Galactic Structure and Radioactivity Source Distributions

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Abstract

A probable sky map of the emission from a short-lived isotope produced by massive stars is presented. The model is based on the nonaxisymmetric component of a dust distribution model developed to reproduce Galactic FIR emission. Features seen in COMPTEL observations are qualitatively reproduced.

Key words:

1 Introduction

The opening of the gamma ray window presents us with the possibility of tracing star formation (SF) on a Galactic scale via short-lived isotopes produced by supernovae (SN). An example is the isotope $^{26}\text{Al}$, whose half-life is short (0.75 Myr) and is believed to be primarily produced by Type II SN, with progenitors of mass $>10M_\odot$, and WR stars of mass $>20M_\odot$. The correlation between the distribution of $^{26}\text{Al}$ and SF activity derives from the brief lifetimes of these massive stars, typically shorter than 20 Myr, and the short half-life of $^{26}\text{Al}$, the latter insuring that the emitting material does not have time to turbulently mix throughout the ISM. Empirical support is found in the observed correlation between $^{26}\text{Al}$ emission and millimeter radiation (Knödlseder et al., 1999b), while $^{26}\text{Al}$ emission has been used to place theoretical constraints on the global SF rate (Knödlseder, 1999a; Timmes, Diehl, & Hartmann, 1997).

To date the only gamma ray all-sky survey available is that from the Compten Gamma-Ray Observatory, which produced a low resolution sky map of MeV radiation showing irregular emission along the Galactic plane. In the future these observations will be supplemented by the INTEGRAL mission. The purpose of this paper is to give a description of the anticipated Galactic emission from short-lived isotopes, as seen from the Sun’s position in the Milky Way, and as inferred from a model of the Galactic distribution of dust and stars.

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2 Star formation on a Galactic scale

Spiral arms can be regarded as star formation fronts. While SF does not take place exclusively in spiral arms, they can be regarded as the principal sites of SF activity in most disk galaxies. Indeed, it is for this reason that they are visible at optical wavelengths as complexes of HII regions. Our position within the Milky Way impedes a complete mapping of its spiral arms, but observations of Galactic HII regions have allowed a partial tracing of the spiral arms on our side of the Galaxy (Georgelin & Georgelin, 1976; Taylor & Cordes, 1993).

This tracing of the Milky Way’s spiral arms is found to trace well the far-infrared (FIR) emission associated with spiral arms (Drimmel & Spergel, 2001). The Galactic FIR emission was observed by the COBE satellite, and is due to interstellar dust, entrained in the gaseous component of the Galactic disk. The time scales for Galactic dust production and redistribution is considerably longer than the dynamical time scales that produces the concentration of gas and dust into the spiral arms, making the dust a good tracer of the azimuthal variation of the gas as well. It is therefore no surprise that a tracing of the spiral arms based on the location of HII regions can be used to model the FIR emission, since SF preferentially occurs where the gas density is highest.

For our purposes here I adopt the nonaxisymmetric component of the dust density model, used to reproduce the COBE FIR observations, as a tentative model of the probable flux density from a short-lived isotope produced by massive stars, such as \(^{26}\)Al. For details of the model, please refer to Drimmel & Spergel (2001). The nonaxisymmetric component is shown in Figure 1, showing clearly the spiral arms. The reader should also note another feature near the Sun, a small dust lane that corresponds to the Orion “arm”.

I have argued above that the nonaxisymmetric component of the dust distribution is logically associated with SF, so using it to describe \(^{26}\)Al emission is strictly valid only if SF and \(^{26}\)Al production are contemporaneous, as Galactic differential rotation will shear the distribution of newly born stars with respect to the spiral arm pattern. However, as the lifetimes of \(^{26}\)Al producers are much shorter than the period of Galactic rotation, the resulting azimuthal offsets are negligible over most of the Galaxy, as shown in Figure 2.

