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INTEGRAL contributions to γ-ray line studies

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Abstract. During its 16 years in space, the INTEGRAL mission contributed more to astrophysical soft γ-ray line measurements than any other observatory before. With the high spectral resolution telescope SPI and the imager IBIS, a multitude of γ-ray lines have been detected, characterised, and used as tools to study the environments of a variety of sources and regions. In this work, the milestones of INTEGRAL γ-ray line measurements, and the developments and progress of research over time will be reviewed. In addition, an outlook what still remains to be discovered in the legacy data base of all INTEGRAL instruments will be provided. This includes the 511 keV line from positron annihilation in the bulge and disk of the Galaxy, MeV-line emission of decaying long-lived radioactive nuclei, such as ^{26}Al and ^{60}Fe from massive stars and their core-collapse supernovae (CCSNe), and immediate energy providers in explosive events as traced by the decay-chains from ^{7}Be, ^{22}Na, ^{44}Ti, and ^{56}Ni. INTEGRAL also contributes to solar physics and cosmic-ray (CR) studies by measurements of excitation lines of stable ^{2}H, ^{12}C, ^{16}O, as well as pulsar characteristics due to cyclotron lines. This work summarises the unique information about these objects, that can today only be extracted by measurements of γ-ray lines with INTEGRAL.

Key words. Gamma-ray lines; High-resolution spectroscopy; Nucleosynthesis; Cosmic rays; Supernovae; Antimatter: positrons

1. Introduction

1.1. Learning from γ-ray lines

Currently, the INTEGRAL satellite is the only active observatory that mounts instruments which are capable of studying the wealth of astrophysical objects that emit γ-ray lines. The coded-mask spectrometer SPI, with its 19 high-resolution Ge detectors, can resolve γ-ray lines between 20 and 8000 keV - the ideal range to study nucleosynthesis, the origin of antimatter, CR acceleration, magnetic fields of compact objects, and the interstellar medium (ISM). With a resolution power of 100–1000 (e.g. 3.1 keV FWHM at 1809 keV), SPI is invaluable for determining absolute and direct measurements of fluxes, Doppler-shifts, -broadenings, and kinematically or relativistically distorted line-shapes from a large variety sources.

The high photon energies from nuclear de-excitation, e.g. after radioactive decays or the annihilation of electrons (e^{-}s) with positrons (e^{+}s), are beneficial to obtain an unobscured view onto the physical processes

