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DIFFUSE GAMMA RAY LINES AND GALACTIC STRUCTURE

BY

MARK D. LEISING

A THESIS SUBMITTED
IN PARTIAL FULFILLMENT OF THE
REQUIREMENTS FOR THE DEGREE

MASTER OF SCIENCE

APPROVED, THESIS COMMITTEE:

Donald D. Clayton, Professor of
Space Physics and Astronomy
Chairman

C. R. O'Dell, Professor of
Space Physics and Astronomy

R. A. Wolf, Professor of
Space Physics and Astronomy

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ABSTRACT

The distribution of galactic constituents which may be related to either supernovae or novae are examined and reasonable distributions for supernovae and novae are chosen. The gamma ray fluxes from long-lived radioisotopes synthesized in each type of explosive event is then calculated as a function of galactic longitude, in the hope that the angular distribution can identify the source of the gamma ray line from the decay of $^{26}$Al seen by detectors on the HEAO 3 and SMM spacecraft. Implications of the observed fluxes and these model distributions are considered and possible relevant observations by the OSSE detector on Gamma Ray Observatory are examined.
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I. INTRODUCTION

Understanding the origin and distribution of the chemical elements has been a primary objective of astrophysics for the past several decades. The science of nucleosynthesis has developed as an intertwining of experimental nuclear physics and theoretical astrophysical modeling and has been largely successful in explaining the available observational data. These data have so far consisted mainly of relative abundance determinations in solar system matter, in the envelopes of stars and in the interstellar medium. It is hoped that to this we can add observations of gamma ray lines—representing direct evidence that nucleosynthesis is presently occurring in the Galaxy, and possibly adding insight into the structure and dynamics of the Galaxy.

The detection of gamma rays from the radioactive decay of $^{26}\text{Al}$ in the interstellar medium by the gamma ray spectrometer on the third High Energy Astronomy Observatory (Mahoney et al., 1982, 1984) represents a significant confirmation of the theory of nucleosynthesis. Based on models of nucleosynthesis in supernovae Ramaty and Lingenfelter (1977) and Arnett (1977) predicted observable fluxes from $^{26}\text{Al}$, which beta decays with a mean lifetime of $1.04 \times 10^5$ years to a 1.809 MeV excited state of $^{26}\text{Mg}$ which emits a gamma ray in transition to the ground state. $^{26}\text{Al}$ is now thought to be produced in novae (Arnould et al., 1980; Wallace and Woosley, 1981) and red giants (Norgaard, 1980) as well as in supernovae (Arnould et al., 1980; Woosley and Weaver, 1980). The gamma rays from any single event at a typical distance would not be detectable, but as the lifetime of $^{26}\text{Al}$ is much longer than the mean time
between events a steady state concentration should accumulate in regions of the interstellar medium where those events are prevalent, resulting in a diffuse gamma ray flux from the galactic plane. This is likely the source of the observed gamma rays, but a recent (~10^5 years ago) very near single supernova can not yet be ruled out (see Clayton, 1984).

While this discovery is exciting in itself, gamma ray spectroscopy could become a very useful probe of individual objects, the Galaxy, and even other galaxies, essentially unaffected by absorption and scattering. With improved angular resolution it should be possible to identify the mechanism (or mechanisms) of production since the different predicted sources are expected to have different spatial distributions. In the near future it will probably only be these different distributions which can definitively determine the sources.

At present there is probably too little angular information to identify the source of the emission, but the Oriented Scintillation Spectrometer Experiment (OSSE) on the Gamma Ray Observatory will be a well collimated instrument with good angular resolution and might be able to map the distribution of radioactivities if they exist in sufficient concentrations. Thus it is useful to consider quantitative models of the expected distributions, which I do here, based on observations of other galactic constituents which might reasonably be related to nucleosynthesis. These distributions might possibly also be useful in the analysis of the HEAO 3 data, as the statistical significance of the detection and even the true cosmic flux depend on the longitude distribution assumed (explained below). Because the OSSE detector will not necessarily survey the entire galactic plane, the calculated distribu-
tions could identify key locations to observe for determination of the source.

With a galactic spatial distribution one can also calculate the implication of the observed flux for the density of radioactive aluminum at a given place in the Galaxy. This might be important for the local region in particular, because excess $^{26}\text{Mg}$ found in the Allende meteorite seems to imply that an isotopic ratio of $^{26}\text{Al}/^{27}\text{Al} = 5 \times 10^{-5}$ existed in the local interstellar medium when the solar system formed (Lee et al., 1977). There is debate as to whether this simply reflects the normal condition of the interstellar medium, or if a nearby supernova injected the $^{26}\text{Al}$ into the forming solar system.
II. THE HEAO 3 DISCOVERY OF $^{26}$Al

Because it points out the need for models of the angular distribution of the gamma rays I will briefly describe the HEAO 3 instrument and the difficulties faced in its data analysis. All that follows in this section is summarized from Mahoney et al. (1982, 1984).

The HEAO 3 gamma ray spectrometer (known as HEAO C-1) was a collection of four coaxial high purity germanium detectors in an anti-coincidence cesium-iodide shield. The experiment pointed perpendicular to the spin axis of the HEAO 3 spacecraft which was normally pointed toward the sun. For two two-week periods, in the fall of 1979 and in the spring of 1980, the spacecraft axis was pointed toward a galactic pole allowing HEAO C-1 to scan the galactic plane. The published analysis related to $^{26}$Al is limited to data obtained during these two periods as it seems there were some inconsistencies in the fluxes recorded during the normal scans.

The dearth of angular information results from the characteristics of the shield, which was far from a perfect collimator. For photons of 1.809 MeV the shield transmission was 0.1 to 0.2 even at large angles from the viewing axis and defined an aperture of 42$^\circ$ FWHM centered on the viewing axis. Because of this all parts of the galactic plane contribute counts in the instrument at all times. Thus it is necessary to correct for the aperture response and fit the data to an assumed longitude distribution. Because the instrument never measured the background, both source counts and background had to be fit to the observed counts. It was actually even worse than this as both earth and space-
craft blockage had to be corrected for.

To estimate the galactic flux the count rate in the instrument was modeled as the sum of a constant background and variable source counts computed from the considerations described above. The galactic plane was divided into bins of scan angle longitude, with the count rate in the $i^{th}$ bin $R_i = B + S_i$ where $B$ is the background and $S_i$ is the source counts computed for the $i^{th}$ bin according to:

$$S_i = A_0 \int d\xi f(\xi) T(\hat{n}, \xi) E(\xi)$$

where $A_0$ is the effective detector area, $g$ is the assumed longitude variation of the flux normalized to unity at the galactic center, $f$ is the normalization flux from the galactic center, $T$ is the transmission function of the shield, $\hat{n}$ is the viewing direction, and $E$ represents earth blockage of the galactic plane. Thus $g$ was assumed to be like the distribution of $> 100$ MeV gamma rays, $T$ was measured in the lab, $E$ and $A_0$ were known and $f$ and $B$ were fit to the observed counts $R_i$.

The relative contributions of source and background depend on the longitude distribution assumed, but the average of the data from individual scans yields a flux from the galactic center direction of $4.8 \times 10^{-4}$ photons cm$^{-2}$ s$^{-1}$ rad$^{-1}$ at 1.809 MeV, at the 4.7 $\sigma$ level of significance. The line width was $< 3.0$ keV, essentially the resolution of the instrument, consistent with differential rotation of the Galaxy.
Solar Maximum Mission

Recently, analysis of data from the gamma ray spectrometer on the Solar Maximum Mission shows evidence of a line feature at 1.81 MeV (Share, private communication). The instrument's $2\pi$ steradian aperture points continuously at the sun and so scans the ecliptic plane. There appears to be an annual modulation in intensity of the line, with the peak intensity coinciding with the passage of the galactic center through the field of view. The intensity of the line is consistent with the HEAO 3 results above.
III. SYNTHESIS OF $^{26}$Al

Here I wish to sketch very briefly the nucleosynthesis relevant to $^{26}$Al. I will not consider in any detail the nova and supernova models as they are very complicated and uncertain. It is thought that explosive burning of hydrogen-rich material in nova envelopes and in the outer layers of supernovae can be responsible for significant $^{26}$Al production through rapid proton captures if temperatures of a few times $10^8$ K are reached (Wallace and Woosley, 1981; Arnould et al., 1980).

