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Nuclear Astrophysics with *INTEGRAL*

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Abstract
Observations of gamma-ray lines from nuclear transitions in the decay of radioactive isotopes produced in supernovae and novae, with the purpose to provide the most direct way of validating current models of explosive nucleosynthesis processes, rank among the prime scientific objectives of the *INTEGRAL* mission which will also grasp valuable nuclear astrophysics data on hydrostatic nucleosynthesis processes in massive stars and on high energy interactions involving accelerated particles.

1 Introduction:

The ESA (European Space Agency) scientific mission *INTEGRAL* (International Gamma-Ray Astrophysics Laboratory) is dedicated to the study of cosmic sources actives in the energy range 15 keV to 10 MeV with concurrent source monitoring in the X-ray (3-35 keV) and visible (500-850 nm) bands. The *INTEGRAL* Observatory will be launched in September 2001 by a Russian PROTON rocket into a highly eccentric 72-hour orbit. The nominal lifetime of the Observatory will be 2 years with possible extension to up to 5 years. A large fraction of the observing time will be made available to the worldwide scientific community. The scientific goals of *INTEGRAL* are addressed through the simultaneous use of high resolution spectroscopy with fine imaging and accurate positioning of celestial sources in the gamma-ray domain. Fine spectroscopy over the entire energy range will permit spectral features to be uniquely identified and line profiles to be determined for physical studies of the source region. In such a context, one of the two main *INTEGRAL* instruments, the spectrometer SPI (figure 1), has been designed to perform spectral analysis of localized and extended regions with performances at 1 MeV such as an energy resolution $E/\Delta E \approx 500$ and a 3σ narrow line sensitivity of $5\ 10^{-6}$ photons s^{-1} cm^{-2} (10^6 s exposure).

Figure 1: *Schematic view of the spectrometer SPI. The instrument features an array of 19 hexagonal high purity germanium detectors cooled by an active device to an operating temperature of 85 K. An hexagonal coded aperture mask is located 1.7 m above the detection plane in order to image large regions of the sky (fully coded field of view ≈ 16 degrees) with an angular resolution of 2 degrees. In order to reduce background radiation, the detector assembly is shielded by a veto system which extends around the bottom and side of the detector almost completely up to the coded mask. A plastic veto is provided below the mask to further reduce the 511 keV background. The spectrometer SPI is being developed under prime contractor responsibility of CNES (the French Space Agency) by a consortium of institutes in France (CESR Toulouse, CEA Saclay), Germany (MPE Garching), Italy (IFCTR Milano), Spain (U Valencia), Belgium (U Louvain), UK (U Birmingham), USA (UC San Diego, LBL Berkeley, NASA/GSFC Greenbelt). Principal Investigators are G. Vedrenne (CESR Toulouse), and V. Schonfelder (MPE Garching).*

2 Nuclear Gamma-Ray Line Astronomy:

Born of the union of astronomy and nuclear physics, nuclear astrophysics aims to explain the relative abundance of the elements and their isotopes. Following the founding paper of Burbidge et al. (1957), it is now well established that most of the elements are synthesized by the very nuclear reactions which are the source of stellar energy and which are responsible for their evolution. Stellar nucleosynthesis occurs either during stellar hydrostatic equilibrium or explosive stages, the latter marking either the end evolution of most massive stars (core collapse supernovae of both types, II and Ib), or a subsequent stage of the evolution of less massive stars in binary systems (novae and thermonuclear supernovae of type Ia). Material enriched with freshly synthesized nuclides is ejected from the sites where these nuclides are produced, either on the occasion of the most violent explosive stages of stellar evolution, or as a result of less dramatic processes, as e.g. intense stellar winds common to most massive stars. Such material mixes with interstellar matter, a medium from which new stellar generations are born. This enrichment of the Galaxy in "metals" (elements with atomic charge $Z > 2$) by successive cycles of nucleosynthesis is attested by astronomical data on element abundance measured at the surface of stars of different ages.

Such abundance measured in various astrophysical objects reflects the cumulative nucleosynthesis in the whole past. The great merit of gamma-ray line astronomy is to give useful hints on the present nuclear activity in the Universe. Indeed, nuclear gamma-ray lines, being the by-product of the de-excitation of atomic nuclei, are emitted from media where excited nuclei are copiously produced and a mechanism likely to populate atomic nuclear energy levels is the disintegration of unstable nuclei. However, the number of measurable gamma-ray emitters is limited compared to the whole list of unstable nuclei of the periodic table. Only a handful of isotopes is available: those produced with significant abundance by stars and having mean lifetimes between 0.3 to 10^6 years (see Table 1). As a matter of fact, nucleosynthesis processes occur in dense media fully opaque to gamma rays. Radioactive isotopes that can be detected by the gamma-ray line emission they give rise to are therefore those with sufficiently long lifetimes allowing them to disintegrate in media more transparent to gamma rays, whether they are carried away from the sites where they were synthesized, or whether their source medium quickly dilutes with time.

