

Observations of cosmic nuclear gamma-ray lines

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Abstract. Nucleosynthesis in stars and supernovae creates radioactive nuclei, which are ejected into the interstellar medium by stellar winds and explosive events. Their radioactive decay is accompanied by the emission of gamma-ray lines that can be observed by space observatories. Different isotopes are identified and their distribution and kinematics is studied using spectroscopic information. With more than five years of INTEGRAL/SPI observations we can spatially resolve the ²⁶Al emission along the Galactic disk, derive the scale height of the Galactic ²⁶Al distribution and provide constraints on ²⁶Al kinematics for different regions. Groups of massive stars are detected in ²⁶Al and thus can serve as laboratories to study the feedback of the freshly synthesised nuclei into the surrounding interstellar medium. We predict the yields of massive star clusters using population synthesis models. Additionally, INTEGRAL has observed the decay lines of ⁴⁴Ti, constraining the dynamics of ⁴⁴Ti within the Cassiopeia A supernova remnant.

1. Production of long-lived isotopes in massive stars

Gamma-ray telescopes observe the decay of radioactive elements which are produced during stellar and explosive nucleosynthesis [1]. The long-lived isotopes ²⁶Al, ⁶⁰Fe and ⁴⁴Ti with half-lives of 0.717 My, 2.62 My and 58.9 y, respectively [2–4], are produced in massive stars, supernovae and novae.

²⁶Al is mainly produced by proton capture on ²⁵Mg in the context of the Ne-Na cycle and the Mg-Al chain in massive stars, in the AGB phase of intermediate mass stars and in nova explosions [5]. ²⁶Al decays into ²⁶Mg, emitting a γ -ray photon of 1808.65 keV [2].

Massive stars are as well known to produce ⁶⁰Fe during the final stages of stellar evolution via successive neutron captures on stable iron nuclei [6]. The decay of ⁶⁰Fe into ⁶⁰Co is accompanied in 2% of the decays by the emission of a 58.6 keV photon [2]. This line has not been detected up to now. In a successive decay into ⁶⁰Ni two additional photons at 1173.23 keV and 1332.50 keV are released [2].

The decay time scales of these two elements are similar to the timescales of massive star evolution. After the first detection of ²⁶Al by HEAO 3 [7] it was shown with COMPTEL that ²⁶Al is distributed mainly along the Galactic disk [8, 9], supporting a massive star origin [10]. ⁶⁰Fe was detected from the Galaxy with RHESSI [11] and INTEGRAL [12, 13]. Predictions of the yields of massive stars depend strongly on the prescription of nuclear reaction rates, stellar