The nova phenomenon is thought to result from the accretion of proton-rich material from a companion onto the surface of a degenerate carbon-oxygen white dwarf. This results in a steady-state hot CNO cycle with rapid proton captures so that the cycle is limited by the positron decays of the proton-rich nuclei $^{14}$O and $^{15}$O, and all initial CNO nuclei tend to pile up in these two nuclei. The relevant reactions are:

$$^{14}$O($e^+, \nu$) $^{14}$N(p,\gamma) $^{15}$O($e^+, \nu$) $^{15}$N(p,\alpha) $^{12}$C(p,\gamma) $^{13}$N(p,\gamma) $^{14}$O

This cycle can account for significant energy generation, and at temperatures of $T = 5 \times 10^8$ K the reaction $^{15}$O(\alpha,\gamma) $^{19}$Ne can cause leakage out of the cycle into heavier nuclei. Even at slightly lower temperatures more typical of novae ($T = 2.5 \times 10^8$ K), $^{20}$Ne and $^{24}$Mg initially in the star can undergo further processing through a Ne-Na-Mg cycle:

$$^{20}$Ne(p,\gamma) $^{21}$Na(p,\gamma) $^{22}$Mg($e^+, \nu$) $^{22}$Na(p,\gamma) $^{23}$Mg($e^+, \nu$) $^{23}$Na(p,\alpha) $^{20}$Ne
and a Mg-Al-Si cycle:

\[ ^{24}\text{Mg}(p,\gamma) \rightarrow ^{25}\text{Al}(e^+,\gamma) \rightarrow ^{25}\text{Mg}(p,\gamma) \rightarrow ^{26}\text{Al}(p,\gamma) \rightarrow ^{27}\text{Si}(e^+,\gamma) \rightarrow ^{27}\text{Al}(p,\alpha) \rightarrow ^{24}\text{Mg}. \]

The relevant reactions are shown schematically in Figure 1. The relative importance of the various reactions depends, of course, on the temperature and density of the particular model in question, but significant \(^{26}\text{Al}\) production can occur if \(^{24}\text{Mg}\) is present, either initially or from the breakout of lower mass cycles.

Woosley and Weaver (1980) investigated the production of \(^{26}\text{Al}\) from explosive neon burning in shock heated regions of massive stars. After helium burning the dominant nuclei are \(^{12}\text{C}\), \(^{16}\text{O}\), and \(^{22}\text{Ne}\). Hydrostatic carbon burning then produces a whole range of intermediate mass isotopes, but strongly converts \(^{12}\text{C}\) to \(^{20}\text{Ne}\) and \(^{22}\text{Ne}\) to \(^{25}\text{Mg}\). When the neon-rich regions are shock heated to temperatures of \(T = 2-3 \times 10^9\) K, a particles are photoejected from \(^{20}\text{Ne}\) and captured by other \(^{20}\text{Ne}\), the major net result being \(2^{20}\text{Ne} + ^{24}\text{Mg} + ^{16}\text{O}\). Significant amounts of \(^{23}\text{Na}\), \(^{25,26}\text{Mg}\), and \(^{27}\text{Al}\) are also produced, and the reaction \(^{25}\text{Mg}(p,\gamma)\) \(^{26}\text{Al}\) produces the gamma ray line candidate. This process is strongly temperature dependent because for \(T < 2 \times 10^9\) K, the carbon burning ashes are ejected unprocessed while for \(T > 3.5 \times 10^9\) explosive oxygen burning dominates, producing isotopes with \(A > 28\).
Figure 1. Dominant reactions in explosive H-burning (adapted from Wallace and Woosley, 1981).
IV. THE DISTRIBUTION OF RECENT NUCLEOSYNTHESIS IN THE GALAXY

In order to calculate the distribution of gamma rays from the decay of recently synthesized materials it is necessary to map the large scale distribution of the suspected sources. Supernovae occur too infrequently to consider them directly, so associations with more easily observable galactic constituents must be determined. Novae, while more numerous, are only observed relatively near to the solar position and it is not clear how they should be related to other well-sampled galactic objects, so a true galactic distribution is difficult to derive. Novae can be observed in a few nearby galaxies and since the known part of the galactic distribution compares well with the corresponding features in M31, the spatial distribution seen there can be considered reasonable for our Galaxy.

A. Supernovae

Supernovae are considered Population I objects and might be expected to be spatially correlated with other Population I constituents. If supernovae (specifically Type II) represent the relatively youthful demise of massive O and B stars which form in (or on the edge of) dense molecular clouds, maintain ionization in HII regions and leave behind pulsar remnants and radioactivities after explosion, then the galactic distributions of all these Population I constituents ought to be similar. I will review some evidence which suggests they are similar and choose what seems to be the best quantitative distribution. I also
consider the light from the disk of our Galaxy and others as a possible tracer of Population I activity.

Mahoney et al. assumed a longitudinal distribution of $^{26}$Al gamma rays like that observed in gamma rays of energy $E > 100$ MeV. This high energy radiation field can be thought of as the sum of contributions from the decay of pions produced in cosmic ray–interstellar matter interactions, cosmic ray electron bremsstrahlung, pulsar emission, and inverse Compton scattering—in roughly descending order of importance. While these processes might be related to supernovae to varying degrees, it is not clear which process dominates the variation with longitude nor specifically how they are related to supernovae. Neither the source nor the distribution of cosmic rays is well understood and roughly half of the mass of the interstellar medium with which they interact is atomic hydrogen which does not correlate with any tracers of recent star formation. Various authors have fit the high energy gamma ray data well using several different assumptions. Bignami et al. (1975) fit the data by assuming that cosmic ray density is proportional to the density of matter, for which they used the measured atomic hydrogen distribution enhanced by a certain factor to take into account molecular hydrogen. Stecker et al. (1975) concluded that the $> 100$ MeV emissivity varies like the sum of atomic and molecular hydrogen mass densities to a power $\alpha$ where $1.2 < \alpha < 1.5$. Higdon and Lingenfelter (1976) found good agreement with the observations for uniform cosmic ray intensity throughout the Galaxy interacting with the measured HI and $H_2$ distributions plus a contribution from unresolved pulsars. Thus it is not certain that high energy gamma rays should identify regions of star formation and nucleo-
synthesis, but it is interesting to compare other reasonable distributions to theirs.

Perhaps the most obvious tracer of supernova nucleosynthesis is supernova remnants, which can be observed to relatively large distances as nonthermal radio sources. However, distance determinations are difficult and are reliable for only a limited number of remnants. There have been very few remnants observed within a few kiloparsecs of the galactic center, so the frequency of occurrence there is very uncertain. The surface density of supernova remnants as a function of galactocentric distance has been determined by Kodaira (1974) and is shown in Figure 2. While this distribution cannot be considered quantitatively significant, it is important that it is similar to the distributions of the other tracers considered below. Supernova remnants also seem to be well confined to the plane of the Galaxy. Ilovaisky and Lequeux (1972) found the median of the distance to the plane to be $Z = 40$ pc.

Seiradakis (1976) considered the distribution of 149 pulsars, which are useful because reliable distance measurements are available in their dispersion measures. His radial distribution is shown in Figure 3. No pulsars were detected within 3 kpc of the galactic center nor farther than 14 kpc from it. The $Z$-distribution was found to be a Gaussian with full width at half maximum of 660 pc. This is considerably wider than any of the other Population I distributions, but may just be a result of the pulsars' high velocities.

Ionized hydrogen can be observed to large distances through radio recombination lines. The distribution of giant HII regions observed in the H109\alpha line is generally consistent with spiral structure and is
Figure 2. The radial distribution of supernova remnants in arbitrary units (Kodaira, 1974).

