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LETTERS

Radioactive ^{26}Al from massive stars in the Galaxy

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Gamma-rays from radioactive ^{26}Al (half-life $\sim$7.2 $\times$ 10^5 years) provide a 'snapshot' view of continuing nucleosynthesis in the Galaxy[1]. The Galaxy is relatively transparent to such γ-rays, and emission has been found concentrated along its plane[2]. This led to the conclusion[1] that massive stars throughout the Galaxy dominate the production of ^{26}Al. On the other hand, meteoritic data show evidence for locally produced ^{26}Al, perhaps from spallation reactions in the protosolar disk[3–5]. Furthermore, prominent γ-ray emission from the Cygnus region suggests that a substantial fraction of Galactic ^{26}Al could originate in localized star-forming regions. Here we report high spectral resolution measurements of ^{26}Al emission at 1808.65 keV, which demonstrate that the ^{26}Al source regions corotate with the Galaxy, supporting its Galaxy-wide origin. We determine a present-day equilibrium mass of 2.8 ($\pm$0.8) solar masses of ^{26}Al. We use this to determine that the frequency of core collapse (that is, type Ib/c and type II) supernovae is 1.9 ($\pm$1.1) events per century.

Excess ^{26}Mg found in meteorites shows that the hot disk-accretion phase of the presolar nebula was apparently characterized[3,4] by an amount of radioactive ^{26}Al (relative to the stable ^{27}Al isotope) with a rather well-determined ^{26}Al/^{27}Al ratio of $\sim 4.5 \times 10^{-5}$. This is surprising, given that ^{26}Al decays within $\sim$1 Myr: the time it takes for a parental molecular cloud to form protostellar disks after decoupling from nucleosynthetically enriched interstellar gas is much longer[6]. Therefore, the meteoritic determinations of the ^{26}Al/^{27}Al ratio have been interpreted as an *in situ* ^{26}Al enrichment of the young solar nebula[7], either by a nearby supernova or by an AGB star event injecting fresh nucleosynthesis products at the 'last moment', or by enhanced cosmic-ray nucleosynthesis in the magnetically active early Sun with its accretion disk[5]. The mean ^{26}Al content of the interstellar medium in the Galaxy would therefore decouple from the solar value.

Observation of 1808.65-keV γ-rays from the decay of radioactive ^{26}Al in the interstellar medium, however, demonstrated that ^{26}Al nucleosynthesis does occur in the present Galaxy. The irregular distribution[2,8] of ^{26}Al emission seen along the plane of the Galaxy provided the main argument for the idea that massive stars dominate the production of ^{26}Al (ref. 1). Massive stars preferentially form in clusters; some of the nearby massive-star regions appear prominent in ^{26}Al emission (for example, in the Cygnus region), while others do not. Because the massive star census in the Galaxy is well known only out to distances of a few kiloparsecs, and many regions of the Galaxy are occulted for direct measurements, we are left with considerable uncertainty about a Galaxy-wide interpretation of the γ-ray measurements, with respect to the possibility of localized efficient ^{26}Al-producing regions. The total amount of ^{26}Al in the Galaxy, and hence the mean interstellar ^{26}Al/^{27}Al ratio, is thus rather uncertain.

If ^{26}Al sources are indeed distributed throughout the Galaxy, Galactic rotation will cause Doppler shifts of the γ-ray line energy, depending on the location of the source region within the Galaxy. Offsets in the line energy range up to 0.25 keV, and are particularly pronounced towards longitudes around $\pm 30°$ (ref. 9). From 1.5 years of data from our Ge spectrometer telescope (SPI) on the INTEGRAL γ-ray observatory of the European Space Agency (launched in October 2002) we derived new spectra of celestial ^{26}Al emission (see Supplementary Information for details of observations and analysis method). From the inner Galaxy, we obtain an ^{26}Al measurement at 16σ above the background, and significantly ($>3\sigma$) detect the ^{26}Al line emission in six 0.5-keV-wide energy bins across the line centre—this allows an unprecedented investigation of ^{26}Al γ-ray line

