26 AL STUDIES WITH INTEGRAL'S SPECTROMETER SPI

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ABSTRACT

26 Al radioactivity traces recent nucleosynthesis throughout the Galaxy, and is known to be produced in massive stars and novae. The map from its decay gamma-ray line suggests massive stars to dominate, but high-resolution line spectroscopy is expected to supplement imaging of 26 Al source regions and thus to help decide about the 26 Al injection process and interstellar environment, hence about the specific massive-star subgroup and phase which produces interstellar 26 Al. The INTEGRAL Spectrometer SPI has observed Galactic 26 Al radioactivity in its 1809 keV gamma-ray line during its first inner-Galaxy survey. Instrumental background lines make analysis difficult; yet, a clear signal from the inner Galaxy agrees with expectations. In particular, SPI has constrained the line width to exclude previously-reported line broadenings corresponding to velocities >500 km s⁻¹. The signal-to-background ratio of ∼ percent implies that detector response and background modeling need to be fine-tuned to eventually enable line shape deconvolution in order to extract source location information along the line of sight.

Key words: nucleosynthesis; supernovae; novae; massive stars; instruments: gamma-ray telescopes.

1. INTRODUCTION

Radioactive 26 Al traces recent nucleosynthesis activity throughout the Galaxy through gamma-rays emitted with their decay after a lifetime τ=1.04 My. The gamma-ray photon energy is 1808.65 (±0.07) keV in the laboratory frame. Such gamma-rays penetrate interstellar matter easily and reach gamma-ray telescopes even from within dense molecular clouds. Their densities are

\[ \rho \leq 10^{-18} \text{g cm}^{-3} \], the line-of-sight mass column reaches \( \int \rho \, ds \ll \text{g cm}^{-2} \). Therefore interstellar clouds occult sources at almost all other frequencies of the electromagnetic spectrum; only stellar envelopes reach column densities above a few g cm⁻², the optical depth for such gamma-rays, so that radioactivities inside stars and the early supernova and nova phases remain hidden from direct observations.

All-sky mapping of 26 Al gamma-rays with the COMPTEL imaging telescope (see Fig. 1) [Oberlack 1997; Plüschke et al. 2001] has convincingly shown that the 26 Al sky reflects recent nucleosynthesis over the entire Galaxy, rather than peculiar interstellar 26 Al in the solar vicinity; the latter had been suggested from 26 Al enrichments of the early solar system as inferred from meteorites.

Presolar grains in meteorites have shown in recent years that all candidate sources of 26 Al (novae, AGB stars, Wolf-Rayet stars, and core-collapse supernovae) indeed produce 26 Al [Amari et al. 2001; Nittler et al. 1996]. Yet, we consider plausible that massive stars dominate the Galactic 26 Al budget.
2. STATUS OF $^{26}$AL STUDIES

A number of experiments have measured cosmic $^{26}$Al gamma-rays. As the spatial resolutions of instruments vary between allsky except Earth’s shadow (RHESSI, $\approx 230^{\circ}$), $\approx 180^{\circ}$ (SMM), and $\approx 3$-$4^{\circ}$ (SPI/INTEGRAL, COMPTEL), flux values can be compared only for large regions such as the bright ridge (Fig.1) of the inner Galaxy (defined as the inner radian, $\approx \pm 30^{\circ}$; the latitude integration range is less critical, $\approx \pm 15^{\circ}$ see Fig.1). Fig.2 summarizes the flux values which have been derived for this region from 9 experiments, 5 of them with reported significant detections. The discrepancies among experiments may indicate instrumental systematics, but partly also may be due to instrument field-of-view differences (see e.g. Wunderer et al. (2004)) and the definition of background regions. Therefore, from this integrated flux of $\approx 1 \pm 1 \times 10^{-7} \text{ph cm}^{-2} \text{s}^{-1}$ only weak constraints on the sources of $^{26}$Al can be derived when integrated yields per type of source from models are compared to this value. Interpretations depend on the spatial distribution in the Galaxy, from models smoothly following interstellar gas as represented by exponential disks with typical scales $R \approx 3.5$ kpc and $z \approx 0.1$ kpc (Ferriera et al. 1995; Diehl et al. 1996), to irregular models such as Cygnus (see Fig.1 and Diehl et al. 1996; Knödlseder et al. 1999). From COMPTEL, a total Galactic mass of $\approx 2 \pm 1$ M$_{\odot}$ has been estimated (Knödlseder et al. 1996, 1999). All candidate sources all have been reported to be able to produce such amounts (Timmes et al. 1997; Mevnet et al. 1997; Forrestini & Charbonnel 1997; Starrfield et al. 2000). But yields for AGB stars are probably most uncertain (0.01-4 M$_{\odot}$, Mowlavi & Meynet 2000), and nova yields in current models are 0.1–0.4 M$_{\odot}$ (Jose et al., 1997) and would reach the observed total only under extreme mixing assumptions or if scaled with the ejected-mass ratios between models and nova observations to obtain such high values; therefore these two candidate-source arguments are somewhat controversial. For massive stars in their Wolf-Rayet and core-collapse supernova stages, much detailed modeling is available, and both are compatible with these inferred 2 M$_{\odot}$ of $^{26}$Al in the Galaxy (though on the low side) (Prantzos & Diehl 1996; Vuissiez et al. 2003; Rauscher et al. 2002).