Figure 3. The radial distribution of pulsars in arbitrary units of density (Seiradakis, 1976).
highly concentrated in the region $4 < R < 8$ kpc (Burton et al., 1975). Lockman (1976) has surveyed a portion of the galactic plane in great detail in the H$\alpha$ recombination line. It is not clear whether the emission originates in a low density distributed medium or from many discrete HII regions, but it is seen continuously within 45° of the galactic center. The radial distribution derived by Lockman under the assumption of circular rotation is shown in Figure 4. It is peaked around $R = 5.5$ kpc as are the other distributions, but is slightly more concentrated toward that radius. Although there is little data on the Z-distribution of the ionized gas, it seems to be strongly concentrated toward the plane. Gordon et al. (1972) found no emission more than 70 pc from the central plane.

Until a decade or so ago it was generally believed that atomic hydrogen was the dominant component of the interstellar medium, but recent observations have shown a similar total mass of molecular hydrogen, although with a much different spatial distribution. It is difficult to detect $H_2$ directly. Its Lyman absorption bands in the ultraviolet allow its detection within a kiloparsec of the sun. Since $H_2$ has no permanent dipole moment, no dipole radiation is expected from vibrational-rotational transitions, only weak quadrupole transitions, in the infrared, are possible. The next most abundant molecule is CO which has rotational transitions in the millimeter wavelength radio region. As the dominant mode of excitation of CO is collisions with $H_2$, CO observations can in principle yield information on the distribution of $H_2$.

Extensive surveys of the galactic plane have been made of the $J = 1 \rightarrow 0$ transition of CO at 2.6 mm (see, for example, Scoville and
Figure 4. Power in the H166α line, per kiloparsec, derived under the assumption of circular galactic rotation (Lockman, 1976).

Figure 5. Radial distribution of $^{12}$C$^{16}$O volume densities (left ordinate) at $b = 0^\circ$ and projected surface densities (right ordinate) (from Gordon and Burton, 1976).
Solomon, 1975; Burton et al., 1975; Gordon and Burton, 1976; and the review of Burton, 1976). The radial distribution of CO as found by Gordon and Burton (1976) is shown in Figure 5. This distribution is qualitatively similar to the other Population I distributions, and because it is relatively well determined since several authors find similar results, I will use it to establish a quantitative distribution for the calculations to follow.

The thickness of the CO disk is consistently found to have FWHM ~ 130 pc (Scoville and Solomon, 1975; Burton and Gordon, 1976), in accordance with the scale heights of massive stars, HII regions and supernova remnants. There is some uncertainty in conversions of CO emissions to \( H_2 \) densities. Because \( ^{12}\text{CO} \) lines are optically thick, lines from \( ^{13}\text{CO} \), assumed to be optically thin, are used along with measured abundance ratios to determine the column density of \( H_2 \). If \( ^{13}\text{CO} \) lines are optically thick, as suggested to be true by Phillips et al. (1979), higher \( H_2 \) densities result.

I will wish to normalize the distribution to surface densities at the solar radius, for which I use \( R_s = 10 \) kpc (Ovenden and Byl, 1983). Based on the most recent surveys Sanders (1983) determines \( \sigma(R_s = 10 \) kpc) = \( 7 \, M_\odot \text{pc}^{-2} \), for the total mass of the local interstellar medium, of which about \( 4 \, M_\odot \text{pc}^{-2} \) is in molecular form. Based on ultraviolet observations by the Copernicus satellite, Jenkins (1976) finds a similar value for the total local interstellar mass density, but asserts that only 20% is in molecules. The Galaxy is not perfectly axially symmetric (as I will assume) according to either HI or CO observations, which could account for the discrepancy. It is also possible that the ultra-
violet observations are insensitive to the more dense molecular clouds. Using Sanders' value for the local density of molecules leads to a total galactic mass of $4 \times 10^5 M_\odot$ in molecular clouds, compared to $5 \times 10^3 M_\odot$ of atomic hydrogen.

Another interesting way to determine the distribution of recent nucleosynthesis is to assume that it is proportional to the amount of light given off by luminous young stars. Of course it is not possible to be selective in choosing light from certain types of disk stars on a galactic scale, but simple models of the light distribution in galaxies yield excellent fits to observed star counts in our galaxy for a large range of stellar luminosities (Bahcall and Soneira, 1980).

It is well established that the surface brightness of spiral galaxies can be fit with a combination of an exponential for the disk component and a de Vaucouleurs profile (developed for elliptical galaxies) for the spheroidal component (de Vaucouleurs, 1959; Freeman, 1970; Kormendy, 1977). That is, the surface brightness (or surface density of stars) is

$$B(R) = e^{-R/h} \quad \text{Disk}$$

$$B(R) = 10^{-3.32[(R/R_E)^{1/4} - 1]} \quad \text{Spheroid}$$

For the Galaxy, the space density of stars of the spheroidal component is normalized to 1/800 of that of the disk component, at the solar position, $R_\odot = 10$ kpc. The standard value for $h$ is 3.5 kpc for the Galaxy. I use $R_E = 3.3$, as several authors including de Vaucouleurs (1977) find
Many spiral galaxies have disks which appear to have holes in them near their centers. It is likely that our galaxy also has this cutoff in the disk near the region where the spheroid begins to dominate. Kormendy (1977) suggests fitting the disk light with a function like $B(R) = B_0 \exp[-R/h - (R/R_0)^n]$ where $R$ is the approximate inner radius of the disk and $n$ defines the sharpness of the cutoff. Kormendy finds that $n = 3$ works well for disk galaxies. Based on dynamical models Ostriker and Caldwell (1979, 1983) suggest $\beta = 3$ kpc.

If supernovae are expected to be the major source of the recently synthesized radioactive species only the disk component need be considered, but if novae are significant contributors to the gamma ray flux (as they might be for decay of $^{26}$Al) both components of the Galaxy must be considered.

Whether the exponential disk is physically meaningful or simply the result of the fitting procedure is not yet clear. Seiden et al. (1984) show that power law distributions of matter derived from rotation curves (most frequently $1/r$) look like exponentials over a large range of galactic radii. They argue that the radial dependence of the surface density of gas will be the same as that of the massive halo if the halo is what supplies the disk gas and specific angular momentum is conserved. Since the atomic hydrogen density is observed to be relatively constant over the optical portion of the disk, the molecular hydrogen surface density should vary as the power law deduced from the rotation curve. If the star formation rate is proportional to the density of molecular clouds, the surface brightness should be also. Nevertheless, exponen-
tials fit well the observed surface brightness of the Galaxy and other galaxies, so I will not argue the intrinsic significance here.

The disk light profile with parameters as discussed above is plotted in Figure 6. It is interesting that all of the above galactic constituents which might be associated with star formation and nucleosynthesis have very similar radial profiles. I have also calculated the corresponding gamma ray flux distributions for each, as described below for the molecular mass distribution and they are essentially the same within the errors of the determination of each distribution. Thus I do not discuss them further for I am more interested in the differences between the expected novae and supernovae distributions, or between the supernovae distribution and that assumed by Mahoney et al.

Radial Metallicity Gradient

Considering supernova nucleosynthesis, it is also possible that a galactic abundance gradient could influence the gamma ray observations. The idea is that $^{26}\text{Al}$ is a secondary nucleosynthesis product from seed nuclei whose abundances vary systematically. The existence of such gradients in the disk of spiral galaxies, including ours, is well established (see, for example, Peimbert, 1979). Mayor (1976) and others have found $d \log(\text{Fe/H})/dR = -0.02$ to $-0.08$ kpc$^{-1}$ with $-0.07$ kpc$^{-1}$ a representative value for the gradient in nearby stars. Torres-Peimbert and Peimbert (1977) surveyed planetary nebulae and found $d \log(\text{He/H})/dR = -0.02$ kpc$^{-1}$, $d \log(\text{O/H})/dR = -0.06$ kpc$^{-1}$, and $d \log(\text{N/H})/dR = -0.18$ kpc$^{-1}$. HII regions have been observed by many authors. Early estimates
Figure 6. Surface brightness profile of disk.
of the gradients are \( \text{d} \log(\text{O/H})/\text{d}R = -0.1 \) and \( \text{d} \log(\text{N/H})/\text{d}R = -0.14 \) kpc\(^{-1}\) from Peimbert (1979), who considered 18 HII regions. A more recent estimate by Shaver et al. (1984) is \( \text{d} \log(\text{O/H})/\text{d}R = -0.07 \) kpc\(^{-1}\).