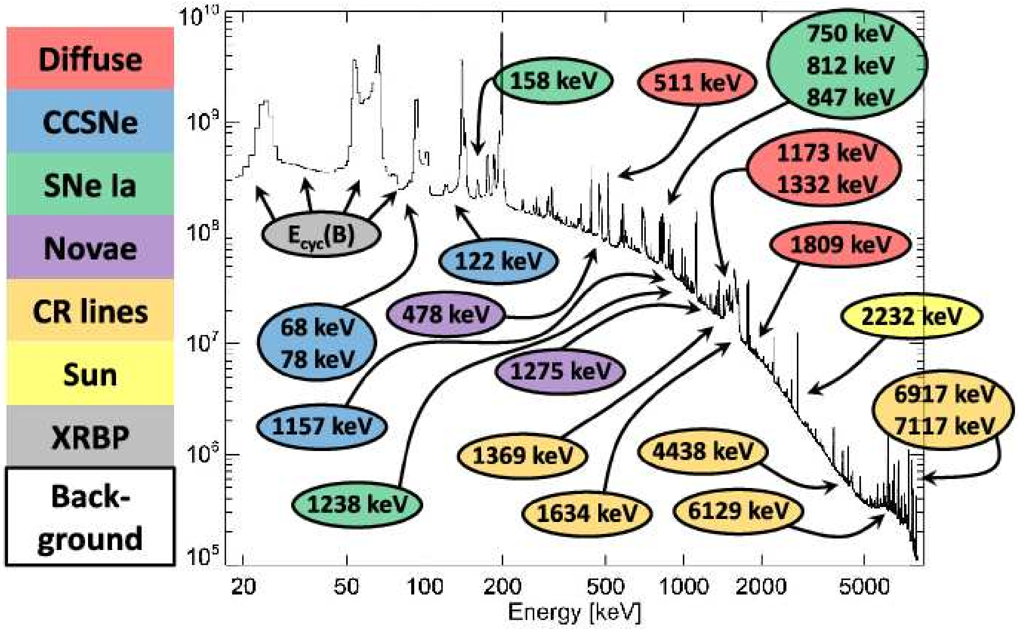

Fig. 1. SPI single event background spectrum (black histogram) from 16 mission years. In colours, prominent γ-ray lines from a variety of astrophysical sites are indicated. Note that there is substantial overlap between γ-ray lines from different source types. The indicated lines are either expected to be measurable or have already been detected and studied with INTEGRAL. See text for details.

that are active in a source. With the wealth of γ-ray lines, it is thus possible to “X-ray” deep into astrophysical objects and probe emission mechanisms directly where they are happening - before being processed towards outer layers.

1.2. Beyond the background issue

Measurements of celestial γ-ray line sources are difficult because typically, less than one in a hundred photons originates from the sky. The remainder is instrumental background (BG) which comes from nuclear excitations of satellite and instrument material, being bombarded by CRs. Understanding and modelling this instrumental BG in great detail is key to astrophysical γ-ray line measurements. The absolute BG amplitude, its rapid variation with time, and detector performance changes during the ongoing INTEGRAL mission make a stand-alone BG template unreliable. Instead, an overly empirical, yet physically motivated and flexible BG model is required to reduce the large systematics that may occur. In recent years, a lot of effort has been put into the construction of such a BG model. Diehl et al. (2018) showed the requirements of long-term monitoring of detector behaviours in the space environment around Earth, and fine spectroscopy of instrumental γ-ray lines. Based on the resulting and regularly updated SPI BackGround and Response DataBase, Siegert et al. (2019) constructed a BG model which is applicable for a large variety of sciences cases and photon energies, and discussed worked examples, also inclucing continuum emission. It was shown that residual systematics are now barely of the order of statistical uncertainties, which dominate the total measurements by far. Finally, modelling the BG is not an issue any more.

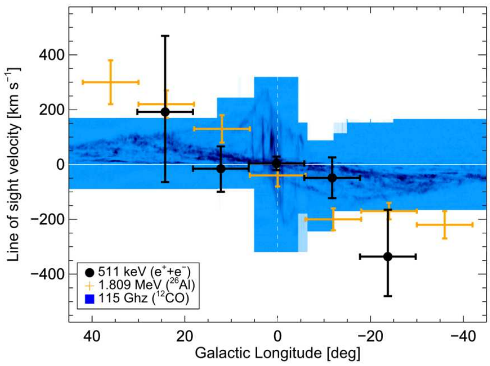

Fig. 2. Positron annihilation longitude-velocity diagram. Shown are **preliminary** Doppler-shift data points from the galactic 511 keV line (black, Siegert et al. 2019, in review) and ^{26}Al Doppler measurements (Kretschmer et al. 2013) on top of the galactic rotation curve from CO $J = 1 \rightarrow 0$ emission (Dame et al. 2001).

2. Overview of prominent γ-ray lines

In Fig. 1, a selection of γ-ray lines, which INTEGRAL either already detected or which are on the list of science goals (Vedrenne et al. 2003), is shown on top of the instrumental BG spectrum. In the following, the characteristics of these prominent γ-ray lines will be outlined. Examples of recent developments will be given in Sect. 3. This paper shall provide an overview of INTGRAL capabilities and achievements, rather than reviewing the individual science cases in great depth or listing every astrophysical object and γ-ray line.

