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UNDERSTANDING COMPTEL ^{26}Al 1.8 MeV MAP FEATURES

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ABSTRACT

The COMPTEL sky map of the 1.8 MeV line emission from ^{26}Al shows an extended diffuse distribution along the Galactic plane with a peculiar large scale asymmetry about the Galactic center (GC) and a clumpy structure with several noticeable hot spots. The most prominent hot spot at the GC appears shifted to positive longitude by about 2°. Nearby supernova remnants or Wolf-Rayet stars are plausible explanations for individual hot spots such as in the Vela region. We show that the global asymmetry and most hot spots can be understood by a more general model: the ^{26}Al sources are confined in the spiral arms of our Galaxy, and coagent star formation is responsible for additional clumpiness. The off-centered GC hot spot is probably due to the observed asymmetrically distributed circumnuclear molecular gas interacting with a central stellar bar, whose existence has been inferred from IR observations.

Subject headings: Galaxy: center — Galaxy: structure — gamma rays: theory

1. INTRODUCTION

The long-lived (mean life $\sim 1.0 \times 10^6$ yr) radioactive isotope ^{26}Al is produced by explosive nucleosynthesis in novae and Type II supernovae (SN II's) and by hydrostatic nucleosynthesis in asymptotic giant branch (AGB) and Wolf-Rayet (W-R) stars (e.g., Schönfelder & Varendorff 1991). ^{26}Al decays into ^{26}Mg, emitting a 1.809 MeV photon which interacts with matter mainly via Compton scattering with a unity optical depth H I column density of 5.6×10^{24} cm^{-2}. Thus, the 1.8 MeV line emission of ^{26}Al could be seen from the entire Galaxy, making it not only an excellent tracer of galactic nucleosynthesis over the past million years (Ramaty & Lingenfelter 1977; Arnett 1977), but also a potentially powerful probe of the spatial structure from which it is produced.

The general concensus from satellite and balloon observations in the last decade (e.g., Schönfelder & Varendorff 1991 and references therein) was that the 1.8 MeV emission is diffuse but concentrated in the Galactic plane with a flux in the Galactic center (GC) direction of $\sim 4 \times 10^{-4}$ photons s^{-1} cm^{-2} rad^{-1}, and the ^{26}Al distribution was assumed to be smooth and symmetric about the GC. Recent 1.8 MeV observations by the Compton Imaging Telescope (COMPTEL) aboard the *Compton Gamma-Ray Observatory*, however, show substantial asymmetry about the GC as well as highly structured emission, and the integrated flux from the inner Galaxy is lower than previous (non-imaging) measurements (Diehl et al. 1994a). The question arose whether the observed structure is due to *diffuse steady state nucleosynthesis* or a composite of *localized* sources, or both. In this *Letter*, we discuss several possible options for the global appearance of the COMPTEL 1.8 MeV sky map. Our study supports and expands the idea that most map features are diffuse and are related to the Galactic spiral structure (Prantzos 1991).

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2. COMPTEL 1.8 MeV MAP FEATURES

The COMPTEL instrument, with a sensitivity of $\sim 10^{-5}$ photons s^{-1} cm^{-2} and spatial resolution of a few degrees, has recently surveyed the entire sky. Maps of the 1.8 MeV line emission are generated using both the maximum-likelihood and maximum-entropy techniques (Diehl et al. 1993; 1994a, b; see also Fig. 1a) and reveal some distinctive characteristics of the ^{26}Al distribution:

1. The ^{26}Al source distribution is concentrated on the plane but has a global asymmetry about the GC with a significant excess in the first quadrant; the emission to the east stops beyond 35° and only reappears in Cygnus ($\sim 80°$), while to the west it extends out to at least 240°.
2. The map shows an irregular and clumpy structure with several hot spots seen in the GC, 32°, Cygnus, Vela (263°), Carina (280°), 310°, and 345° regions. However, we caution that current COMPTEL data analysis may have somhow overemphasized the clumpiness (Diehl et al. 1994c).
3. The most prominent hot spot near the GC is actually offset to the southeast ($l \sim 2°$ and $b \sim -2°$).

COMPTEL flux calibration at 1.8 MeV (Diehl et al. 1994a) gives 3.6×10^{-5} photons s^{-1} cm^{-2} for the GC hot spot. The integrated flux in the inner Galaxy of $\sim 2 \times 10^{-4}$ photons s^{-1} cm^{-2} rad^{-1} is a factor of 2 lower than the nominal value from previous nonimaging large field-of-view instruments. This disagreement suggests that the large-scale model distribution which had been used in analysis of the previous measurements, namely that of high-energy γ-rays taken from *COS B*, is misleading.