These gradients reflect either an increase in disk nucleosynthesis with decreasing galactocentric radius or increased initial metal abundances in the disk from infalling matter from the halo. Much larger abundance gradients are seen in the spheroidal component which could account for the second possibility. The larger gradient in nitrogen relative to oxygen might be said to substantiate the theory of nucleosynthesis since it is believed that nitrogen is produced in stars which already contain carbon and oxygen. I will consider the effect of the gradient observed by Shaver et al. on the gamma ray observations.

B. Novae

Galactic novae have been discussed at length by Payne-Gaposchkin (1954, 1957) and more recently updated by her (1977). In general, the observed novae are concentrated near the plane and toward the center of the Galaxy. According to the list of novae compiled by Payne-Gaposchkin (1954, 1977) the latitude distribution is such that the mean \(|b|\) is 9° while the median \(|b|\) is 6° and 95% of all observed novae are found with \(|b| < 20°\). The longitude distribution is strongly peaked toward \( \lambda = 0°\), with half of the observed novae within 10° of the galactic center. Selection effects probably cause the concentrations in the plane and toward the center to appear less severe than they truly are. The narrow gas distribution of the plane probably obscures many novae with \( b > 0 \)
and the molecular cloud ring together with increased starlight from the central region could well hide many novae there.

Kopylov (1955) observed that the nova surface density, $D$, varied like $d \log D/dR = -0.22 \text{ kpc}^{-1}$ and $d \log D/dZ = -2.4 \text{ kpc}^{-1}$ where $R$ is galactocentric distance and $Z$ is distance to the galactic plane.

Minkowski (1950) noted a strong correlation between the distributions of novae and planetary nebulae. In the direction of the outer Galaxy novae are found in a very thin layer while toward the galactic center they are found in a somewhat thicker layer. Kopylov (1955) also noted a close association between white dwarves and novae. These facts have led to the belief that novae form an intermediate subsystem.

A less spatially biased sample of novae is found in M31 (Hubble, 1929; Arp, 1956). Sharov (1971) has studied the distribution of novae there in detail. He noted that near the nucleus the distribution is spheroidal while beyond about 2.4 kpc novae form a flattened intermediate system. According to Sharov the gradient of nova surface density in M31 is $d \log D/dR = -0.81 \text{ kpc}^{-1}$ for $1 < R < 2.4 \text{ kpc}$ and $d \log D/dR = -0.16$ for $2.4 < R < 17 \text{ kpc}$. There is some uncertainty as to the density of novae very near the center of M31, as very few are seen inside 1 kpc. Hubble and Arp both favored a true deficit of novae at the center, while Sharov believes that the sharp increase in brightness of the background there hinders the observation of novae. This interpretation seems viable because in a spheroidal system one would expect to see some novae in projection, at least. I use a constant surface density inside 1 kpc to model the novae in the Galaxy after those in M31.
It is by no means certain that novae in our Galaxy should be distributed like those in M31, however there are similarities. Kopylov may have used too large a value for interstellar absorption (Sharov, 1963) in obtaining his radial gradient, and Schmidt-Kaler (see Plaut, 1965) finds the radial gradient is $d \log D/dR = -0.18 \text{kpc}^{-1}$ in the Galaxy, very similar to that at the corresponding position in M31.
V. GAMMA RAY FLUX

A. Supernovae

Now I assume that the observed distribution of molecular clouds (observed in CO lines) is representative of Population I objects in general and recent star formation and nucleosynthesis in particular. Stecker and Jones (1977) fit the radial distribution of various Population I constituents with functions of the form \( \sigma = (R/10)^A \exp(-BR/10) \); where \( \sigma \) is the surface density (or column density) of matter, and \( R \) is the galactocentric radius in kiloparsecs. The CO data of Burton et al. (1975) yield a least-squares fit to this function with \( A = 7.4, B = 13.9 \). This is plotted in Figure 7. Such a distribution is quantitatively very similar to the distribution of pulsars (for which \( A = 6.2, B = 12.4 \)) from Seiradakis (1976) and qualitatively similar to the other Population I distributions discussed above (see Figs. 2–6).

First I assume that supernova nucleosynthesis is simply proportional to the surface density of matter in the molecular clouds. Then the surface density of \(^{26}\text{Al}\) (and other isotopes) is proportional to the mass and the surface emissivity (photons emitted per unit area per unit time) in 1.809 MeV gamma ray is

\[
\sigma = \sigma_0 13.9 \left( \frac{R}{10} \right)^{7.4} \exp(-1.39 R) \text{ photons cm}^{-2} \text{ s}^{-1}
\]

normalized to column densities at the solar radius, \( R_0 = 10 \text{ kpc} \). It is also interesting to consider the effect of a galactic metallicity gradi-
Figure 7. Surface density of molecular clouds (analytic fit to data of Burton et al. [1975]).
ent on the gamma ray flux. Here I use the gradient determined by Shaver et al. (1983) as representative (see above). They find that the mass fraction of metals varies like \( Z = Z_\odot \exp[0.16(10 - R)] \). If it is assumed that this gradient truly reflects an increase with decreasing radius in the production of secondary nucleosynthesis products (e.g., \( ^{26}\text{Al} \)), then one might expect that the emissivity in the aluminum line would vary as

\[
\sigma = \sigma_0 e^{15.5 \left( \frac{R}{10} \right)^7} e^{-1.55R} \text{photons cm}^{-2} \text{s}^{-1}
\]

I ignore any implications the gradient might have on interpretation of the CO abundances. Note that the effective exponential scale length (which is modified by \( (R/10)^{7.4} \)) changes from approximately 4 kpc to slightly less than 3 kpc with the gradient. (Scale length measured near \( R_\odot \).)

For the moment I will consider fluxes seen by an instrument with a well defined aperture. The flux is calculated in two parts. The first is for those regions where the gamma ray emitting thickness of the disk is completely within the field of view of the telescope (this is most of the galactic plane). The second region is that part of the disk, near the sun, inside the point at which the cone subtended by the telescope contacts the thickness of the disk (see Fig. 8). These calculations are done for a wide field instrument, such as HEAO 3, for which I use an aperture of 60° to determine at what distance the latitude extent is entirely in the field of view. The actual HEAO 3 instrument has non-zero transmission even for directions at large angles from the viewing
Figure 8.  a) Element of area of galactic plane for integration along line of sight from a to b.  b) Cross-section of near-solar galactic plane with (idealized) acceptance cone of telescope.
axis. I also calculate count rates as a function of longitude for such an instrument to see if the difference expected from supernovae and novae is significant enough to warrant further analysis to attempt to determine the angular distribution.

Considering an element of area of the galactic plane a distance $x$ away, with emissivity per unit area $\sigma$, and angular extent $d\ell$, the flux is

$$df = \frac{\sigma dA}{4\pi x^2} = \frac{\sigma x \, dx \, d\ell}{4\pi x^2}$$

The flux in a given direction of galactic longitude, $\ell$, is obtained by integrating along the line of sight to the edge of the galaxy, which I take to be 15 kpc from the galactic center. There is little evidence for any Population I activity beyond that distance, and these models give negligible contribution from beyond, so the exact cutoff is not significant. The differential flux per radian of longitude is then

$$\frac{df}{d\ell} = \int_a^b \frac{\sigma dx}{4\pi x}$$

I have assumed an axially symmetric interstellar medium, so $\sigma$ is just a function of $R$, galactocentric radius. The surface emissivity can be related to the distance along the line of sight, $x$, through

$$R = (x^2 + R_0^2 - 2xR_0 \cos \ell)^{1/2}.$$ The lower limit to the integral is the distance at which the disk thickness just fits within the cone of the telescope. For a 60\degree telescope $a = [(\sqrt{3})/2]h$, where $h$ is the disk thickness. The upper limit, as described above, is given by
\[ b = \left( 325 - 300 \cos[180 - \varphi - \sin^{-1}(0.67 \sin \varphi)] \right)^{1/2} \text{kpc} \]

which is the distance along the line of sight to a point 15 kpc from the galactic center.