Other arguments can be derived from a comparison of the $^{26}$Al map with tracers of the candidate sources. From comparisons of heated-dust distribution, free-electron distribution, and H$_{\alpha}$ maps, an $^{26}$Al origin in massive stars has been found most plausible (Prantzos & Diehl, 1996; Chen et al. 1999; Diehl et al. 1998; Knödlseder et al. 1999). In particular, the ionizing power and $^{26}$Al yields from massive stars have been shown to be consistent: the Galactocentric gradient for supernova and Wolf-Rayet star space densities predicts an $^{26}$Al yield profile as a result of different metallicity dependencies for these source types (Prantzos & Diehl, 1996), which matches the $^{26}$Al map profile more closely for a Wolf-Rayet origin (Knödlseder, 1999); furthermore, the presence of significant $^{26}$Al in the young Cygnus massive-star region with probably-low supernova history suggests that the Wolf-Rayet phase of massive stars dominates over the contribution from core collapses (Knödlseder et al. 2002).

But, detailed proof is not available yet. Convincing arguments could be derived from better estimates of the distances and locations of candidate sources. This can be achieved in localized source regions such as Cygnus, Vela, and Orion (see contributions by Knödlseder et al., and Schanne et al., these Proceedings, and Diehl et al. (2001)): population-synthesis modeling of the $^{26}$Al content in the region can be compared to the gamma-ray measurements, to check for consistency of the age of the stellar population with nucleosynthesis models (see Cervino et al. 2000, Plischke et al. 2000, Knödlseder et al. 2004). Moreover, high-resolution spectroscopy together with spatial resolution on the scale of degrees, such as available with INTEGRAL (Winkler et al. 2003), may allow exploitation of Galactic rotation to locate source regions in the inner Galaxy (see below).

The measurements of the $^{26}$Al gamma-ray line profile with experiments featuring high-resolution spectroscopy (see Fig.3) are somewhat controversial. The GRIS balloon-borne experiment had obtained a significantly-broadened line, corresponding to interstellar velocities of decaying $^{26}$Al nuclei of 540 km s$^{-1}$ (Naya et al. 1996): this had been difficult to understand, unless large (kpc-
Figure 3. Measurements/constraints of the intrinsic, astrophysical width of the 1809 keV \(^{26}\)Al line: For the inner Galaxy three different experiments have been made, SPI also reported a measurement for the Cygnus region. The significant broadening reported by GRIS is not seen by other experiments.

Figure 4. The instrumental background spectrum in the vicinity of the \(^{26}\)Al line is dominated by continuum. But a feature from several blended lines at 1810 keV, although much weaker than adjacent background lines from Al and Bi activation at 1779 and 1764 keV, respectively, complicates spectroscopy of the \(^{26}\)Al line.

Figure 5. The instrumental background feature underlying the \(^{26}\)Al line is probably composed of 3 lines, at energies 1805.5, 1808.7, and 1810.7 keV, respectively. Here we show how a line at 1808.6 keV with instrumental resolution is embedded in this feature (top). The residual spectrum (bottom) indicates the two other instrumental line components at 1805 and 1811 keV, both represented well by a Gaussian of instrumental width. Line intensity ratios are 0.09/0.52/0.39, for the 1805.5, 1808.7, and 1810.7 keV lines, respectively, with an uncertainty ±0.015 in each of these.

sized) cavities in the interstellar medium or dust grains would hold the bulk of \(^{26}\)Al (e.g. Chen et al., 1997; Sturner & Naya, 1999). But all satellite-based Ge detector experiments report \(^{26}\)Al line widths consistent with instrumental resolutions or only slightly broadened (Mahoney et al., 1982; Smith, 2003; Diehl et al., 2003; Knödlseder et al., 2004) (see Fig. 3); this suggests some unknown systematic distortion of the GRIS measurement. Still, gamma-ray spectroscopy in space at the 0.1 keV level is an experimental challenge; careful assessments of instrumental response and background are essential.

