7-15-1985

Angular Distribution of Interstellar Al-26

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THE ASTROPHYSICAL JOURNAL, 294:591–598, 1985 July 15

ANGULAR DISTRIBUTION OF INTERSTELLAR ^{26}Al

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Received 1984 October 26; accepted 1985 January 29

ABSTRACT

Although the detection by *HEAO 3* of ^{26}Al in the interstellar medium has profound consequences for nucleosynthesis, the origins of the ^{26}Al cannot be determined without information on its angular distribution. Both as an aid to further *HEAO 3* and *Solar Maximum Mission* data analysis and also for observational planning for Gamma-Ray Observatory, we present angular distributions and local concentrations of ^{26}Al for five different assumptions about its distribution in the galactic disk: it is proportional to $\sigma_{\rm CO}$ (case A); it is proportional to $\sigma_{\rm CO}$ times a galactic metallicity gradient (case B); it is proportional to average disk brightness $B(R)$ (case C); it is proportional to total gas $\sigma_{\rm CO} + \sigma_{\rm H\,I}$ (case D); it is proportional to nova rate (case E). Physical justifications of these assumptions are given. Only the nova distribution, strongly peaked toward the galactic center, will be easily distinguishable from the others, although they also have significant differences that will be discernible with adequate counting statistics. We find for these distributions that the present average isotopic ratio at the solar galactocentric radius is $^{26}{\rm Al}/^{27}{\rm Al} = 5 \times 10^{-6}$ to within a factor of 2—too large for steady state supernova nucleosynthesis but too small to provide an explanation of ^{26}Mg excess in Allende inclusions.

Subject headings: interstellar: abundances — nucleosynthesis —stars: novae

I. INTRODUCTION

The discovery of ^{26}Al in the interstellar medium by *HEAO 3* (Mahoney *et al.* 1982) raised many questions of importance to astrophysics: (1) How is the ^{26}Al distributed in the Galaxy? (2) What is the isotopic ratio $^{26}{\rm Al}/^{27}{\rm Al}$ in today's interstellar medium? (3) What is the nucleosynthesis source of ^{26}Al? (4) Is the steady state concentration enough to account for the isotopic ratio inferred from meteoritic minerals to once have existed in the primitive solar system? The discovery teams (see also Mahoney *et al.* 1984; Share *et al.* 1985) were unfortunately not able to answer the first question with a statistically significant angular distribution. What they were able to do was to show that, if the angular distribution is identical with that of high-energy γ-rays, there is a statistically significant (4.7 σ) detection of the 1.809 MeV γ-ray at a flux level $df/dl = 4.8 \times 10^{-4}$ cm^{-2} s^{-1} radian^{-1} at $l = 0°$. The next three questions were addressed by Clayton (1984), who reasoned, respectively: (2) the present ratio is $^{26}{\rm Al}/^{27}{\rm Al} = (1$–$2) \times 10^{-5}$ if it is taken to be a constant activity per gram within $4 \times 10^9\ M_\odot$ of interstellar gas; (3) supernova nucleosynthesis cannot maintain this concentration, and thus novae seem the best source; and (4) because this isotopic ratio is so close to $^{26}{\rm Al}/^{27}{\rm Al} = 5 \times 10^{-5}$, inferred to have existed once in the most ^{26}Mg–rich Allende inclusions, the argument requiring a neighboring supernova injection into the forming solar system is no longer compelling.

In this work we reexamine these questions with the aid of simple but plausible models for the geometric distribution of the ^{26}Al activity and for the interstellar gas. Because of the short 1.04×10^6 yr lifetime of ^{26}Al, that radioactivity resides today relatively near (≤ 100 pc away from) its nucleosynthetic sites, inheriting their spatial distribution and yields. We will accordingly conduct our geometrical surveys by taking ^{26}Al production to be proportional either to a group of markers of recent star formation or to an inferred distribution of the rate of occurrence of novae. In the former case we will also evaluate the difference introduced if the ^{26}Al yield is also taken to be proportional to the gas metallicity, which we will take to be measured by the O/H galactic gradient. And we will add a more careful estimate of the mass distribution of interstellar gas than Clayton (1984) did. Although our results will confirm many conclusions reached previously, we will find an isotopic ratio 2–3 times smaller in the phase-averaged interstellar gas; we will find that the galactic metallicity gradient introduces about a 40% reduction of that ratio; and we will find significantly different angular distributions of γ-ray flux for the star formation and nova formation distributions of ^{26}Al concentration. We emphatically suggest that the angular distribution of this γ-radiation be a prime observational target for the Orientation Scintillation Spectrometer Experiment (OSSE) detector on Gamma-Ray Observatory (GRO; Kurfess *et al.* 1983).