To this flux I must add that from the nearby galactic disk. While this is only a small fraction of the galaxy, the gamma ray flux can be significant since it is so close. It will be seen to be important for viewing the galactic anticenter. For example, for a disk of half-thickness 70 pc (i.e., molecular clouds) and a 60° aperture, this region is a cylinder with radius 120 pc, so I will consider the column density to be constant over this region, that is, \( \sigma = \sigma_0 \).

For the simple case of a uniform disk of thickness \( h \), a telescope of angle \( \alpha \) sees volume emissivity \( \rho = \sigma_0 / h \). Then the flux is

\[
\frac{df}{d\ell} = \frac{2}{4\pi} \int_0^{2\pi} \int_0^{\pi} \left( \frac{\pi + x}{2} \right) \sin \theta \, d\theta \, a \cdot \sin \theta \left( \frac{\alpha^2}{4\pi h} \right) \cdot a \cdot \left( \sin \theta \right) \left( \frac{\alpha^2}{4\pi h} \right)
\]

For \( \alpha = 60° = 1.05 \text{ radians}, \ a = (\sqrt{3}/2)h \),

\[
\frac{df}{d\ell} = \frac{\sqrt{3} \sigma_0}{8\pi} = 0.07 \sigma_0
\]

It is interesting that this does not depend on the height of the disk, only the solid angle of the telescope. The scale height does determine the lower limit of the integration along the line of sight, and so does influence the relative importance of the two parts of the flux.

A more realistic case is an exponential dependence of gas density on distance above the midplane, \( Z \). Although the molecules of the inter-
stellar medium are distributed in Z more like a Gaussian than an exponential, it is interesting that a collection of radioactive species ejected out of the plane with uniform normal velocities results in an exponential in height above the plane if decay occurs before substantial deceleration. Now I am concerned with the emitting atoms closer than the distance at which the telescope subtends two exponential scale heights. If the central density is such that

$$2 \int_0^\infty \rho_0 \exp(-2Z/h) \, dZ = \sigma_0,$$

then \( \rho_0 = \sigma_0 / h \), where \( h \) is two scale heights. The flux per radian of longitude is

$$\frac{df}{d\zeta} = \frac{\rho_0}{4\pi} \int e^{-2z/h} \, d\rho \sin \theta \, d\theta = \frac{\sigma_0}{4\pi h} \int e^{-(2r \cos \theta)/h} \, dr \, d(\cos \theta)$$

$$= \frac{\sigma_0 \sqrt{3h}}{4\pi h} \int_0^\infty \, dr \left[ e^{r/h} - e^{-r/h} \right] \frac{h}{2r} \text{ for } \alpha = 60^\circ.$$ 

Using \( \int \frac{1}{x} e^{ax} \, dx = \ln x + \frac{ax}{1!} + \frac{a^2 x^2}{2 \cdot 2!} + \ldots \)

$$\frac{df}{d\zeta} = \left[ 2 \frac{r}{h} + \frac{r^3}{9h^3} + \ldots \right] \frac{\sigma_0 \sqrt{3h}}{8\pi} \left| \frac{\sqrt{2}}{2} \right| = 0.072 \sigma_0 \text{ per radian}$$

This is not very different from that calculated for the simple disk of thickness \( h \) with uniform density.

The total flux from a given direction can be written

$$\frac{df}{d\zeta} = \sigma_0 \left[ e^{B} \int_a^b \frac{rA_{\alpha-B}r}{4\pi x} \, dx + 0.07 \right] \text{ photons cm}^{-2} \text{ s}^{-1} \text{ rad}^{-1}$$
where $r^2 = (x^2 + R_e^2 - 2xR_e \cos \ell)/R_e^2$, $\sigma_e$ is in units of cm$^{-2}$ s$^{-1}$, and for supernova nucleosynthesis in the present context $A = 7.4$, $B = 13.9$ (in the case of constant metallicity), $B = 15.5$ (with a radial metallicity gradient).

The integration was performed numerically using Newton-Cotes quadratures, at one degree intervals around the galactic plane. The flux is plotted as a function of longitude, normalized to unity in the direction of maximum flux, in Figures 9 and 10, for constant mass fraction of metals and with metallicity gradient, respectively. The following calculations are chosen because of their relevance to the discussions of Mahoney et al. (1982, 1984). The results are presented in Tables 1 and 2.

**Without Metallicity Gradient**

Within $60^\circ$ centered on the galactic center, the average flux per radian is

$$\overline{F_c} = \frac{1}{31} \sum_{\ell=0}^{30} \frac{df(\ell)}{d\ell} = 1.33 \sigma_e.$$

Similarly, from the anticenter direction the average flux per radian is

$$\overline{F_A} = \frac{1}{31} \sum_{\ell=150}^{180} \frac{df(\ell)}{d\ell} = 0.24 \sigma_e,$$

which is down a factor of 5.6 from that toward the center. This lower anticenter flux and the deficit within $\sim20^\circ$ of the center (relative to
Figure 9. Gamma ray flux versus longitude for emissivity proportional to density of CO.
Figure 10. Gamma ray flux versus longitude for emissivity proportional to C0 density times metallicity gradient.
the "molecular cloud ring" at \(-25^\circ\) most distinguish this distribution from that assumed by Mahoney et al. (1984). Both of these differences are physically reasonable since the peak of the high energy gamma rays near \(\xi = 0\) might well be due to inverse Compton scattering and electron bremsstrahlung from enhanced electron density and photon field at the galactic center, or unresolved pulsars (Stecker et al., 1975); while those from the outer galaxy are likely dominated by cosmic ray interactions with atomic hydrogen (Bloemen et al., 1984) — processes not directly related to recent nucleosynthesis.

The total galactic production is given by \(Q = \int_0^{15} 2\pi R f(R) dR\). Changing \(R\) to \(R = r\) gives, in the notation used above,

\[
Q = 2\pi \sigma_0 e^{Br} \int_0^{15} R^{A+1} e^{-Br} dr.
\]

For this distribution, \(Q = 1.12 \times 10^{6}\times \sigma_0 (\text{cm}^{-2}\text{s}^{-1})\) photons s\(^{-1}\). Then, as in Mahoney et al., \(\overline{F}_c / Q = 1.19 \times 10^{-6} (\text{cm}^{-2} \text{rad}^{-1})\). This element of their analysis is probably not in question.