2.1. Diffuse emission.

The diffuse large-scale emission from e$^-$-e$^+$ annihilation at 511 keV is puzzling astrophysisicts for more than 50 years. This emission signal is the strongest persistent γ-ray line seen fron Earth. Despite its large flux of $(2.74 \pm 0.03) \times 10^{-3}$ ph cm^{-2} s^{-1}, equivalent to about 5×10^{43} e$^+$ annihilating every second in the Milky Way, the origin of e$^+$s leading to this signal is still undiscovered. INTEGRAL contributed to this puzzle by high-resolution spectroscopic analyses, describing the environments in which e$^+$s annihilate (temperatures between 7000 and 40000 K, at ionisation fractions of 2–20 %; e.g. Churazov et al. 2005; Jean et al. 2006; Siegert et al. 2016b). In the first INTEGRAL mission years, only the bulge was seen in 511 keV emission, giving rise to a possible dark matter origin (Boehm et al. 2004). This turned out to be improbable after investigations of the Milky Way satellite galaxies (Siegert et al. 2016c). After more than seven years of exposure, the disk was finally detected, but its size is still under debate (Bouchet et al. 2010; Skinner et al. 2015; Siegert et al. 2016b). In addition, the disk may show different annihilation conditions than in the bulge (see Sect. 3.1, Siegert et al. (2016b), and Siegert et al. 2019, in review). Although, in principle, every astrophysical object can produce e$^+$s, the true sources remain hidden as propagation away from the e$^+$ sources (Alexis et al. 2014; Panther 2018) blurrs the signal. Intrinsic e$^+$ production has been directly measured only in rare cases with INTEGRAL, e.g. in the type Ia supernova (SN Ia) SN2014J Churazov et al. (2014); Siegert (2017) or the microquasar V404 Cygni (Siegert et al. 2016a). However, the escape from these sources either holds large uncertainties or purely relies on theoretical assumptions.

A secured source of e$^+$s ($\approx$ 10 %; e.g. Prantzos et al. 2011; Siegert 2017) in the Galaxy is the β^+-unstable isotope ^{26}Al which is produced predominantly in massive star nucleosynthesis, and ejected in stellar winds and CCSNe into the ISM. After the first all-sky emission map of decaying ^{26}Al at 1.809 MeV (τ_{26} = 1.05 Myr) with COMPTEL (Oberlack et al. 1996, e.g.), SPI improved both, the significance of the line signal over the INTEGRAL mission time Diehl et al. (2006); Wang et al. (2009); Kretschmer et al. (2013); Siegert (2017), and imaging beyond COMPTEL and empirical model fits (Bouchet et al. 2015).

With SPI's unprecedented spectral resolution, outperforming COMPTEL by more than an order of magnitude, it was possible to determine the kinematics of individual massive star regions (Diehl et al. 2010; Siegert & Diehl 2016) as well as to form a global picture of the hot ISM kinematics of the Milky Way (Kretschmer et al. 2013; Krause et al. 2015). These works provided and interpreted the first γ-ray line rotation curve, which shows a $\approx$ 200 km s^{-1} excess velocity with respect to the galactic rotation speed. Only a preferred direction of ^{26}Al ejecta towards less dense regions can explain this unique measurement. Finally, ^{26}Al mesurements allowed for a completely independent estimate of the CCSN rate in the Galaxy of $\approx$ 2 century^{-1} (Diehl et al. 2006; Siegert 2017).

Related to ^{26}Al and ongoing nucleosynthesis in the Milky Way is the longer-lived ^{60}Fe (τ_{60} = 3.75 Myr) with emission lines at 1173 and 1332 keV. Unlike lighter elements, ^{60}Fe is ejected in SN events only. Consequently, measurements of the emission ratio between the two isotopes provides already strong constraints about massive star evolution models. In particular, this ratio can also reflect the age of a stellar association. Due to radioactive build-up in satellite material (the decay rate of BG from ^{60}Co is smaller than the activation from CRs), the corresponding BG lines are linearly rising with time Diehl et al. (2018). This makes renewed analyses with even a lot more data one of the most complicated tasks. Wang et al. (2007) found a 4–5σ signal from the two lines in the galactic ridge with a ^{60}Fe-to-^{26}Al-ratio of (15 ± 6) %, by combining all INTEGRAL/SPI event types. After 16 mission years, profiting from improved BG modelling, Wang et al. (2019, in prep.) can confirm the ten year old results, and will provide the most accurate and most sensitive measurements of galactic-wide ^{60}Fe emission.

