A coded mask is essentially a kind of "multiple pinhole camera". [FIG] The screen is a detector layer made of a number of photomultipliers (up to 16,000 in the case of ISGRI !), allowing to find the direction of the incoming photons. To disentangle the ambiguities in the (general) case of the presence of several sources in the field of view, the pinhole array pattern is chosen such that the projections of the various source "images" shadowed by the mask can be deconvolved. Typically half of the incoming flux must however be absorbed in the opaque parts of the mask, to obtain the shadow pattern for each source. Obviously the method cannot work as easily for features angularly more extended than the maximum separation of the pinholes, so that a special observing mode (dithering on the sky) had to be implemented.

Another source of complication, especially for SPI, is the background. Dithering allows to some extent to reveal extended features of astrophysical origin, but the main problem is the internal background produced by nuclear interactions between interplanetary energetic particles (or solar origin, and/or accelerated by the solar wind) and the spacecraft, which create a forest of instrumental γ-ray lines, sometimes located critically close to lines of astrophysical interest (Weidenspointner et al. 2003).

[1] But not impossible with a Bragg crystal refraction technique, such has been recently experimented in a ballon, Halloin et al. (2003).

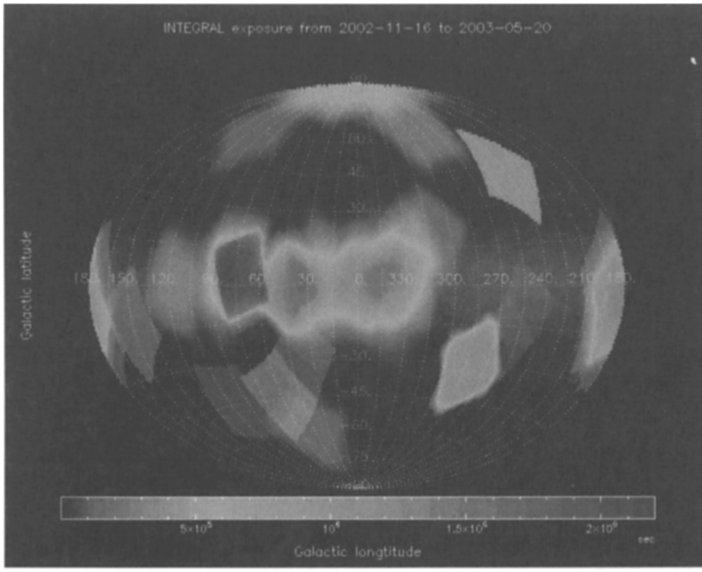

Figure 4. Exposure map of INTEGRAL observations, from Nov. 16, 2002 to May 20, 2003

3. Observations: present status and stellar program

3.1. General

INTEGRAL is an observatory open to the international community. For two years, 1/3 of the observing time is guaranteed to the INTEGRAL consortium, but the remaining 2/3 are open. AO-2 has recently been issued, with an enormous pressure factor (about 20), due mainly to the fact that some exposures (in particular with SPI on diffuse features) can be very long: 10^6 sec is equivalent to approximately two weeks, and there are only 52 weeks in a year, i.e., only 26 such observations can be performed ! But in general point sources like compact binaries or AGN are bright enough that $\sim 10^5$ sec exposures are sufficient. So far all instruments are nominal, and a significant fraction of the sky has already been covered, in particular along the galactic plane, which is monitored weekly to search for variable sources like novae. [FIG](For more information, consult the ISDC-Astrophysics Newsletter, at http://isdc.unige.ch) For completeness, we note that INTEGRAL is quite efficient to detect γ-ray bursts: the detection rate is about 1/month in the "fully coded field of view" of SPI, with a position accuracy of a few arcmin (thanks to the combination of instruments at different energies), and a special worldwide alert system has been implemented.

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3.2. Stellar observations

Not very many stellar observations are planned with INTEGRAL, but they will bring crucial information on stellar physics, both about the internal structure and nucleosynthesis, and about surface phenomena. This currently concerns three sources: the Cygnus region (PI J. Knödlseder), the relatively nearby WR star γ Vel (PI N. Mowlawi), and the Algol binary system (PI M. Güdel). [FIG]

- *Massive stars.* The main goal is to detect and map with SPI the ^{26}Al emission from the O stars in Cygnus, and from γ Vel. The first results of the 1 Msec Cygnus observations, which cover a wide area, have been published (Bouchet et al. 2003; Diehl et al. 2003), with the clear detection of Cyg X-1, Cyg X-3, and EXO 2030+375. Of course, the individual O stars in Cygnus will not be resolved, but the final goal is to compare the overall ^{26}Al diffuse emission from this area, especially in view of the large number of hidden O stars uncovered by way of their global IR emission coming from UV radiation reprocessed by the surrounding dust of their parent cloud (Knödlseder et al. 1999). A more specific test of nucleosynthesis models will be possible with the observation of the WR star γ Vel, which is relatively isolated in the sky. The detection of a high-energy non-thermal synchrotron + Compton continuum from electrons accelerated in its massive wind (White & Chen 1992) will also be sought.

- *Late-type stars.* Among bright, active late-type stars is the binary system Algol, for which a detailed mapping of the manetic active regions has been possible during an eclipse (Favata & Schmitt 1999). The goal here is to search for evidence of electron acceleration up to MeV energies by way of their synchrotron emission, which should be possible with IBIS during one of the frequent flares of Algol. This will give precious (and stellar for the first time) clues to particle acceleration during flares.

4. Conclusions and Expectations

The two main instruments useful for stellar observations are IBIS and SPI. The spectral and imaging performances of IBIS are now validated by various observations of known sources (the Crab and Vela pulsars in particular). For SPI, the imaging and spectroscopy of weak sources like stars is difficult because of the very complex spatial (galactic) and spectral (instrumental) background estimation. The INTEGRAL teams, and the ISDC, are working very hard to sort out the problems. A special issue of *Astronomy & Astrophysics* on the first results obtained with INTEGRAL has appeared in Nov. 2003 (vol. 411), and preliminary results are regularly posted on the ISDC web site. The stellar observations are in progress, and will undoubtedly break new ground in stellar physics –stay tuned !

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