If the spatial distribution is normalized to the flux quoted, that is if \(\overline{F}_c = 4.8 \times 10^{-4}\) photons cm\(^{-2}\) s\(^{-1}\) rad\(^{-1}\), the column emissivity at the sun in 1.809 MeV photons is \(\sigma_0 = \overline{F}_c / 1.33 = 3.46 \times 10^{-4}\) photons cm\(^{-2}\) s\(^{-1}\). For a radioactive species the decay rate is the number of that species divided by its mean lifetime. This implies a surface density of \(1.14 \times 10^{10} \text{^{26}Al}\) atoms cm\(^{-2}\) at 10 kpc from the galactic center. This corresponds to a mass density of \(^{26}\text{Al}\) of \(4.95 \times 10^{-13} \text{ g cm}^{-2}\). The surface density of gas (all constituents) near the sun is \(7 M_\odot \text{ pc}^{-2} = 1.5 \times 10^{-3}\) g cm\(^{-2}\) (Jenkins, 1976; Sanders, 1983), giving a mass fraction of
X(\text{^{26}Al}) = 3.3 \times 10^{-10} needed to explain the gamma ray flux. The mass fraction of \text{^{27}Al} in solar system matter is X(\text{^{27}Al}) = 6.6 \times 10^{-5} (Cameron, 1982). If this is also assumed to be characteristic of the local interstellar medium, an isotopic ratio of \text{^{26}Al/^{27}Al} = 5.0 \times 10^{-5} results. The isotopic ratio (from a single type of source) can be expressed as \text{^{26}Al/^{27}Al} = [P(\text{^{26}Al})/P(\text{^{27}Al})] (\tau/T) (see, for example, Clayton, 1984) where [P(\text{^{26}Al})/P(\text{^{27}Al})] is the production ratio in the nucleosynthetic event, \tau is the lifetime of \text{^{26}Al}, and T is the time since the beginning of synthesis of \text{^{27}Al}, taken here to be 10^{10} years. If the \text{^{26}Al} is distributed as are the molecules of the interstellar medium, the HEAO 3 flux implies [P(\text{^{26}Al})/P(\text{^{27}Al})] = 0.05. This is fifty times the production ratio expected based on calculations by Woosley and Weaver (1980) for explosive neon burning in massive stars. Arnould et al. (1980) find [P(\text{^{26}Al})/P(\text{^{27}Al})] can approach unity in certain proton-rich zones of explosive hydrogen burning in supernovae, but this cannot account for the inferred production ratio when all modes of production of \text{^{27}Al} are summed together.

A different, perhaps more reasonable method of normalizing the distributions to the reported flux is used by Leising and Clayton (1984). The implied surface densities are only slightly different and don't change the conclusions reached here.

With Metallicity Gradient

If the mass fraction of \text{^{26}Al} varies with distance from the galactic center like metals in HII regions, the implications of the quoted flux
are only slightly different from the case discussed above. The following quantities are calculated in an analogous manner to those above. The flux from the center direction (averaged over 60°) is

\[
\bar{F}_c = 2.13 \sigma_e
\]

and from the anticenter

\[
\bar{F}_A = 0.23 \sigma_e
\]

which is down by a factor of 9.5 from the center direction. The fit to the HEAO 3 data with such a model should be significantly different from the model assumed (like > 100 MeV gamma rays). Again

\[
Q = 2\pi R_c^2 \sigma_e e^B \int_0^{1.5} r^{A+1} e^{-Br} dr,
\]

with the notation used above. With A = 7.41 and B = 15.5, Q = 1.99 \times 10^{46} \sigma_e (cm^{-2} s^{-1}) photons s^{-1}. Then \(\bar{F}_c/Q = 1.07 \times 10^{-46} \text{ cm}^{-2} \text{ rad}^{-1}\). The observed flux implies \(\sigma_e = 2.16 \times 10^{-4} \text{ photons cm}^{-2} \text{ s}^{-1}\) which gives a surface density of \(7.1 \times 10^9 \text{ }^{26}\text{Al} \text{ atoms cm}^{-2}\). This corresponds to a mass fraction of \(X(^{26}\text{Al})_o = 2.0 \times 10^{-10}\), and thus an isotopic ratio \(^{26}\text{Al}/^{27}\text{Al} = 3.0 \times 10^{-6}\), which leads to a production ratio \([\text{P}(^{26}\text{Al})]/[\text{P}(^{27}\text{Al})] = 0.03\). This is at least fifteen times the largest estimate of Woosley and Weaver (1980), thirty times a more reasonable estimate, even for this most optimistic distribution based on supernova nucleosynthesis. Note that the metallicity gradient lowers the implied isotopic
ratio to 60% of its value in the absence of a gradient.

So even with the vast uncertainties involved, it seems unlikely that a steady state galactic distribution of supernova nucleosynthesis can account for the gamma ray flux. Even if the true flux is a factor of two lower (an extreme estimate) than the published value due to an incorrect assumed longitude distribution, the discrepancy remains too large to credit supernovae as the source based on current theory.

The isotopic ratio without gradient is about three times smaller than the ratio inferred by Clayton (1984). This difference occurs primarily because my model of the ISM is more than twice as massive as the one used by Clayton, secondarily because the total $^{26}\text{Al}$ is slightly smaller owing to the slightly greater value of F/Q associated with my model, and third because the observed flux has been reduced by Mahoney et al. (1984) to about 80% of their original (1982) report.

B. Novae

As discussed above I adopt the radial distribution of novae observed in M31 by Sharov (1971) as similar to what might be found in our galaxy. The surface density of novae, based on the observed gradients, is

$$\sigma = 228 \sigma_0 \quad R < 1 \text{ kpc}$$

$$= 1.48 \times 10^3 \sigma_0 e^{-1.87R} \quad 1 < R < 2.4 \text{ kpc}$$

$$= 40.4 \sigma_0 e^{-0.37R} \quad 2.4 < R < 17 \text{ kpc}$$
Figure 11. The radial distribution of novae in M31 (Sharov, 1971).
which is normalized to the surface density $\sigma_0$ at 10 kpc and made to be continuous throughout the galaxy. This distribution is plotted in Figure 11. Its shape is similar to the density of light from a de Vaucouleurs spheroid. The Z distribution of novae in both galaxies is such that the great majority of them, even in the central bulge, should be in the field of view of the HEAO 3 instrument as it scans the plane, except for within ~150 pc of the sun, where the scale height of novae is ~181 pc (Payne-Gaposchkin, 1957). The same is not true for the 3.5° x 11° field of view of the OSSE experiment on GRO. This could present problems for observations by OSSE because of its background subtraction technique.

As above, the flux per radian of longitude is

$$\frac{df}{d\ell} = \int_a^b \frac{\sigma(R)}{4\pi} dx + 0.07 \sigma_0 \text{ photons cm}^{-2} \text{ s}^{-1} \text{ rad}^{-1}$$

where $\sigma_0$ is expressed in photons cm$^{-2}$ s$^{-1}$, and where the upper limit is the distance along the line of sight to a galactocentric radius of 17 kpc. The flux is plotted in Figure 12, normalized to unity in the direction of maximum flux, here the galactic center. The average flux per radian from within 60° centered on the galactic center is $\overline{F}_c = 2.61 \sigma_0$, and the corresponding flux from around $\ell = 180^\circ$ is $\overline{F}_A = 0.26 \sigma_0$, a factor of ten down from the center flux. The total galactic production of 1.809 MeV photons is

$$Q = \int_0^{17} 2\pi \sigma(R) dR = 3.0 \times 10^6 \sigma_0 (\text{cm}^{-2} \text{ s}^{-1}) \text{ photons s}^{-1}.$$
Figure 12. Gamma ray flux from nova distribution like M31.
Thus $\bar{F}_c/Q = 8.7 \times 10^{-47}$ cm$^{-2}$ rad$^{-1}$. This quantity is amazingly similar for all reasonable distributions I have considered. Even a point source at the galactic center gives $\bar{F}_c/Q = 8.4 \times 10^{-47}$. This quantity is nearly invariant because as the emission becomes more concentrated toward the galactic center, the bulk of it becomes further from the sun but is also more concentrated in the field of view. All results are summarized in Tables 1 and 2.

If the flux observed by Mahoney et al. (1984) is the true cosmic flux, the emissivity at 10 kpc is $\sigma = 1.76 \times 10^{-4}$ photons cm$^{-2}$ s$^{-1}$. This corresponds to $5.8 \times 10^9$ $^{26}$Al atoms cm$^{-2}$, which is $2.5 \times 10^{-13}$ g cm$^{-2}$ of $^{26}$Al, or a mass fraction in the local interstellar medium of $X(^{26}\text{Al})_\odot = 1.7 \times 10^{-10}$. The implied isotopic ratio is then $^{26}$Al/$^{27}$Al = $2.6 \times 10^{-6}$, using Cameron's (1982) abundances. This would seem to raise doubts that novae nucleosynthesis could have maintained the concentration of $^{26}$Al inferred to be in the protosolar nebula from measurements of excess meteoritic $^{26}$Mg. That is, an isotopic ratio $^{26}$Al/$^{27}$Al = $5 \times 10^{-5}$, found in the Allende meteorite (Lee et al., 1977), was probably not a standard condition of the interstellar medium at 10 kpc, if novae are the main source of $^{26}$Al, unless the rate of novae was significantly greater five billion years ago. In fact, it is more likely that the gas mass was greater then, not the nova rate — resulting in a smaller isotopic ratio.