Table 1: Radioactive isotope disintegration chains producing the most easily detected gamma-ray lines

Decay chain	Most favorable cosmic sites	Released gamma-ray lines	
		Lifetime (year)	Energy (MeV)
$^{56}Ni \rightarrow ^{56}Co \rightarrow ^{56}Fe$	Supernovae	0.31 (a)	0.847, 1.238, 1.771
$^{57}Co \rightarrow ^{57}Fe$	Supernovae	1.1	0.122, 0.136
$^{22}Na \rightarrow ^{22}Ne$	Novae	3.8	1.275
$^{44}Ti \rightarrow ^{44}Sc \rightarrow ^{44}Ca$	Supernovae	70-96 (a,b)	0.068, 0.078, 1.156
$^{26}Al \rightarrow ^{26}Mg$	Red Giants, WR Stars, Novae, Supernovae	1.1 10^6	1.809
$^{60}Fe \rightarrow ^{60}Co \rightarrow ^{60}Ni$	Supernovae	2.2 10^6 (a)	1.173, 1.322

Note to Table 1: (a) Longest lifetime in the case of twofold decay chains (b) Uncertain estimate

Particle interactions may also lead to the formation of excited nuclei, either by inelastic collisions, or spallation reactions. Nuclear excitation of stable and abundant isotopes by means of inelastic collision by accelerated (5-50 MeV/n) particles results in a prompt gamma-ray emission due to the very short lifetime of the excited nuclear levels. However, these non-thermal processes, in order to be observable, require particularly intense fluxes of accelerated particles.

3 Observational Highlights:

3.1 Thermal Nucleosynthesis: Thermal nucleosynthesis of radioactive isotopes is present under two forms. *Hydrostatic nucleosynthesis* is at work in Wolf-Rayet (WR) stars (massive stars experiencing heavy mass losses through intense stellar winds) and AGB stars (red giants developing thermal pulses). *Explosive nucleosynthesis* occurs in core collapse supernovae (SNII, SNIb), thermonuclear supernovae in binary systems (SNIa) and novae.

3.1.1 Hydrostatic Nucleosynthesis: This mechanism is active in rather quite stellar stages, where temperature and density are constant over a long period of time. As far as gamma-ray line astronomy is concerned, the principal process of interest is the production and ejection of ^{26}Al by WR stars, that seem to be the best candidate according to the recent analysis of the observations performed by the COMPTEL experiment on board the *Compton Gamma-Ray Observatory* (Knödlseder, 1997). During hydrogen burning, ^{26}Al is produced via radiative proton captures by ^{25}Mg; after having removed the unprocessed envelope and thus uncovered the convective core, stellar winds carry away such a fresh ^{26}Al before decaying. The decay finally produces a line at 1.809 MeV within the optically thin interstellar medium. The mass of ^{26}Al thus generated is estimated to about 10^{-4} $M_{\odot}$. Thanks to the unprecedented performances of SPI (very high sensitivity to narrow lines combined to a wide field of view and to noticeable imaging capabilities), *INTEGRAL* observations will be decisive for the study of the 1.809 MeV emission due to ^{26}Al decay in providing detailed mapping of the galactic emission outlined by COMPTEL (see Figure 2).

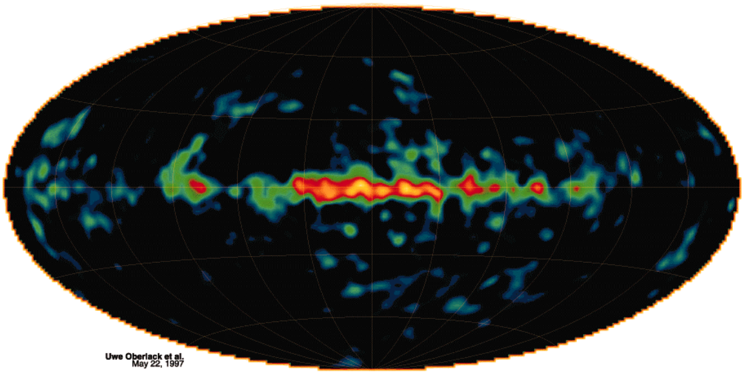

Figure 2: *Map in galactic coordinate of the 1.809 MeV line emission due to ^{26}Al decay resulting from the data recorded by the COMPTEL experiment on board the Compton Gamma-Ray Observatory (after Oberlack et al. 1996).*