2.2. Supernova nucleosynthesis.

The list of γ-ray lines from nucleosynthesis products in both CCSN and type Ia SNe is extremely long. Either radioactive elementes are produced directly and decay on their characteristic time scales, producing γ-rays, or excitation of stable elements lead to specific lines.

The abundance of ejected material and the distance to the SN determines the absolute flux level, so that with nowadays instruments, only the strongest lines can be detected. In the case of CCSNe, the key measurements were the detection and characterisation of the ^{44}Ti decay chain γ-ray lines at 68, 78, and 1157 keV. With its half-life time of about 60 years, ^{44}Ti provides kinematic and morphological information of young SN remnants (SNRs), such as Cassiopeia A (Cas A, e.g. Siegert et al. 2015) and SN1987A (e.g. Grebenev et al. 2012).

These two SNe appear special as they are the only remnants where ^{44}Ti has been detected. Even though the CCSN rate in the Milky Way is about two events per century, only Cas A is seen, with its one order of magnitude more ejected ^{44}Ti mass than expected from theory. Younger SNRs, such as G1.9+0.3 or type Ia remnants like Tycho, are either too far away or show a lack of ^{44}Ti production. This makes ^{44}Ti to one of the most valuable γ emitters to study SN physics. While ^{44}Ti was shown to power the late optical light curve of SNe (e.g. Seitenzahl et al. 2014), the first light is mainly powered by the ^{56}Ni decay chain. Here, the fast decay to ^{56}Co (6 d) with the strongest lines at 158 and 812 keV, and then to stable ^{56}Fe (77 d) with lines at 847 and 1238 keV lead to the characteristic and quasi-standardisable light curves of type Ia SNe.

During INTEGRAL's operation time, two type Ia events were in reach for measuring these lines, SN2011fe in M101 and SN2014J in M82. While SN2011fe was too distant for SPI or IBIS to measure any γ-ray emission (OMC measured the optical light curve very accurately; Isern et al. 2011), INTEGRAL achieved an astrophysics milestone with the first measurements of the ^{56}Ni decay lines from SN2014J.

SPI and IBIS detected about 0.06 $M_\odot$ of ^{56}Ni on the the exploding white dwarf's surface (Diehl et al. 2014; Isern et al. 2016). The ^{56}Ni core mass was determined to be around 0.5 $M_\odot$ (Churazov et al. 2014; Diehl et al. 2015), as expected from standard type Is theory, and INTEGRAL also provided the first γ-ray line light curve of the rise and fall of ^{56}Co (Diehl et al. 2015).