3. CONTRIBUTION FROM LOCAL SOURCES

Obvious candidates for the 1.8 MeV hot spots are nearby single sources with high ^{26}Al yields, such as W-R stars or core-collapse supernova remnants (SNRs); the ^{26}Al yield from a single nova or AGB star is orders of magnitude below the

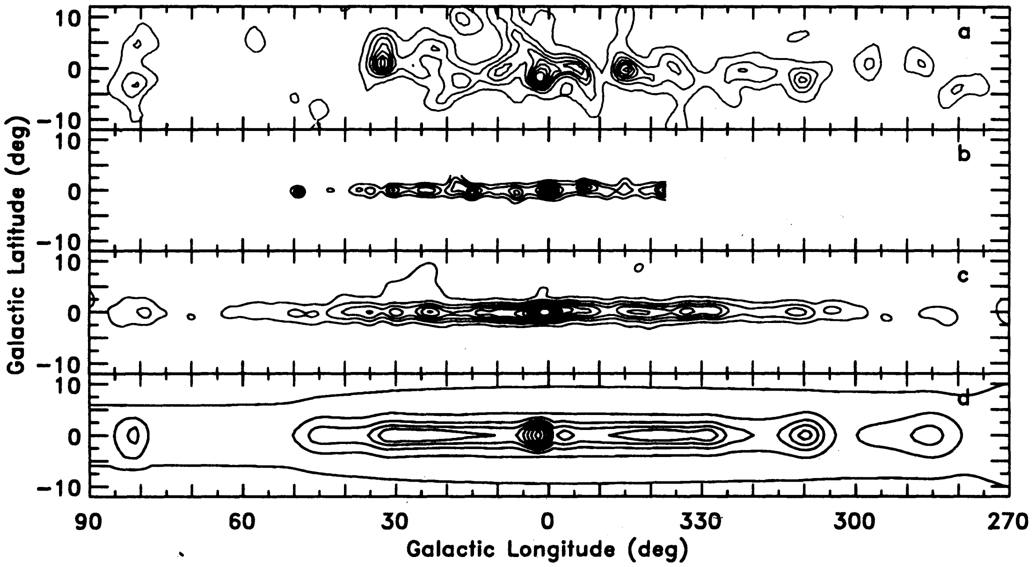

FIG. 1.—(*a*) The maximum-entropy flux map of the first and fourth quadrant of the Galactic plane at 1.8 MeV seen by COMPTEL during 1991–1992 (Diehl et al. 1994b). (*b*) The radio continuum survey at 5 GHz covering $55° < l < 335°$ and $-3° < b < 3°$ (Altenhoff et al. 1970); the contour levels are in steps of 0.16 K to a maximum of 1.83 K. There is also strong 5 GHz emission in Cygnus (Wendker 1984). (*c*) The distribution of the velocity-integrated CO emission at 115 GHz (Dame et al. 1987); the contour levels are from 9.1 K km s^{-1} to 227 K km s^{-1} in steps of 14.5 K km s^{-1}. (*d*) The column density map of a model ^{26}Al distribution (see text); the contour levels are in arbitrary units. The maps in (*b*)–(*d*) are all smoothed to an angular resolution of 3°.

COMPTEL sensitivity limit (Diehl et al. 1993). In the case of the Vela region, the COMPTEL feature includes both the Vela SNR and the W-R binary star γ^2 Vel (WR 11).

The ^{26}Al yield of a W-R star is $\sim 10^{-6}$ to 10^{-5} $M_\odot$ (and maybe up to 2×10^{-4} $M_\odot$) for an initial mass range of 40 $M_\odot$ to 120 $M_\odot$ (Walter & Maeder 1989; Oberlack et al. 1994). Therefore, γ^2 Vel, being at 450 pc and the only W-R star within 1 kpc, will have a 1.8 MeV flux of $\leq 1.2 \times 10^{-5}$ photons s^{-1} cm^{-2}, which makes it only a marginally detectable source (Oberlack et al. 1994) and excludes any other hot spots from being produced by single W-R stars. Recent calculations (Weaver & Woosley 1993), on the other hand, show that a 15–20 $M_\odot$ SN II of solar initial composition produces $\sim 10^{-4}$ $M_\odot$ of ^{26}Al with an uncertainty of about an order of magnitude. This gives an expected 1.8 MeV flux of $\sim 1.2 \times 10^{-4}(D/100\ \mathrm{pc})^{-2}$ photons s^{-1} cm^{-2} for a SNR at distance D. The observed 1.8 MeV flux from the Vela SNR, 2.2×10^{-5} photons s^{-1} cm^{-2}, is within this range for the reasonable assumption of $D \leq 400$ pc (Oberlack et al. 1994).