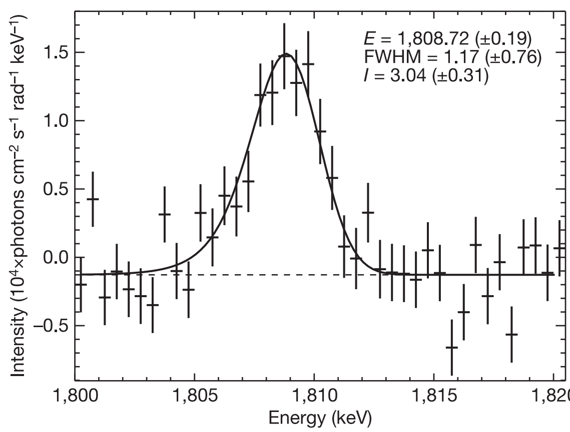

Figure 1 | Measurement of the ^{26}Al line from the inner Galaxy region with SPI/INTEGRAL. Our INTEGRAL sky exposure is fairly symmetric around the centre of the galaxy and extends over the full Galactic plane, though emphasizing the range of $\pm 45°$ longitude and $\pm 15°$ latitude (see Supplementary Information). This spectrum (shown with error bars of s.d.) was derived from sky model fitting to the set of 19 Ge detector count spectra for each of the 7,130 spacecraft pointings, using the COMPTEL ^{26}Al image as a model for the spatial distribution of emission, and was background-modelled from auxilliary measurements. The fit (solid line) combines the instrumental resolution, which is derived by accounting for degradation from cosmic-ray degradation irradiation and for annealings during the time of our measurement, with a gaussian for the intrinsic, astrophysical ^{26}Al linewidth. For this integrated result from the inner Galaxy, the line centre is determined to be at 1,808.72 ($\pm 0.2_{stat} \pm 0.1_{syst}$) keV (statistical and systematic uncertainties shown), well within the laboratory value for the ^{26}Al line of 1,808.65 (7) keV. The integrated intensity from the inner region of the Galaxy is determined to 3.3 ($\pm$0.4) $\times 10^{-4}$ photons cm^{-2} s^{-1} rad^{-1}, averaging over this and other plausible spatial-distribution models (hence uncertainty shown as sum of statistical and systematic; see Supplementary Information for method and details).

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parameters (Fig. 1). We find that the observed lineshape approaches the one expected from instrumental resolution. The linewidth of celestial emission, which would be observable as additional broadening, is therefore rather small. The high spectral precision of our instrument can now be combined with its imaging capability to search for signatures of Galactic rotation, that is, to determine ^{26}Al line-centre energies for different regions along the Galactic plane.

Our method of deriving spectra must adopt a model for the distribution of emission over the sky (see Supplementary Information). When we split such a model in the region of interest ($-40°\ldots+40°$) into three longitude segments through cuts at $-10°$ and $10°$, and determine ^{26}Al line energies for these regions, we systematically find that the ^{26}Al line energy clearly falls above the laboratory energy east of the Galactic centre, and slightly below towards the west (see Fig. 2 and Supplementary Information). Such a signature is expected from Galactic rotation. This strongly supports the view that the observed ^{26}Al source regions are located in the inner region of the Galaxy, rather than in localized foreground regions, as they appear to follow the global Galactic kinematics. This affirms a Galaxy-wide interpretation of the ^{26}Al γ-ray measurement, which had previously been argued for indirectly on the grounds of correlating the ^{26}Al γ-ray image with different tracers of candidate sources[1,10].

The total ^{26}Al γ-ray flux that we obtain is $3.3\,(\pm0.4)\times10^{-4}$ photons $\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$. This value is conventionally quoted for the inner Galaxy region ($-30° < l < 30°$; $-10° < b < 10°$) and the combined uncertainty from statistics and systematics is shown; the flux varies by $\sim$4% when we use a range of models, which we consider to be plausible tracers of ^{26}Al sources[1,10] (see Supplementary Information). This can be converted to an equilibrium mass produced by ongoing nucleosynthesis throughout the Galaxy in steady state, once the three-dimensional spatial distribution is known. Our best three-dimensional model is based on free electrons liberated by ionizing radiation from massive stars—such electrons can be measured at radio wavelengths, and the results have been translated into a geometrical model[11,12]. Using this and alternative plausible models[13] (see Supplementary Information), we infer a mass of $2.8\,M_\odot$ (where $M_\odot$ is the mass of the Sun) of ^{26}Al in the entire Galaxy. We estimate this value to be uncertain by $\pm0.8\,M_\odot$, from the combined statistical uncertainty of our measurements and the spatial-model uncertainty. The ^{26}Al/^{27}Al ratio implied[13,14] for the average interstellar medium is 8.4×10^{-6} (assuming an interstellar gas mass of $4.95\times10^{9}\,M_\odot$, and a numerical abundance of $\log N(^{27}\mathrm{Al}) = 6.4$, on a scale given by $\log N(\mathrm{H}) = 12$), about one order of magnitude lower than the solar-nebula value.