3. INTEGRAL SPECTROMETER DATA AND ANALYSIS

The SPI spectrometer on INTEGRAL features a 19-element Ge detector camera embedded in a massive shield of BGO detectors, with imaging capability due to a tungsten coded-mask mounted in the telescope aperture (Vedrenne et al., 2003; Roques et al., 2003). At 1809 keV, the SPI spatial resolution is estimated as 2.8°, point source sensitivity as \(2.5 \times 10^{-5}\) ph cm\(^{-2}\)s\(^{-1}\) for a narrow line, and spectral resolution has been measured as 3.0 keV (Roques et al., 2003; Jean et al., 2003). Spectral resolution varies over time, due to cosmic-ray irradiation of the detectors which degrades the charge collection efficiency; this is rectified periodically through detector annealing procedures, restoring the quoted resolution (Roques et al., 2003). Spectral analysis must account for these temporal variations to enable line shape studies.

The SPI sensitivity is constrained by the underlying instrumental background. In the vicinity of the \(^{26}\)Al line (see Fig. 4), a broad spectral feature is observed, which probably is a blend of 3 background lines. Background is expected at 1808.65 keV from excited \(^{26}\)Mg produced from spallation of Al and from \(\alpha\)-captures on Na, and at 1810.7 keV from \(^{56}\)Mn(\(\beta^-\))\(^{56}\)Co(\(EC\))\(^{56}\)Fe (Weidenspointner et al., 2003). But other nuclear lines may contribute: In particular, there is a strong
hint for another, yet unidentified line, at 1805.5 keV (see Fig. 4). The total event rate in the instrumental feature is $2 \times 10^{-1}$ Hz, which compares to an expected celestial $^{26}$Al event rate of a few $10^{-3}$ Hz at 1808.6 keV from diffuse emission in the inner Galaxy.

4. SPI RESULTS AND ISSUES

From the first part of the inner-Galaxy deep exposure (GCDE), the detection of the 1809 keV gamma-ray line from $^{26}$Al could be reported (Diehl et al., 2003) from $\approx 1$ Ms of exposure selected as useful at the time). Considerable uncertainties had to be faced, since underlying background is large and variable. Different approaches to spectral analysis and background treatment are essential at this early stage of the mission to get estimates of systematic uncertainties and the overall consistency of results, because the coded-mask encoding of the signal is rather weak for diffuse emission. The $^{26}$Al sky intensity from the inner $\pm 30^\circ$ of the Galaxy was derived as $(3\pm 5) \times 10^{-4}$ ph cm$^{-2}$ s$^{-1}$, the line width was found consistent with SPI's instrumental resolution of 3 keV (FWHM). Figure 7 shows a spectrum obtained from these data through one of the analysis approaches discussed in Diehl et al. (2003). An offset by $\leq 0.3$ keV in line energy was attributed to the preliminary energy calibration.

In the meantime, the exposure of the inner Galaxy has been more than doubled, and data corruption during processing have been minimized, so that an effective exposure (live time) of 3.6 Ms is obtained (see Fig. 4). Additionally, the energy calibrations have been improved (Lonjou et al., 2004), and the background behavior has been studied in much more detail; several approaches to model the instrumental lines and continuum are being employed and refined (Weidenspointner et al., 2003; Jean et al., 2003). We usefully exploit the performance record of SPI over mission time for energy calibration; in addition, background modeling benefits from such continuous data, and in particular from exposures off the plane of the Galaxy which are presumably free of celestial $^{26}$Al signal. (For the earlier analysis, only off-source data from Crab and LMC exposures could be used, because of several changes of operational mode in the early part of the mission.) With now $\approx 4$ Ms of Galactic Plane exposure from the INTEGRAL Core Program (Fig. 6), and more than 2 Ms of additional performance data at other times, the background history can be traced much more accurately.