Few other SNRs would have plausible 1.8 MeV emission above the COMPTEL sensitivity limit. The local SNRs, e.g., the Local Bubble and Loop I, are closer than 500 pc, but because of their large sizes their ^{26}Al emission is spread over a large portion of the sky and will appear as a weak, extended halo that is probably undetectable by COMPTEL (del Rio et al. 1994). We have searched the COMPTEL sky survey data but failed to detect flux excess from the Cygnus Loop (770 pc), the nearest SNR in the Cygnus region. We conclude that the Cygnus 1.8 MeV feature (and maybe any other hot spot except Vela) is not from a single SNR, and individual local sources do not provide a ready explanation of the COMPTEL 1.8 MeV map clumpiness.

The number of sources required to supply the observed flux of a hot spot increases sharply with distance. For example, if the extended Cygnus feature is from the active massive star-forming regions at a distance of 1.5–2 kpc, it must contain at least 20–30 SNRs or W-R stars or both. Consequently, for novae and AGB stars at a distance of >10–100 pc and for SNRs and W-R stars at >1–2 kpc, a hot spot can be produced only by the collective contribution of a large number of weak sources. The low individual yields and the observed clumpiness in the 1.8 MeV map suggest that novae and AGB stars make only a minor contribution to the observed flux, because concentration of thousands of these sources within localized regions is unlikely. Careful studies of each hot spot region are important, however, to identify potential local groups of associated sources which may cause localized deviations from the global Galactic star formation and nucleosynthesis picture.

4. CORRELATION WITH SPIRAL ARM STRUCTURE?

Prantzos (1991) and Ramaty & Prantzos (1991) were the first to recognize that a diffuse 1.8 MeV emission may show global asymmetry and clumpiness if the ^{26}Al distribution is dominated by sources confined to the Galactic spiral arms. The global asymmetry would come from the nonaxisymmetry of the spiral pattern and the clumpiness would be the result of enhanced emission along the tangent directions of the arms. Both effects have been seen, more or less, in sky maps of other major spiral arm tracers, e.g., giant H II regions or giant molecular clouds. Del Rio et al. (1994) discussed the contribution of the local spiral arms to the observed ^{26}Al emission features, especially in the Cygnus and Carina regions.

Current star-forming regions with their young SNRs and the SN II progenitor massive stars probably coincide better than anything else with the distribution of candidate ^{26}Al sources in the Galaxy. Young SNRs are luminous synchrotron radio sources, and massive stars produce free-free emission in stellar winds or H II regions. Hence one might expect the sky maps of the radio continuum survey at 5 GHz (Altenhoff et al. 1970) as well as the molecular clouds seen in CO at 115 GHz (Dame et al. 1987) to resemble closely what is seen in the COMPTEL 1.8 MeV map. In Figure 1*b* we show the 5 GHz map of Altenhoff et al. (1970) and in Figure 1*c* the CO map of Dame et al. (1987).

Both maps have been smoothed to a resolution of 3°, comparable to that of the COMPTEL 1.8 MeV map (Fig. 1*a*).

There are indeed some similarities between these maps. A bright GC hot spot is seen in all maps, and it is slightly *shifted to the east* (although not to the southeast) in the CO map, similar to what is seen in the 1.8 MeV map. In Figures 1*b* and 1*c*, fainter hot spots can be identified along the tangent arm directions at the 3 kpc arm (24°), Scutum (30°), Carina, 310°, and probably 330°, and also in the Cygnus region. The coincidence of many of these features with those seen in Figure 1*a* suggests that there is a *possible* link between the ^{26}Al source distribution and the Galactic spiral structure.

However, the overall distribution of both the 5 GHz and CO emission is confined more closely to the Galactic plane. It also extends farther out in the first quadrant (i.e., it has a weaker global asymmetry) and appears less clumpy than the ^{26}Al distribution. For the individual map features, we find that some coincide only in their crude locations but not their relative strengths, e.g., the hot spots in the 5 GHz and CO maps are stronger at the GC but much weaker at Scutum. Some hot spots are almost totally mismatched, e.g., the 1.8 MeV features at 345° and 320° are not seen in the CO and 5 GHz maps, and the weak feature at 330° in the CO corresponds to a valley in the 1.8 MeV map. Finally, the 5 GHz GC hot spot has no apparent offset.