3.1.2 Explosive Nucleosynthesis: The time scale of explosive nucleosynthesis is so short that beta decay has no time to operate. Under these conditions, a host of isotopes are made under the form of their radioactive (proton-rich) progenitor. As far as *core collapse supernovae* (SNII and SNIb) are concerned, ^{56}Ni, ^{57}Ni and ^{44}Ti are of the highest interest for gamma-ray line astronomy, as well as ^{26}Al, presumably also formed in these events. The mass of the radioactive isotopes thus generated depends on the temperature and density reached behind the shock wave and in front of the boundary between the imploding core giving rise to a neutron star and the ejected material. The estimation of these parameters is uncertain since they are sensitive to fine details of the pre-supernova structure and evolution and to the hydrodynamics of the explosion. In *thermonuclear supernovae* (SNIa), the exploding object is a white dwarf (WD) overloaded by the material accreted from a companion. When the critical Chandrasekhar mass (of about 1.4 $M_{\odot}$) is exceeded, the star looses its stability. Degenerate carbon burning becomes explosive and a large fraction of the WD is transformed into ^{56}Ni. *Nova explosions*, originating also from accreting WD, much more frequent than SNIa but much less spectacular, are expected to release radioactive isotopes such as ^{7}Be, ^{22}Na and ^{26}Al.

Even in the case of an instrument as sensitive as the *INTEGRAL* spectrometer, only nearby core collapse supernovae (within the Local Group of galaxies) are expected to produce detectable gamma-ray line emission through the decay of the radioactive isotopes they generate. However, thanks to the long lifetime of ^{44}Ti, *INTEGRAL* will be in a position to detect the line emission from the decay of ^{44}Ti released by recent galactic supernovae, including most of the supernovae that should have occurred since the last observed explosion, namely the supernova that Kepler observed in the year 1604. Search for such hidden supernovae ranks among the most exciting objectives of *INTEGRAL*, especially when taking into account the COMPTEL detection of the 1.156 MeV line emission from the decay of ^{44}Ti in the direction of two nearby recent supernovae (Iyudin et al. 1994; 1998).

Because of the large amount of radioactive material they release (of the order of 0.5 M_O in the form of ^{56}Ni) and thanks to the fact that the ejected material becomes promptly transparent to gamma rays, thermonuclear supernovae produce so bright line emissions during the tens of days following the event that *INTEGRAL* will be in a position to study distant SNIa, particularly in the Virgo cluster of galaxies. Possibility will then be given to assess the very source of SNIa luminosity and to provide useful hints on the use of SNIa as “calibrated candles” able to trace the past history of the Universe.

3.2 Non Thermal Nuclear Excitation: The second mode of production of cosmic gamma-ray lines is associated with flows of fast particles. Interactions of energetic nuclei generated by shock wave acceleration with the ambient target medium could, in principle, produce a wealth of gamma-ray lines. In such a context, observations of carbon and oxygen lines at 4.44 and 6.13 MeV would be the clue to the irradiation of molecular cloud by carbon and oxygen nuclei produced by massive stars and further accelerated to moderate energy (Parizot, 1997).

4 Conclusion:

With the launch in the near future of the *INTEGRAL* spacecraft, a golden age of nuclear astrophysics will open in Europe, at the point of convergence of nuclear physics and astrophysics. Time is ripe to join our efforts, especially having in mind the fact that *INTEGRAL* is an observatory-type mission with most of the total observing time being awarded as the general program to the scientific community at large. Proposals for observations will be selected on their scientific merit only by a single Time Allocation Committee. The first call for observation proposals will be issued one year prior to launch. The Integral Science Data Center (ISDC) will serve all users of *INTEGRAL*, in particular the entire general observer community. The ISDC is the place where the archive and derived products will be built and made accessible to the world wide astronomical community. All scientific data will be made available to the scientific community one year after they have been released to the observer. This guarantees the use of the scientific data for different investigations beyond the aim of a single proposal. Explicit references on *INTEGRAL* can be found either in the proceedings of past *INTEGRAL* Workshops (held in Saint Malo and in Taormina) as well as in the *INTEGRAL* World Wide Web pages (http://astro.estec.esa.nl/SA-general/Projects/Integral/integral.html).

References

Burbidge, M., Burbidge, G., Fowler, W., & Hoyle, F. 1957, Rev. Mod. Phys. 29, 547.

Iyudin, A.F. et al. 1994, A&A 284, L1.

Iyudin, A.F. et al. 1998, Nature 396, 142.

Knödlseder, J. 1997, PhD Thesis, Université Paul Sabatier, Toulouse.

Proceedings of the 2nd *INTEGRAL* Workshop, Saint Malo, 1996, “The Transparent Universe”, Eds: C. Winkler, T.J.-L. Courvoisier & P. Durouchoux, ESA SP-382, 1997.

Proceedings of the 3rd *INTEGRAL* Workshop, Taormina, 1998, “The Extreme Universe”, in press.

Oberlack, U. et al. 1996, A&AS C120, 311.

Parizot, E. 1997, PhD Thesis, Université Paris VII.