For an adequate model of background in the Ge detector spectra, we use adjacent energies to force an absence of celestial signal outside the $^{26}$Al line; in the $^{26}$Al line region, we adopt the spectral signature of background from off-source measurements. As one approach, we scale this template at fine time resolution to model line background intensity variations from saturated event counts in the Ge detectors as a tracer of activation, and account for radioactive build-up where lines are identified with an isotope (see Jean et al., 2003; Knödlseder et al., 2004 for further details on this approach). To make use of SPI as an imaging spectrometer, we may not only impose constraints on characteristics expected for background, but also on the shadow pattern cast by celestial photons as they illuminate the Ge camera through the coded mask; else the discrimination of the celestial component against the background component will be blurred. We implement this through an assumption on the intensity distribution in the sky, and fit the scaling factor of this sky model per each spectral bin, producing as result a spectrum.
of celestial intensity. Software tools `spdifit` and `spi_obs_fit` are used for this analysis (see Diehl et al. 2003, Knödlseder et al. 2004). These efforts improve the sensitivity to the celestial signature substantially, beyond on/off methods. In Fig. 5 we illustrate how additional data and better calibrations and background treatment improve spectra for the inner Galaxy; the analysis approach shown here is closest to the one which produced the result shown in Fig. 4.

The distribution of $^{26}$Al emission is modeled here by the emission of dust as observed by COBE/DIRBE at 240 μm, background is modeled from adjacent energy bands adjacent to the line (1786-1802 and 1815-1828 keV), plus a line complex template extracted from off-source observations of the LMC (Fig. 7), and of all observations available at latitudes $\geq 20^\circ$ (Fig. 5), respectively, always normalized following the intensity of saturated events in Ge detectors. Again, variations of sky models do not affect results, but background models have a significant impact. Biases are possible which suppress Galactic $^{26}$Al or which still retain a contribution from the structured instrumental background. Therefore, quantitative results for the Galactic large-scale $^{26}$Al emission significantly beyond our earlier paper (Diehl et al. 2003), in particular intensity and gamma-ray line shape details, will have to await sufficiently deep understanding of the biases of each of our analysis approaches, through simulations and through tests on other source cases. Fine-tuning to optimize performances of each approach, plus uncertainty estimates per approach are in progress, so that consistency of these $^{26}$Al results can be demonstrated.

Further sophistication of such analysis would be the generation of $^{26}$Al sky intensity distributions on the sky. This becomes feasible, once the celestial signal is sufficiently significant so that it can be broken down into different "pixels" on the sky. First steps towards this have been taken by splitting the sky intensity models for different quadrants of the Galaxy, and by the iterative imagining methods adapted from COMPTEL analyses (Knödlseder et al. 1999, Strong 2003). Publication agreements within INTEGRAL’s Science Working Team have led to a split of studies of different Galactic quadrants, pursued by different subgroups. These spatially-resolved $^{26}$Al results will thus be published elsewhere. Most sensitive large-scale spatially-resolved studies require one to exploit all pointings along the Galactic plane, and model background accurately around all these observing times.

Once this will be achieved, the Doppler motion of source regions at different locations within the Galaxy is expected to leave a characteristic imprint on the $^{26}$Al gamma-ray line shape. Simulations have been performed to demonstrate capabilities of SPI observations (Kretschmer et al. 2003, 2004). Fig. 9 shows the idealized simulated line shape (centroid, intensity, width) versus Galactic longitude from $^{26}$Al ejected by nucleosynthesis events into a supernova-like environment (see Kretschmer et al. 2003 for details), adopting current Galactic rotation models and a spatial distribution model of sources derived from pulsar dispersion measurements, which model free electrons in the Galaxy (Taylor & Cordes 1993). It has been shown that the ionization from massive stars produces a spatial distribution reminiscent of observed $^{26}$Al gamma rays. The ionization power and the $^{26}$Al yields from the population of massive stars throughout the Galaxy make up a consistent description of massive-star origin for $^{26}$Al (Knödlseder 1999). If sufficiently large regions on the sky with Doppler motions in opposite directions are integrated and compared against each other, a displacement of the line centroids as large as 0.5 keV should result. With SPI’s energy resolution of 3 keV, this will be significant for a statistical accuracy corresponding to 3 Ms of exposure throughout these regions of the Galactic plane, assuming that systematic uncertainties are negligible in comparison (see Fig. 10). This appears achievable over the duration of the INTEGRAL mission, yet presents a significant challenge for data analysis in the light of current uncertainties.

5. SUMMARY

The Galactic emission from $^{26}$Al provides unique insight into the massive star population of the Galaxy and its interaction with the interstellar medium. Several experiments have set the stage for addressing the related astrophysical questions with INTEGRAL’s spectrometer: the Galaxy-wide flux measurement still lacks the precision required for source type discrimination. Local intensity measurements such as in the Cygnus region will be a valuable complement to this study, because in this case source populations are better constrained than in the inner Galaxy (see Knödlseder et al. 2004). Fine spectroscopy promises to become a diagnostic, both for source distributions within the Galaxy (through
Figure 10. Line profiles from regions east (dotted) and west (dashed) of the Galactic Center show an effective displacement of line centroids by 0.5 keV. SPI’s instrumental energy resolution blurs these idealized profiles (dash-dotted, long-dashed lines), so that the statistical precision of 3 Ms of exposure is needed over these regions.