A much narrower latitude extent at 5 GHz than at 1.8 MeV is probably due to the fact that efficient synchrotron radiation is produced from relatively young ($\leq 10^5$ yr) SNRs, in which the kinetic energy of the ejecta has not yet been significantly dissipated. Also, efficient free-free emission in stellar winds or H II regions is limited to the high-density region in the vicinity (a few pc) of the central stars. The slowly decaying ($\sim 10^6$ yr) ^{26}Al atoms, on the other hand, may continue to radiate in the expanding SN II ejecta long after ($\gg 10^5$ yr) the explosions and so might be able to produce 1.8 MeV emission far away (> 100 pc) from the SN II sites. Thus, old ($> 10^5$ yr) SNRs may have long ceased to be synchrotron sources but are still contributing to the observed 1.8 MeV flux. It is also true that along the Galactic plane, many objects are radio sources but are not 1.8 MeV sources. For example, an O star wind is a free-free radio source but does not have much, if any, ^{26}Al, and neither does an H II region unless it contains a well-evolved W-R star.

Therefore, although the ^{26}Al sources originate from the same objects in the spiral arms as the radio sources do (all of which originate in molecular clouds), their distribution along the arms could be quite different. Figures 1*a*–1*c* clearly show that the radio continuum and ^{26}Al sources always coincide with some molecular gas, but the reverse is not true. The *current* birthrate of massive stars is relatively patchy along the arms (i.e., mainly in the form of OB associations), and so would be the *last* generation of massive stars which were the progenitors of the current ^{26}Al sources. We would naturally expect some mismatch between the 1.8 MeV, 5 GHz, and CO map features, since there is no reason to believe that generations of massive star formation always take place at the same locations.

5. A MODEL OF GALACTIC ^{26}Al DISTRIBUTION

We conclude from Figures 1*a*–1*c* that the ^{26}Al sources are probably confined to the spiral arms but do not correlate closely with the spiral arm tracers. Further progress thus requires construction of a model distribution which follows the basic spiral arm pattern with additional astrophysical assumptions to fill the known tracer imperfections and biases.

A handy first-order template of the basic spiral arm distribution, first used by Prantzos (1991) for this purpose, is the Galactic free-electron distribution developed in pulsar distance studies (Taylor & Cordes 1993). In this model the Galactic free-electron density is distributed *smoothly* on a four arm spiral pattern derived from giant H II region observations (Georgelin & Georgelin 1976) and is calibrated by using the observed dispersion measure of about 80 pulsars with known distance. An apparent defect of the Taylor & Cordes model is that there are simply too few pulsars to make it accurate enough. For example, the model distribution has a hole instead of a peak at the GC and does not include the Cygnus region where active massive star formation would have had generated ample free electrons. Nevertheless, it is arguable that the free electrons may correlate with ^{26}Al better than other arm tracers, because free electrons produced in SN II explosions may survive to large distances with ^{26}Al atoms and, while not radiating much, be detected via pulsar dispersion measurements. Such a correlation, however, could well be nonlinear because free electrons can also be produced by other means, e.g., by stellar ionization radiation and supernova blast waves.

Based on the free-electron distribution of Taylor & Cordes (1993) plus several smooth, *axisymmetric* diffuse distributions of plausible tracers, Prantzos (1993) presented a family of model longitude profiles of the integrated (over latitude) 1.8 MeV emission which show the global asymmetry and several peaks at the tangent arm directions, particularly the Carina region. Such an approach, however, does not offer the most meaningful comparison between the model and observations, and the axisymmetric diffuse components certainly cannot produce an off-centered GC hot spot.

To expand this effort, we now attempt to construct a more realistic model of the ^{26}Al source distribution and compare our results directly with the observed 1.8 MeV flux map by using the column density map of the model distribution, which to a scaling factor is the same as the model 1.8 MeV flux map. We assume that except for the GC and Cygnus, the ^{26}Al number density on the arms is proportional to that of free electrons (Taylor & Cordes 1993), and then add extra ^{26}Al at the GC and Cygnus according to their local physical conditions (discussed below). The results are shown in Figure 1*d*.

It is very encouraging to see that such a simple model can indeed match the major COMPTEL map features quite well in terms of the global asymmetry and hot spots. The latitude distribution is now wider, as we expected, and the global asymmetry is more apparent, similar to what we see in the ^{26}Al map. The location and relative strength of the model hot spots in the outer Galaxy, e.g., at 280° and 310°, actually match with the 1.8 MeV observations better than both the 5 GHz and CO maps.