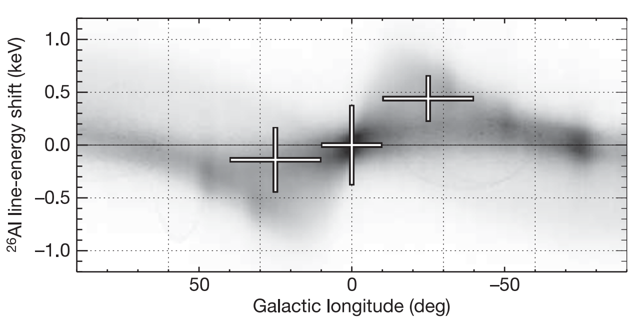

Figure 2 | Line position shifts with viewing directions along the inner Galaxy. Galactic rotation will shift the observed ^{26}Al line energy owing to the Doppler effect, to appear blue-shifted at negative longitudes and red-shifted at positive longitudes. Our expectations (greyscale) can be modelled from the Galactic rotation curve and a hypothetical three-dimensional distribution of ^{26}Al sources. From such models, we typically expect Doppler shifts of 0.25 keV, varying by $\sim$0.05 keV with assumptions about inner-Galaxy rotation and spatial source distribution (see Supplementary Information), for the integrated longitude ranges $40°\ldots10°$ and $-10°\ldots-40°$, respectively. We show here one of our models (in greyscale), based on free electrons in the insterstellar medium[11,12], with an exponential distribution perpendicular to the Galactic plane (scale height 180 pc); for our longitude intervals $40°..10°$ and $-10°\ldots-40°$; this predicts integrated Doppler shifts of -0.22 keV and $+0.24$ keV, respectively. The three line energy measurements (s.d. error bars shown) extracted from our observations are consistent with the Galactic-rotation explanation at the 94% probability level (see Supplementary Information for method and details).

In conjunction with stellar yields and a distribution function of stellar birth masses this provides an independent estimate of the star-formation rate in the Galaxy. Although we know the star-formation rates for external galaxies and specific regions in the solar neighbourhood reasonably well, the star-formation rate of the Galaxy as a whole is much less certain, because of occultation from interstellar clouds or other biases. Values based on optical-to-infrared tracers range from 0.8 to $13\,M_\odot$ per year[15–18] (see Supplementary Information). The γ-ray technique has the advantage in that it measures the rate in penetrating radiation over the full Galaxy, and averages over a timescale associated more closely with one (current) generation of massive stars (1 Myr). The signature of Galactic rotation in the ^{26}Al γ-ray line reaffirms that large-scale distributions for tracers of ^{26}Al sources can be applied to obtain a census of massive stars in the Galaxy.

Theoretical nucleosynthesis yields have been derived for massive stars, which are presumed to dominate the Galactic ^{26}Al budget, specifically for core-collapse supernovae and for the preceding Wolf–Rayet phases. Such models have been shown to match the chemical history of the Galaxy as reflected in the abundances of chemical elements to within a factor of two[19], which is an impressive success. ^{26}Al yields (wind-phase and explosive yields) from recent models of several independent research groups (Woosley, S. E., Heger, A. & Hoffman, R. D., manuscript in preparation; Limongi, M., & Chieffi, A., personal communication; refs 20 and 21) converge within about 50% over the full mass range (see Supplementary Information). Yields are moderated by the steep initial mass function (IMF), $\xi \approx m^{-\alpha}$, in our relevant mass range $\sim$10–120 $M_\odot$. We use the Scalo IMF ($\xi \approx m^{-2.7}$) for this higher-mass range, supported by a wide range of astronomical constraints[22], to obtain an average ejected mass per massive star of ^{26}Al of $Y_{26} = 1.4\times10^{-4}\,M_\odot$. With our measured amount of ^{26}Al, this IMF-weighted ^{26}Al yield implies a rate of core-collapse supernovae in the Galaxy, averaged over the radioactive lifetime of ^{26}Al (1.04 Myr); this represents the current core-collapse supernova rate: Evolutionary times for star clusters are $\sim$10–100 Myr, while the formation times of star clusters from giant molecular clouds are $\sim$100 Myr, and the Galaxy's age is $\sim$12 Gyr. (See Supplementary Information for the method of calculation and discussion of uncertainties). Our ^{26}Al measure implies a rate of (1.9 ± 1.1) core collapses per century, corresponding to a star-formation rate of $\sim 4\,M_\odot\,\mathrm{yr}^{-1}$, or a stellar production rate of $\sim$7.5 stars per year. Our high-resolution spectroscopy of ^{26}Al with SPI/INTEGRAL data shows that the Galaxy produces stars at a moderate rate, typical for spiral galaxies of similar type and luminosity.

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Supplementary Information is linked to the online version of the paper at www.nature.com/nature.

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