The observed flux would result from a total galactic luminosity of $5.4 \times 10^{42}$ photons s$^{-1}$, or a total of $1.7 \times 10^{56}$ $^{26}$Al nuclei in the interstellar medium, if distributed as above. If this $3.75 M_\odot$ of $^{26}$Al is in steady state between production and decay, novae must produce that
much in one $^{26}\text{Al}$ mean lifetime, $1.04 \times 10^6$ years. If the average nova ejects $10^{-4}$ $M_\odot$ of matter, and the average mass fraction of $^{26}\text{Al}$ in the ejecta is $X_e(^{26}\text{Al}) = 2.5 \times 10^{-4}$ (Hillebrandt and Thielemann, 1982), $1.5 \times 10^8$ novae are required in $10^6$ years, a rate of 143 novae per year. This rate is some 3.5 times higher than the standard value of 40 novae per year (e.g., Allen, 1973), but is not completely implausible. Arhipova and Mustel (1975) estimate that if all novae brighter than 3$^m$ maximum apparent magnitude are discovered in our galaxy, and the mean absolute magnitude at maximum is $M = -7^m3$, the lower limit of the nova frequency is 50 per year, assuming the novae are distributed in a simple uniform disk. If, however, the novae are distributed like those in M31 with an increasing density near the galactic center, the minimum frequency would be much higher, under the same assumptions.

It should also be noted that the gamma ray flux expected from the distribution of Sharov does not differ greatly in longitude from that of a point source at the galactic center. Mahoney et al. (1984) also fit their HEAO 3 data to a point source at the galactic center which resulted in a positive detection at only the 2.2 $\sigma$ level of confidence. This might present some difficulty for the idea of novae as the source of the line emission, or perhaps novae in our galaxy are not so strongly concentrated in the nucleus as they are in M31.

It was hoped that it might be possible to constrain the models for the source of the observed line based on the observation of a gamma ray line expected from another radioactivity produced in novae, $^{22}\text{Na}$. In explosive hydrogen burning, two proton captures and a beta decay convert $^{20}\text{Ne}$ to $^{22}\text{Na}$ which beta decays with a mean lifetime of 3.75 years, emit-
ting a gamma ray at 1.275 MeV. Mahoney et al. (1982) placed an upper limit of $4.4 \times 10^{-4}$ photons cm$^{-2}$ s$^{-1}$ rad$^{-1}$ on this line.

For two radioactive isotopes produced in the same event, the ratio of the gamma ray fluxes from the two is just equal to their production ratio, if the events responsible for them occur at a constant rate. For an isotope produced at constant rate $P$, with lifetime $\tau$, the number $N$ of that isotope is given by the equation $\frac{dN(t)}{dt} = P - (1/\tau) N(t)$, whose solution is $N = P(t - e^{-t/\tau})$. Then the rate of decay is $N/\tau = P(1 - e^{-t/\tau})$, which just equals the rate of production for times long compared to the mean lifetime. For novae the production rate is $P = X_e M_R N$, where $X_e$ is the mass fraction of ejecta of the isotope, $M_e$ is the mass ejected and $R_N$ is the rate at which novae occur. If all novae are the same and the spatial distribution of novae over the last four years is similar to that over the last million years, the ratio of the fluxes of $^{22}\text{Na}$ and $^{26}\text{Al}$ gamma rays is

$$\frac{F(^{22}\text{Na})}{F(^{26}\text{Al})} = \frac{X_e(^{22}\text{Na})}{X_e(^{26}\text{Al})} \frac{26}{22}$$

where the factor 26/22 converts mass ratio to number ratio.

Early estimates of production of $^{22}\text{Na}$ in novae were very promising for gamma ray astronomy (e.g., Clayton and Hoyle, 1974; Lazareff et al., 1979), but recent estimates are much more pessimistic due to revised nuclear reaction rates. Originally the above ratio would have been estimated as high as $[F(^{22}\text{Na})]/[F(^{26}\text{Al})] = 10$, depending on the nova model, but recently Hillebrandt and Thielemann (1982) found $[X_e(^{22}\text{Na})]/[X_e(^{26}\text{Al})] = 10^{-3}$ for several different nova models. The difference
arises from calculations by Wallace and Woosley (1981) of the cross-
section for the reaction \(^{22}\text{Na}(p,\gamma)^{23}\text{Mg}\), which is responsible for the
destruction of \(^{22}\text{Na}\). They found a value several orders of magnitude
larger than that previously estimated, which results in a much lower
abundance of \(^{22}\text{Na}\) ejected.

These estimates would predict a steady-state flux of \(5 \times 10^{-7}\) pho-
tons cm\(^{-2}\) s\(^{-1}\) at 1.275 MeV, which would remain unobservable into the
distant foreseeable future. While the nova models of Wallace and Woosley
(1981) in general yield similar results to those of Hillebrandt and
Thielemann, one model, a two-zone model which considers convection, pre-
dicts \([X_e(^{22}\text{Na})]/[X_e(^{26}\text{Al})] = 0.08\). Thus a flux from \(^{22}\text{Na}\) only a factor
of ten smaller than that of \(^{26}\text{Al}\), \(\overline{F}_c(^{22}\text{Na}) = 5 \times 10^{-5}\) photons cm\(^{-2}\) s\(^{-1}\)
rad\(^{-1}\), averaged over 60\(^{\circ}\) centered on the galactic center, results from
this model. Since my assumed distribution for novae is so strongly
peaked toward \(l = 0^{\circ}\), the flux within 11\(^{\circ}\) (i.e., OSSE's wider dimension
aligned along the plane) centered on \(l = 0^{\circ}\) would be \(1.2 \times 10^{-4}\) photons
cm\(^{-2}\) s\(^{-1}\) rad\(^{-1}\). Thus the flux seen within 11\(^{\circ}\) would be \(2.4 \times 10^{-5}\) pho-
tons cm\(^{-2}\) s\(^{-1}\) — above the OSSE threshold — but this assumes the latitude
extent of the source is within 3.5\(^{\circ}\) (OSSE's narrow dimension) which is
most likely not the case. Probably only a small fraction of the emis-
sion from novae lies this close to the plane, particularly near \(l = 0^{\circ}\).
The nova distribution, being so strongly peaked, is sensitive to the
method of normalizing to the HEAO 3 flux. Equating the total flux
within 42\(^{\circ}\) from this distribution to the same quantity inferred from
Mahoney et al. (1984) yields a central flux at 1.275 MeV below the OSSE
threshold (see Leising and Clayton, 1984).
Still, increased $^{22}\text{Na}$ production could result from changes in key parameters in the nova models such as lowering the peak temperature or using different initial abundances (i.e., greater than solar X($^{20}\text{Ne}$)). So as there exists great uncertainties in nova models and in regard to the crucial nuclear reactions, it is not impossible that the OSSE detector could make a detection at 1.275 MeV. However, an upper limit, even at the sensitivity of OSSE ($2 \times 10^{-5}$ cm$^{-2}$ s$^{-1}$), would not be especially informative, as it is only at the extremes of the models for nova production of $^{22}\text{Na}$ that the predictions reach that limit.

C. The Gamma Ray Flux Seen Through a HEAO 3-Like Shield

I now wish to consider how the transparency of the HEAO 3 shield would smear out in longitude the gamma ray fluxes calculated above. I do this not to try to simulate the actual count rate recorded by the instrument, but rather to try to see if the shield would render the novae and supernovae distributions indistinguishable. If so, there would be no use in considering further the relevance of these distributions to the HEAO 3 data.