The Cygnus region, containing dense giant molecular clouds (Fig. 1*c*), is extremely active in massive star formation (e.g., Wendker 1984) and so a natural site for intense ^{26}Al production (Fig. 1*a*). We add in our model an extra amount of ^{26}Al in a cone of 8° in diameter and 1 kpc in depth centered at $l \sim 80°$ and located at 2 kpc from the Sun which is thought to be the intense star-forming volume in Cygnus (e.g., Odenwald & Schwartz 1993). The observed 1.8 MeV feature is reproduced (Fig. 1*d*) when the peak ^{26}Al number density in the cone is about 50% higher than that on the arms.

To understand the puzzling offset of the GC hot spot, we propose that a partial answer may be found in the CO data. Within 2° from the GC, three-quarters of the CO emission is found at $l > 0$ (Binney et al. 1991), and the CO intensity peak is shifted to the east by more than 1° (Fig. 1*c*). The cause of this asymmetry is still unknown (Binney & Gerhard 1993). The mere presence of a large amount of asymmetrically distributed molecular gas at the GC, however, will not automatically produce ^{26}Al. A physical mechanism must be at work to trigger intense massive star formation and then SN II explosions in the clouds during the last million years.

We argue that this task is accomplished by the strong interactions between the infalling molecular gas and a *stellar bar* at the GC whose existence has been clearly revealed in IR observations (Blitz & Spergel 1991; Dwek et al. 1994). When the gas flows in response to the rotating potential of the bar and forms shock waves at the interface, it triggers bursts of star formation on its path. Such an active interaction is probably unique in the Galaxy due to the deep potential in the GC region. The asymmetry in the gas distribution is preserved (or even amplified) in the ^{26}Al distribution because the dynamic time scale at the GC ($\sim 10^8$ yr) is much longer than the lifetime of both massive stars and ^{26}Al. For the model GC hot spot, we assume the ^{26}Al in the GC region is distributed on a bar of 1 kpc in length and 0.3 kpc in diameter with the east end tilted toward us at an angle of 30°; the ^{26}Al number density in the east and west half of the bar is found to be a factor of 3 and 2 greater than that on the arms, respectively, to qualitatively reproduce the asymmetry and flux contrast seen in Figure 1*a*. The apparent offset to the south is not reproduced in this simple model since it may require additional information on the streaming motion of the circumnuclear gas perpendicular to our line of sight.

It is clear, however, that our model distribution is smoother than the observations, revealing the caveats of the free-electron distribution model. Similar to the 5 GHz and CO maps, the strength of the 32° hot spot in our model is too weak and correlation is poor in the inner Galactic region, e.g., at 345° and 330°. These disagreements indicate that the distribution of ^{26}Al sources on the spiral arms is not uniform and the observed clumpiness in the 1.8 MeV is more than just the tangential enhancement of the spiral pattern.

6. CONCLUSIONS

Our analysis favors the interpretation that the ^{26}Al sources in general are young objects confined to spiral arms of our Galaxy, and most of the COMPTEL ^{26}Al map features are diffuse in origin, similar to what are seen in the 5 GHz radio continuum and CO maps. Only a few 1.8 MeV hot spots are due to nearby individual sources, e.g., in the Vela region. Following Prantzos (1993), we have constructed a simple model ^{26}Al distribution based on the free-electron distribution in the Galaxy (Taylor & Cordes 1993) with added features at Cygnus and GC that largely resembles the 1.8 MeV map. We propose that the unique, off-centered GC hot spot is probably caused by interactions between the asymmetrically distributed circumnuclear molecular gas and a stellar bar at the GC. However, the ^{26}Al source distribution on the arms appears to be more patchy than our simple model shows. More detailed efforts will have to include information from other tracers of the candidate ^{26}Al sources (e.g., *current* and *relic* massive star-forming activities) and account for local sources and potential localized peculiarities.

Such improved source distributions can be tested with future high-energy resolution instruments such as the INTEGRAL Spectrometer which are capable of detecting the Doppler shift (a few keV) of the 1.8 MeV line due to the differential rotation of the Galaxy (~ 100 km s^{-1}), since the diffuse origin of ^{26}Al implies that most flux in a hot spot is from a single arm with small velocity dispersion. Thus, the highly penetrating 1.8 MeV emission of ^{26}Al may serve as a new, excellent tracer of the spiral arm pattern, especially in the inner Galaxy.

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