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^{26}Al spectroscopy with SPI: The challenge to detect Galactic rotation

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Abstract

The shape of the γ-ray line from radioactive ^{26}Al, at 1808.7 keV energy in the frame of the decaying isotope, is determined by its kinematics when it decays, typically 10^6 yr after its ejection into the interstellar medium from its nucleosynthesis source. Three prior measurements of the line width exist: HEAO-C's 1982 value of $(0 + 3)$ keV FWHM, the GRIS 1996 value of (5.4 ± 1.3) keV FWHM, and the recent RHESSI value of (2.0 ± 0.8) keV FWHM, suggesting either "cold", "hot", or "warm" ^{26}Al in the ISM. We model the line width as expected from Galactic rotation, expanding supernova ejecta, and/or Wolf–Rayet winds, and predict a value below 1 keV (FWHM) with plausible assumptions about ^{26}Al initial velocities and expansion history. We use this model as an input to a model-fitting approach for INTEGRAL/SPI data analysis in the 1808.7 keV line. Our aim is to detect the signature of Galactic rotation and to constrain the contributions of ^{26}Al from different regions of the Galaxy to the total emission, such as putting an upper limit on the contribution of local sources.

Keywords: Nuclear reactions; Nucleosynthesis; Abundances; γ-Rays: observations; Supernovae: general; ISM: supernova remnants; Stars: formation

1. Introduction

The current sites of active nucleosynthesis in the Galaxy are revealed through the γ radiation from the decay of ^{26}Al, a radioactive isotope with a half-life of about one million years that is produced mainly by massive stars. ^{26}Al decays via the β^+ mechanism into an excited state of ^{26}Mg, the nucleus emits a γ-ray photon with an energy of (1808.65 ± 0.07) keV on deexcitation into the ground state. The main argument supporting the massive star origin of ^{26}Al stems from a comparison of the angular distribution of 1.8 MeV emission on the sky with tracers of star formation, such as free–free radio emission (Diehl et al., 1996, Knödlseder et al., 1999, Plüschke et al., 2001).

In Kretschmer et al. (2003), we describe a model of the spatial and spectral features expected from the 1.8 MeV emission of Galactic ^{26}Al due to supernova events. We aim to illustrate what can be inferred from measurements of the ^{26}Al line shape with imaging spectroscopy using current instrumentation – this is chiefly the line's position and its width.

2. ^{26}Al sources in the Galaxy

We model the spatial distribution of ^{26}Al in the Galaxy as a combination of two aspects. On the one hand, we have the large scale space density of nucleosynthesis sites producing and ejecting ^{26}Al into the interstellar medium. On the other hand, each individual source, in general a supernova remnant or a Wolf–Rayet star, disperses the ejected material with a velocity distribution that corresponds to a space density distribution changing over the one million year timescale set by the decay lifetime of ^{26}Al. Our model extends the work of Gehrels and Chen (1996), which considers only the large scale aspects.

Comparisons between the all-sky map of 1.8 MeV γ-ray emission obtained by the COMPTEL telescope and tracers

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for ionised gas, such as H_α or free-free emission show good correlation. This is to be expected if massive stars are a major source of ionising radiation. The correlation leads us to adopt a model of the Galactic space density of free electrons as the basis of our large scale ^{26}Al source density. Such a model has been derived by Taylor and Cordes (1993) from pulsar dispersion measure observations and is shown in Fig. 1. Alternative spatial models, such as the smooth, axisymmetric one by Gómez et al. (2001) will probably yield similar line shape results.

Like the spatial distribution, the Doppler shifts of the ^{26}Al emission can also be separated into a large scale component due to Galactic rotation and a small scale component caused by the ejection behaviour of the individual sources. Olling and Merrifield (2000) determined the Galactic rotation curve by fitting radial velocity measurements of HI and HII regions with a mass model of the Galaxy. However, because their fit results depend on the parameters distance to the Galactic centre and local rotational velocity, the slope of the curve in the region outside the solar circle is not very well determined. Because our interest lies mainly with the inner part of the Galaxy, we adopted an approximation for the radial dependence of the rotation velocity:

$$|\vec{v}|(R) = 220\ \mathrm{km\ s^{-1}} \cdot [1 - \exp(-R/1\ \mathrm{kpc})]$$

We assume circular rotation parallel to the Galactic plane, i.e. the velocity vector is perpendicular to the radius vector and parallel to the plane.