The angular response of the detectors due to the shield characteristics is somewhat complicated (see Mahoney et al., 1980). In addition to the partial transmission of the shield at all angles, leakage into one detector from the collimation hole of another is sometimes important. For simplicity, I model the shield transmission with an analytic function which is generally similar to the actual transmission. I use a Lorentzian function with full width at half maximum of 42° normalized to
unity on the viewing axis. As a function of $\theta$, the transmission is

$$T(\theta) = \frac{212}{212 + \theta^2} \quad |\theta| < 42^\circ$$

$$= 0.2 \quad |\theta| > 42^\circ$$

where $\theta$ is measured in degrees from the viewing axis. This function is shown in Figure 13.

Again I break the flux up into two parts: one from the very near part of the disk and another from the more distant disk. For the more distant part the integral along each line of sight at 360 longitudes is calculated with the limits of integration the same as in the preceding section. At each viewing angle, $\ell$, the counts are summed from around the whole galactic plane, weighted by the appropriate shield transmission, assuming the latitude extent of the emission is near enough to the viewing axis to consider transmission of unity. That is, the distant emission is considered to be distributed in a line at the galactic equator. So the count rate, $C_\ell$, from this part of the plane can be written:

$$C_\ell(\ell) = \int T(\theta) \frac{df}{d\theta} (\theta + \ell) d\theta \quad \text{(in units of surface emissivity, } \sigma_\ell)$$

where $\ell$ is the viewing longitude; $\theta$ is the angle from the $\ell$ direction; $T$ is the shield transmission; and $df/d\theta$ is the differential flux (per radian) computed from the integral along the line of sight in the $\theta + \ell$ direction, of the emissivity weighted by $1/r^2$, expressed in units of $\sigma_\ell$/radian.
Figure 13. Simulated transmission of HEAO-3 shield.
The near part of the disk is actually a cylinder with comparable diameter and height, but for simplicity I will assume the flux is spherically symmetric, and equal to that calculated above for the same part of the disk, namely \( \frac{df}{d\Omega} = 0.07 \sigma_\phi \text{ steradian}^{-1} \). Note that the earlier calculation was done for one steradian and that the units of \( \frac{df}{d\Omega} \) are those of \( \sigma_\phi \) (e.g., cm\(^{-2}\) s\(^{-1}\)) per steradian. Then with the assumption of spherical symmetry the counts in the instrument are just \( 4\pi \) times \( \frac{df}{d\Omega} \) times the average transmission of the entire shield, \( \bar{T} \). Averaged over solid angle, \( \bar{T} = \int d\Omega \frac{T(\theta)}{d\Omega} \) where both integrals are over all solid angles and the Z-axis defines the viewing axis with \( T(\theta) \) shown above. Then \( \bar{T} = 0.23 \), and the counts from the near cylinder of the disk are approximately \( C_{\text{in}} = 4\pi (0.23)(0.07 \sigma_\phi) \text{ cm}^{-2} \text{ s}^{-1} \), independent of the viewing direction of longitude, \( \lambda \). So the total counts, \( C \), in the instrument as a function of longitude is

\[
C(\lambda) = C_0(\lambda) + C_{\text{in}}
\]

This is plotted normalized to unity in the direction of maximum counts for the three distributions of surface emissivity discussed above and labeled in the captions in Figures 14, 15, and 16. The distribution of counts is quite different for the novae and supernovae distributions, being more strongly peaked toward the galactic center for novae. It is possible that the fit to the data could be significantly better for one distribution or the other, but the large background might still leave them indistinguishable. The HEAO 3 data did show an excess from within 60° of the galactic center (Mahoney et al., 1982), but I do not know if
Figure 14. HEAO-3 counts for constant metallicity in matter distributed like CO clouds.
Figure 15. HEAO-3 counts for metallicity gradient in matter distributed like CO clouds.
Figure 16. HEAO-3 counts for novae distributed like those in M31.
enough counts were received by the instrument to determine the distribution with the detail necessary to identify it as similar to one or another of these distributions. It seems unlikely.
VI. SUMMARY AND CONCLUSIONS

The angular distribution of gamma ray line emission from $^{26}$Al is important in, and probably the only hope for, determining what is the source of that emission. Once the source is identified more detailed observations of the angular distribution can possibly give insight into the structure of the Galaxy.

Astronomical data indicate that within the errors of the observations supernova remnants, pulsars, ionized gas, CO emission from molecular clouds, and light from the disk have similar galactic radial distributions. The CO distribution is chosen as being quantitatively well established to provide a tracer of recent nucleosynthesis in the Galaxy.

The large scale galactic nova distribution is uncertain, but the distribution observed in M31 suffers less from selection and distance effects and is chosen as a reasonable distribution for novae in the Galaxy.

The gamma ray fluxes are calculated from these distributions assuming the surface emissivity in gamma ray lines is proportional to the surface density of supernovae or novae. A radial galactic abundance gradient is also investigated with regard to the flux from supernovae, and angular distribution of the gamma rays are calculated for all three models. The supernova related distributions are distinctly different from the angular distribution from novae. For example, two OSSE observations could distinguish between the sources if they are distributed as modeled – one at $\ell = 0^\circ$ and another at $\ell = 25^\circ$. For supernovae the flux from $25^\circ$ should be slightly greater than that at $0^\circ$, but for novae the
flux should be down by about a factor of five at 25° from that at θ = 0°. The center to anti-center flux ratios are also distinguishing, and might be significant to the HEAO 3 data analysis. The ratio $\overline{F}_c/\overline{F}_A$ varies from 6 to 10 for these models compared to $\overline{F}_c/\overline{F}_A = 3$ assumed by Mahoney et al. If the flux actually were distributed with a larger ratio and the data are fitted to their assumed distribution with a constant background, a better fit would be obtained by underestimating the background and thus overestimating the galactic contribution. At least one OSSE observation of the plane of the outer galaxy would be useful.

The ratio $\overline{F}_c/Q$ is nearly invariant for all models examined (including fluxes calculated for the pulsar, supernova, and ionized gas distributions which were not included here), so if the quoted flux is correct, there are approximately 3.5 $M_\odot$ of $^{26}$Al in the interstellar medium, somewhere, today.

Normalizing the distributions to the solar abundance of $^{27}$Al implies isotopic ratios of from $^{26}$Al/$^{27}$Al = $2.6 \times 10^{-6}$ to $5 \times 10^{-6}$, all at least an order of magnitude smaller than that inferred from meteorites. Still the implied production ratio [P($^{26}$Al)]/[P($^{27}$Al)] from supernovae is one and a half orders of magnitude larger than the best theoretical estimates, if supernovae are responsible for the bulk of the observed $^{26}$Al emission, which implies that they are not. All of these results are summarized in Tables 1 and 2.

If novae are responsible for the reported signal, either the nova rate is greater than estimated or the "average nova model" is not typical of those in the Galaxy. A possibility is that both novae and supernovae contribute similar amounts (with possibly an additional contribu-
tion from red giants), so that the distribution is unlike any above (rather a linear combination of the three). It would not be unlike nature to confuse us so. If novae are the dominant source, a detectable signal at 1.275 MeV from $^{22}$Na just might be available to OSSE, but probably only from around $L = 0$. A detection would be extremely useful for constraining nova models, but only after the angular information allowed us to determine the relative contributions of the sources of $^{26}$Al.
### TABLE 1

$\frac{df}{dz}(\ell)$ in Units of $\sigma_0$ Radian$^{-1}$

<table>
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<th>Tracer</th>
<th>$\ell=0^0$</th>
<th>10</th>
<th>20</th>
<th>30</th>
<th>40</th>
<th>50</th>
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<td>1.38</td>
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<td>2.31</td>
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<td>2.34</td>
<td>1.32</td>
<td>0.98</td>
<td>0.76</td>
<td>0.61</td>
<td>0.50</td>
<td>0.35</td>
<td>0.27</td>
<td>0.24</td>
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<td>$\bar{F}_C$</td>
<td>$\bar{F}_A$</td>
<td>$\sigma_\phi$</td>
<td>$(^{26}\text{Al}/^{27}\text{Al})_\phi$</td>
<td>$Q$</td>
<td>$\bar{F}_\phi/Q$</td>
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References