Galactic rotation), and for ejection dynamics and the interstellar medium surrounding the sources in localized regions. SPI measurements of the first 1.5 years have demonstrated that INTEGRAL has the potential to provide answers within the time frame of its mission.

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REFERENCES

Amari S., et al. 2001, ApJ, 551, 1065
Cervino M. et al. 2000, A&A, 363, 970
Chen, W., Gehrels, N., and Diehl, R. 1995, ApJ, 444, L57
Chen, W., Diehl, R., Gehrels, N., et al. 1997, ESA-SP 382, 105
Diehl, R., et al. 2003, A&A, 411, 451
Diehl, R., et al. 2001, New Ast.Rev., 46, 547
Diehl, R., et al. 1996, A&AS, 120, 4, 321
Diehl, R., Dupraz, C., Bennett, K., et al. 1995, A&A, 298, 445
Ferriere K. 2001, Rev.Mod.Phys., 73, 4, 1031
Forrestini M., and Charbonnel C. 1997, A&AS 123, 241
Gehrels, N., and Chen, W. 1996, A&AS, 120, 331
Jean, P., Vedrenne, G., Roques J.-P., et al. 2004, this volume
Jean, P., Vedrenne, G., Roques J.-P., et al. 2003, A&A, 411, L107
Jose J., Hernanz M., Coc A. 1997, ApJ, 479, L55
Knödlseder, J., Lonjou, V., Jean, P., et al. 2004, this volume
Knödlseder, J. 2004, this volume
Knödlseder, J., Lonjou, V., Jean, P., et al. 2003, A&A, 411, L457
Knödlseder, J., et al. 2002, A&A, 390, 945
Knödlseder, J., Bennett, K., Bloemen, H., et al. 1999, A&A, 344, 68
Knödlseder, J. 1999, ApJ, 510, 915
Knödlseder, J., Dixon, D., Bennett, K., et al. 1999, A&A, 345, 813
Knödlseder, J., et al. 1996, A&AS, 120, 4, 335
Kretschmer K., Diehl R., Hartmann D.H. 2004, this volume
Kretschmer K., Diehl R., Hartmann D.H. 2003, A&A, 412, L47
Lonjou, V., et al. 2004, this volume
Mahoney, W. A., Ling, J.C., Jacobson A.S., Lingenfelter R.E. 1982, ApJ, 262, 742
Mahoney, W. A., Ling, J.C., Wheaton W.A., Lingenfelter R.E. 1984, ApJ, 286, 578
Meynet G. et al. 1997, A&A, 320, 460
Mowlavi N. & Meynet G. 2000, A&A, 361, 959
Naya, J. E., Barthelmy, S.D., Bartlett, L.M., et al. 1996, Nature, 384, 44
Nittler L., et al. 1996, ApJ, 462, L31
Oberlack, U. 1997, Ph. D. Thesis, Technische Universität München
Plischke, S., Diehl, R., Schönfelder, V., et al. 2001, ESA SP-459, 55
Plischke, S., Diehl, R., Wessolowski, U., et al. 2000, AIP 510, 44
Prantzos, N., and Diehl, R. 1996, Phys. Rep., 267, 1
Roques, J.-P., Schanne, S., von Kienlin, A., et al. 2003, A&A, 411, L91
Rauscher T., Heger A., Hoffman R.D., et al. 2002, ApJ, 576, 323
Smith, D. 2004, this volume
Smith, D. 2003, ApJ, 589, L55
Starrfield, S., Truran J.W., Sparks, D. 2000, New Ast.Rev. 44, 81
Strong, A.W. 2003, A&A, 411, L127
Sturmer, S. J., and Naya, J. E. 1999, ApJ, 526, 200
Taylor, J. H., and Cordes, J. M. 1993, ApJ, 411, 674
Timmes F.X. et al. 1995, ApJ, 449, 204
Vedrenne, G., Roques, J.-P., Schönfelder, V., et al. 2003, A&A, 411, L63
Vuissoz C., Meynet G., Knödlseder J. et al. 2004, NewAstRev, 48, 7
Wunderer, C. et al. 2004, this volume
Zinner E. 2003, Met.& Plan.Sci. 33, 549