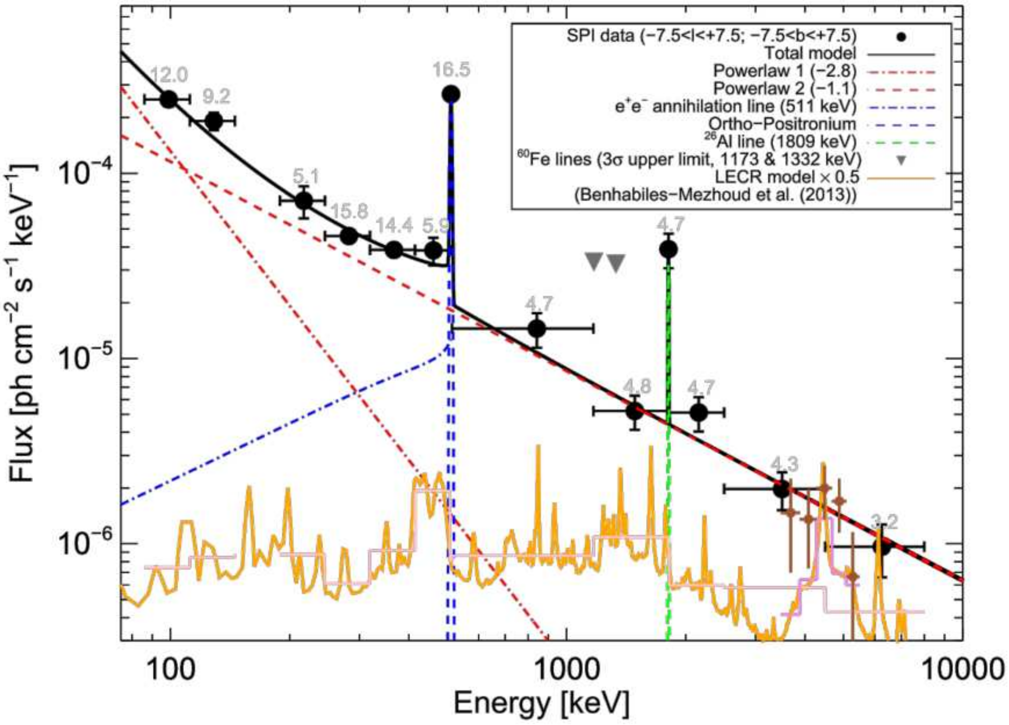

Fig. 3. SPI broadband spectrum of the inner Galaxy ($|b| < 7.5°, |l| < 7.5°$). Shown is a **preliminary** analysis (black data points) from 14 years of SPI data, fitted by a phenomenological model (solid black line, individual components dashed coloured), and a prediction (orange, Benhabiles-Mezhoud et al. 2013) from CR excitation emission (Siegert et al. 2019, in prep.).

3. Recent developments

3.1. Kinematics of positron annihilation

It is assumed that, if e^+s are ejected at MeV energies or higher, they have to cool to the tens of eV scale as otherwise, positronium formation would be less efficient. It may be expected that the e^+-kinematics follow either a prominent source, or the annihilating medium.

Measurements of these kinematics may thus deliver direct evidence for a source population and provides an independent view on the e^+ puzzle. In Fig. 2, the longitude-velocity diagram of the galactic 511 keV line is shown. The preliminary result shows consistency with galactic rotation, the kinematics from ^{26}Al, as well as with no rotation. While all these interpretations imply its own, very specific scenario, faster Doppler-velocities than galactic rotation would require special circumstances (Siegert et al. 2019, in review).

3.2. Low-energy cosmic-ray excitation

Inside the solar system, measurements of low-energy CRs (100 MeV) are difficult, because the contributions from solar particles dominate by far. Consequently, the starting point of CR acceleration hides from being studied. Outside the heliosphere, direct measurements are only possible with the Voyager spacecrafts (Stone et al. 2013), even though only measuring in the solar vicinity. Measurements of excitated nuclear γ-ray lines from ISM components or SNRs would provide an independent and unique mechanism to trace these low-energy CRs in differen environments. The galactic centre is a prominent candidate to detect these excitation lines, for example from ^{12}C at 4438 keV, ^{16}O at 6129 keV, ^{24}Mg at 1369 keV, or ^{20}Ne at 1634 keV (similar to what is seen in solar flares, without the neutron capture line at 2223 keV). In Fig. 3, the preliminary SPI broadband spectrum between 80 and 8000 keV from the galactic centre is shown, together with predictions from CR excitation. Above 4 MeV, the SPI line sensitivity is now compatible with that of COMPTEL and will provide stringent constraints for the low-energy CR spectrum, not only from the galactic centre but also from the most promising SNR Cas A to detect the ^{12}C and ^{16}O lines (Siegert et al. 2019, in prep.).

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