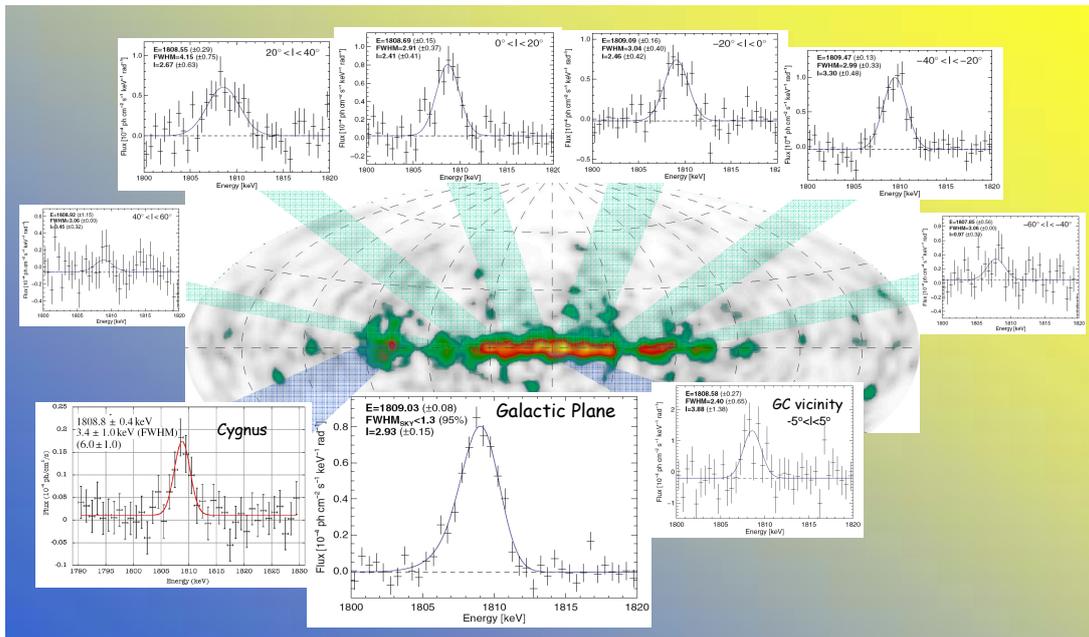


Figure 1. SPI spectra for different regions of the Galaxy [22, 23]. (INTEGRAL picture of the month on integral.esa.int)

winds, convection, mixing and rotation [6, 14, 15]. Since both elements are created by massive stars, the ratio of ^{60}Fe to ^{26}Al provides a good test for stellar models.

In core-collapse supernova explosions, conditions suited for the formation of ^{44}Ti during explosive Si-burning with α -rich freeze-out can be also found. The yields now strongly depend on the dynamics and on the conditions close to the mass cut [16, 17]. Detections of ^{44}Ti from Cassiopeia A have been reported by COMPTEL, BEPOSAX/PDS and INTEGRAL/IBIS [18–20]. ^{44}Ti decays via ^{44}Sc into ^{44}Ca , emitting photons at 67.87 keV, 78.34 keV and 1157.03 keV, respectively. Spectroscopic measurement of the decay lines of the ^{44}Ti decay chain with SPI can constrain properties of the explosion such as velocities of the ejecta.

2. Observations of Galactic ^{26}Al and ^{60}Fe

The International Gamma-Ray Astrophysics Laboratory INTEGRAL is in orbit since 2002. The spectrometer onboard INTEGRAL (SPI) [21] provides an excellent spectral resolution of $E/\delta E = 500$ at 1.3 MeV and offers the possibility to spectroscopically resolve Doppler velocities down to few tens of km s^{-1} .

2.1. Large-scale properties

Diehl et al. have shown that the ^{26}Al line is intrinsically narrow [24], thus ruling out a result obtained earlier with GRIS [25]. Due to continuous observations we could gain in sensitivity and, after 5 y of observations, improve the upper limit for the line width from 2.8 keV to less than 1.3 keV (2σ), corresponding to Doppler velocities of $\approx 150 \text{ km/s}$. This result is consistent with the expectations from Galactic rotation and modest turbulence of the interstellar medium surrounding the ^{26}Al sources.

The ^{26}Al scale height of the inner Galaxy is 130_{-70}^{+120} pc, larger than the scale height of the molecular disk or the massive stars, but smaller than the outer thick disk component of Taylor and Cordes' model for the density distribution of free electrons [26]. We showed that the spiral

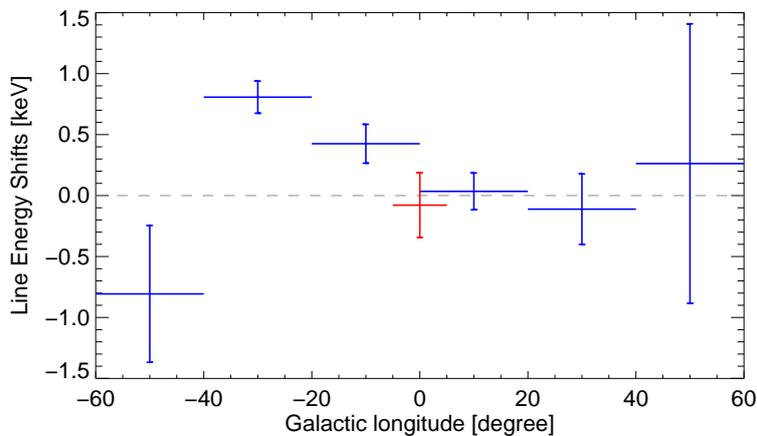


Figure 2. Doppler shifts of the 1809 keV line for different Galactic longitudes. The horizontal error bars represent the longitude interval.