For the other component of the ^{26}Al velocity, the ejection from the nucleosynthesis source, we concentrate first on the behaviour of supernovae. Recent hydrodynamic simulations of type II supernovae (Kifonidis et al., 2003) find that the expansion of the bulk of nucleosynthetic SN ejecta such as ^{26}Al may have velocities less than 1200 km s^{-1}. We represent this by allowing ^{26}Al to expand freely with a velocity of 1500 km s^{-1} until it reaches the radius of the reverse shock formed by circumstellar interaction. After this point, with ^{26}Al expanding at the radius of the SN blast wave, we obtain a conservative upper limit for the radial velocity because ^{26}Al is likely to move slower than the forward shock. We use the values of shock positions and velocities given by McKee and Truelove (1995) for Kepler's supernova remnant as a model of SNR dynamics from circumstellar interaction.

With these assumptions, the duration of freely expanding ^{26}Al is ≈2 kyr. Dissolution of the shell in the ISM occurs at an age comparable to the lifetime of ^{26}Al, when a significant fraction has therefore already decayed. At ≈40 kyr, when 96% of the ^{26}Al is still left, he expansion velocity drops below the characteristic rotational velocity of 220 km s^{-1}, meaning that the contribution from expansion to the overall line width is comparatively small.

3. Line shape diagnostics

We implement the above assumptions in a Monte Carlo scheme choosing ^{26}Al source locations from a spatial distribution proportional to the free electron density as measured by Taylor and Cordes (1993). The ages of the nucleosynthesis events have a uniform distribution within the interval [0,10^7 yr]. The age of the nucleosynthesis event thus determines extent and intrinsic velocity of its ejecta, as well as their 1.809 MeV luminosity. We represent each event by 2^{10} mass elements to reflect its spatial extent.

From source positions, velocities and intensities, together with the observer at $R_0 = 8.5$ kpc and $\Theta_0 = 220$ km s^{-1}, we obtain celestial coordinates and radial velocities for our ^{26}Al source elements. Direction and radial velocity give us the coordinates of the ^{26}Al source mass element in a data space of ^{26}Al decay luminosity as a function of longitude, latitude and photon energy. A projection of this data volume onto the longitude-energy plane results in a map of ^{26}Al line intensities as a function of Galactic longitude and observed photon energy (Fig. 1, right). Intrinsic velocity spreads and spatial source distributions lead to a line

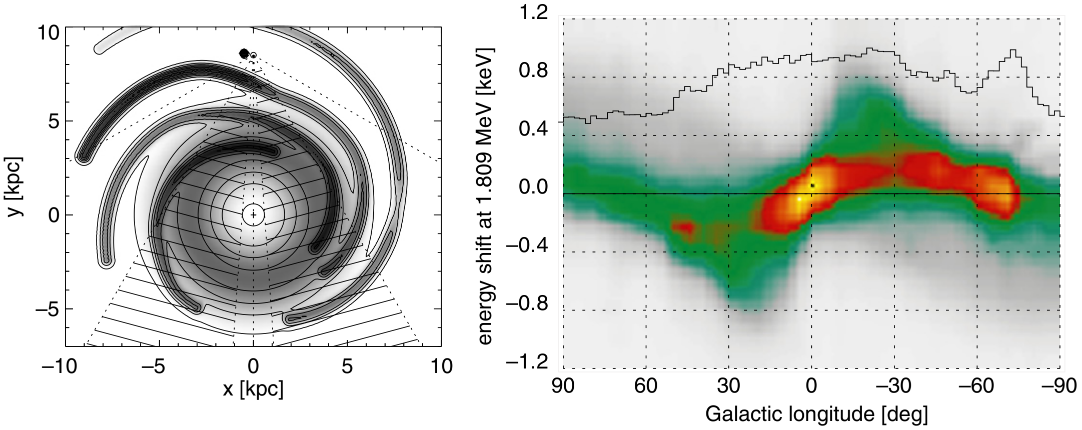

Fig. 1. Left: Model of the free electron density in the galactic plane (Taylor and Cordes, 1993), used as ^{26}Al source density distribution. Dotted lines represent −60°, −30°, −4°, 0°, 4°, 30° and 60° galactic longitude. Hatched areas illustrate the eastern/western parts of the inner galactic region. Right: ^{26}Al line intensity as a function of Galactic longitude and γ-ray photon energy, with the source longitude profile superimposed.

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