While we can have some confidence that azimuthal variation of the dust should correspond to that of \(^{26}\)Al emission, we are left with the question of the radial variation. A priori, it is not obvious that the radial variation in the dust and \(^{26}\)Al will be the same, one being the product of past SF and dynamical evolution, while the other is a result of current SF. Nevertheless it is worth
mentioning that the adopted model for the radial variation of the dust density in the spiral arms is of the same form as the free electron density associated with the arms (Taylor & Cordes, 1993). As this electron density is a consequence of the ionizing radiation of young OB stars, it should also reflect the radial variation of SF activity.

3 Expected sky emission from short-lived isotopes

Having a presumed three-dimensional model of the $^{26}$Al at our disposal, it is now possible to produce a sky map of the expected emission from this isotope, the flux density being proportional to the density of the emitting material. Another approximation made is similar to that made for the FIR, that at the wavelengths (energies) in question, the Galaxy is optically thin. Figure 3 shows the resulting sky map. Several features are worth pointing out in this figure. First, within 90 degrees of the Galactic center the spiral arms are seen as emission peaks along the Galactic plane. Particularly visible are the tangents
Fig. 2. Schematic diagram showing the geometry of the spirals arms as currently seen in the dust (thick solid line) and the geometry resulting after 20Myr of shearing by differential Galactic rotation (astericks), assuming $R_\odot = 8$ kpc, corotation at 0.83$R_\odot$, and a flat rotation curve of 200 km/s.

at Galactic longitudes $-75$ and $-50$ degrees, corresponding to the Sagittarius-Carina and Scutum arms respectively. At Galactic longitudes of approximately 90. and $-100$. two more bright spots are notable for their extent in Galactic latitudes; these are due to the local Orion “arm”, a structure important in our sky only because of our proximity to it. Lastly, emission between $\pm 90$ degrees is attributed to the Perseus arm, whose scale height is significantly larger than the other spiral arms. Another nonaxisymmetric structure that is less obvious in the sky map is the Galactic warp, which causes the Perseus arm to deviate from the Galactic plane.

To better see the variation in the Galactic plane Figure 4 shows the emission profile at $b = 0$. The spiral arms are easily seen by the sawtooth pattern they produce in the profile. This characteristic profile was also predicted by Prantzos (1993) with a very similar model, using the same spiral arm geometry. I also point out that the incompleteness of the spiral arm map on the other side of the Galaxy is not important for producing the sky maps, as their small
Fig. 3. Sky map of the emission resulting from the spiral arms shown in Figure 1. Emission within 20 degrees of the Galactic center is not shown.

Fig. 4. Modelled $^{26}$Al emission profile (arbitrary units) in the Galactic plane (diamonds), plotted with the 240$\mu$m profile (MJy sr$^{-1}$) observed by COBE for comparison. Scale height insures that they remain unresolved.

4 Summary

Using a model based on FIR observations, a predicted map of the emission from short-lived isotopes has been presented at resolutions comparable to the future INTEGRAL mission though, not being a survey mission, it will not produce such a sky map. This model is parametric, using smooth
mathematical functions to describe the distribution of the emitting material, and is thus much simpler than reality. This can be immediately seen by comparing Figure 3 with the COMPTEL sky map at 1.8MeV (?)or see http://cossc.gsfc.nasa.gov/cossc/comptel/[Knod99b. However, the major features in the map at Galactic longitudes > 30 degrees are reproduced on a qualitative level. This includes the location of the spiral arm tangents, the two bright spots attributable to the local Orion “arm”, and the contribution of the Perseus arm to emission toward the Galactic anticenter with its relatively large range in Galactic latitude.

No attempt has been made here to fit the model to actual gamma-ray data; for this the reader is referred to Knödlseder et al. (1996), who uses the same spiral arm geometry, adopting the free-electron density model of Taylor & Cordes (1993) as a template. Perhaps the only significant differences between this model and the one presented here is a reduction factor on the Sagittarius-Carina arm, the Galactic warp and a flair in the spiral arm scale height.

As a worker in the field of Galactic structure, preparing this report underlined for me the value of gamma ray mapping missions, as it provides an avenue for observing and identifying the distribution of SF regions on a large scale. This is important for untangling the contribution from bright young sources which contaminates other wavelengths and frustrates efforts at mapping the mass distribution in the Galactic disk.

References