arm component of this model describes the distribution of ^{26}Al in the inner Galaxy better than a simple exponential disk model. This is consistent with massive stars located in the spiral arms and ejecting ^{26}Al .

2.2. Spatially resolved spectroscopy

We have further continued our spectroscopic study in the inner Galaxy [24, 27] and increased the number of spectra to more than 6 from different sky regions [22, see Fig. 1]. The spectral parameters intensity, line shift and width have been obtained for 20° wide longitude bins and a 10° wide bin centered at the direction towards the Galactic Center. The intensity distribution along the Galactic plane is in agreement with the intensity derived from the COMPTEL ^{26}Al map. The obtained widths of the spectral lines can be explained by the instrumental spectral resolution except for longitude bin $l \in [20^\circ, 40^\circ]$. The line broadening corresponds to velocities of $\approx 480 \pm 170$ km/s. Figure 2 shows the shifts in line position along the Galactic plane. The overall pattern reflects the Doppler shifts expected from Galactic differential rotation. A possible contribution from a Galactic bar is being investigated.

2.3. Nearby star forming regions

In addition to the properties of the Galactic disk as a whole, we investigate ^{26}Al in specific nearby star forming regions. A prominent region in COMPTEL's ^{26}Al map is the Cygnus region with an assembly of well-known nearby OB associations. With SPI, the ^{26}Al line is detected and an upper limit for ^{60}Fe emission is given [23].

In order to interpret our experimental results with respect to yields calculated from stellar models we have updated our population synthesis model of massive stars including rotation, supernova yields, wind prescription and the new value for the ^{60}Fe lifetime in order to predict the time dependence of the ^{26}Al and ^{60}Fe yields [28]. In this way we can calculate the time evolution of the $^{60}\text{Fe}/^{26}\text{Al}$ ratio. For a typical size of a stellar cluster of 100 stars, statistical fluctuations play an important role. We assess the non-gaussianity of the uncertainties by Monte-Carlo simulations.

For Cygnus, the predicted fluxes for ^{26}Al and ^{60}Fe are in agreement with the observations if the age of the ^{26}Al emitting association is younger than 5 My [23]. In future studies we will apply the code as well to other nearby star forming regions such as Scorpius and Centaurus (Sco-Cen) (Diehl et al, in preparation) or Orion, where we have a hint for ^{26}Al emission.

3. ^{44}Ti sources

Using 4 y of SPI data we derived upper limits for the 1157 keV decay line of ^{44}Ti for Cas A. A minimum line broadening that translates into a lower limit for the expansion velocity of the ^{44}Ti ejecta of ≈ 500 km/s is required to explain our non-detection, given the detection of ^{44}Ti with the hard X-ray imager IBIS onboard INTEGRAL [29]. As typical velocities within the remnant are all larger than this limit, this result does not allow to constrain the location of ^{44}Ti .

Up to now no other direct detection of a ^{44}Ti source has been reported [30]. This remains a puzzle as supernova models predict yields that should be reflected as ^{44}Ti sources in the Galactic disk observable with INTEGRAL (see [31] for a discussion).

Acknowledgments

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References

- [1] Leising M and Diehl R 2009 *ArXiv e-prints (Preprint 0903.0772)*
- [2] Firestone R B and Ekström L P 99 Table of Radioactive Isotopes URL <http://ie.lbl.gov/toi/index.htm>
- [3] Rugel G *et al.* 2009 *Physical Review Letters* **103** 072502–+
- [4] Ahmad I *et al.* 2006 *Phys. Rev. C* **74** 065803–+
- [5] Prantzos N and Diehl R 1996 *Phys. Rep.* **267** 1–69
- [6] Limongi M and Chieffi A 2006 *Astrophys. J.* **647** 483–500 (*Preprint arXiv:astro-ph/0604297*)
- [7] Mahoney W A, Ling J C, Jacobson A S and Lingenfelter R E 1982 *Astrophys. J.* **262** 742–+
- [8] Diehl R *et al.* 1995 *Astron. Astrophys.* **298** 445–+
- [9] Plüschke S *et al.* 2001 *Exploring the Gamma-Ray Universe (ESA Special Publication vol 459)* ed Gimenez A, Reglero V and Winkler C pp 55–58
- [10] Knödseder J 1999 *Astrophys. J.* **510** 915–929
- [11] Smith D M 2004 *5th INTEGRAL Workshop on the INTEGRAL Universe (ESA Special Publication vol 552)* ed Schoenfelder V, Lichti G and Winkler C pp 45–+
- [12] Harris M J *et al.* 2005 *Astron. Astrophys.* **433** L49–L52 (*Preprint arXiv:astro-ph/0502219*)
- [13] Wang W *et al.* 2007 *Astron. Astrophys.* **469** 1005–1012 (*Preprint 0704.3895*)
- [14] Woosley S E and Heger A 2007 *Phys. Rep.* **442** 269–283 (*Preprint arXiv:astro-ph/0702176*)
- [15] Tur C, Heger A and Austin S M 2009 *ArXiv e-prints (Preprint 0908.4283)*
- [16] Woosley S E and Weaver T A 1995 *Astrophys. J. Supplement* **101** 181–+
- [17] Diehl R, Prantzos N and von Ballmoos P 2006 *Nuclear Physics A* **777** 70–97
- [18] Iyudin A F *et al.* 1994 *Astron. Astrophys.* **284** L1–L4
- [19] Vink J *et al.* 2001 *Astrophys. J.* **560** L79–L82 (*Preprint arXiv:astro-ph/0107468*)
- [20] Renaud M *et al.* 2006 *Astrophys. J.* **647** L41–L44 (*Preprint arXiv:astro-ph/0606736*)
- [21] Vedrenne G *et al.* 2003 *Astron. Astrophys.* **411** L63–L70
- [22] Wang W *et al.* 2009 *Astron. Astrophys.* **496** 713–724 (*Preprint 0902.0211*)
- [23] Martin P 2008 *La vie et la mort des étoiles massives révélées par l'observation des raies gamma nucléaires grâce au spectromètre INTEGRAL/SPI* Ph.D. thesis Université Toulouse III – Paul Sabatier
- [24] Diehl R *et al.* 2006 *Astron. Astrophys.* **449** 1025–1031 (*Preprint astro-ph/0512334*)
- [25] Naya J E *et al.* 1996 *Nature* **384** 44–46
- [26] Taylor J H and Cordes J M 1993 *Astrophys. J.* **411** 674–684
- [27] Diehl R *et al.* 2006 *Nature* **439** 45–47 (*Preprint arXiv:astro-ph/0601015*)
- [28] Voss R *et al.* 2009 *ArXiv e-prints (Preprint 0907.5209)*
- [29] Martin P, Knödseder J, Vink J, Decourchelle A and Renaud M 2009 *Astron. Astrophys.* **502** 131–137
- [30] Renaud M *et al.* 2004 *5th INTEGRAL Workshop on the INTEGRAL Universe (ESA Special Publication vol 552)* ed Schoenfelder V, Lichti G and Winkler C pp 81–+
- [31] The L S *et al.* 2006 *Astron. Astrophys.* **450** 1037–1050 (*Preprint arXiv:astro-ph/0601039*)