Share *et al.* (1985) recently confirmed that the gamma-ray spectrometer on the *Solar Maximum Mission* shows evidence of a 1.81 MeV line feature from the galactic plane with an intensity consistent with the *HEAO 3* results. Although it is too early to use their preliminary results to attempt to shed light on the angular distribution, their confirmation of its existence raises confidence in the importance of this line feature for galactic studies.

II. GEOMETRICAL MODEL

For this study we assume that the ^{26}Al is confined to a disk of thickness h. We take the solar galactocentric radius to be $R_\odot = 10$ kpc, and we take significant disk nucleosynthesis to terminate at $R = 15$ kpc. Plan and section of this disk are shown in Figure 1. Figure 1*b* shows that the telescope, here idealized as a cone of angle α, sees the entire disk for distances greater than $a = (h/2)\,{\rm cotan}\,(\alpha/2)$; therefore, the integral for the flux observed at Earth is broken into two parts, as shown in Figure 1*a*. For plane-projected distances x from the Sun in the interval $0 < x < a$ we have a volume integral, whereas for $a < x < b$ we can adequately approximate the integral as being

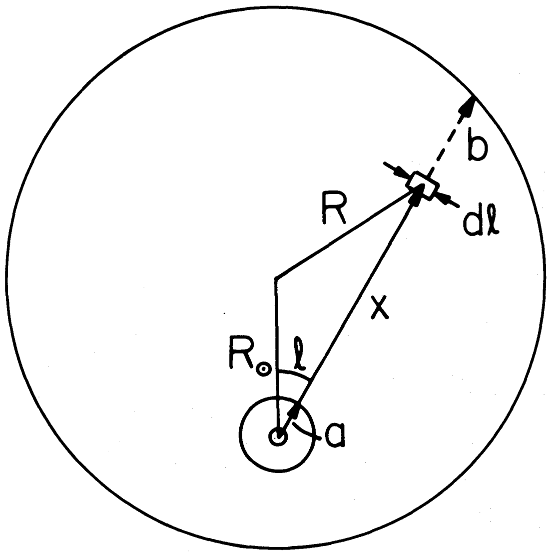

FIG. 1*a*

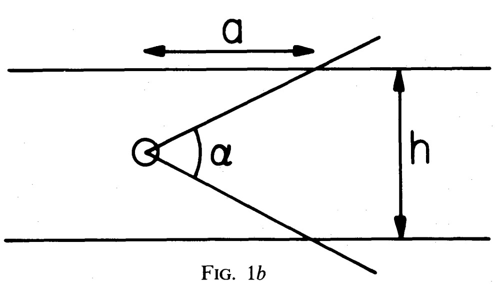

FIG. 1*b*

FIG. 1.—(*a*) Schematic view of galactic plane for integration along line of sight. Volume integral is performed from zero to *a*. Surface integral is performed from *a* to *b*, assuming that emission all lies at $b = 0°$. (*b*) Cross section view of near-solar galactic plane with idealized acceptance cone of telescope.

over a planar surface. In the latter case, let σ designate the emissivity of 1.809 MeV photons per unit area of disk, in which case a differential surface area dA of longitudinal extent dl contributes to the observed flux $df = \sigma dA/4\pi x^2 = \sigma dx dl/4\pi x$. The flux in a small longitudinal angle dl is obtained by integrating this expression along the line of sight to the edge of the galactic radioactivity, which we take to terminate at 15 kpc from the galactic center. Thus for projected distances $x > a$ we have

$$\frac{df}{dl} = \int_a^b \frac{\sigma dx}{4\pi x}, \quad x > a . \tag{1}$$

We take the surface emissivity to be cylindrically symmetric, so that $\sigma = \sigma(R)$, where $R = (x^2 + R_\odot^2 - 2xR_\odot \cos l)^{1/2}$. The lower limit a is $(h/2) \cot (\alpha/2)$ and the upper limit b is $10 \cos l + (100 \cos^2 l + 125)^{1/2}$. For the material nearer than projected distance $x = a$ in Figure 1*b*, we assume that $\sigma = \sigma(R_\odot) \equiv \sigma_\odot$ exists in a disk thickness h of constant mass density $\rho = \sigma/h$. Then it is elementary to see that, because a telescope of solid angle $d\Omega$ looking a distance a through emissivity ρ sees flux $df = (\rho/4\pi) a d\Omega$, and because the solid angle of the wedge α in Figure 1*b* between two planes separated by longitude dl is $d\Omega = 2 \sin (\alpha/2) dl$, to the longitudinally differential flux of equation (1) we must add

$$\frac{df}{dl} = \frac{\rho a}{4\pi} 2 \sin \frac{\alpha}{2} = \frac{\sigma_\odot}{4\pi} \cos \frac{\alpha}{2}, \quad x < a . \tag{2}$$

Thus our procedure is to specify $\sigma(R)$ for the surface emissivity and to sum the contributions (1) and (2).

Before doing so, let us address the criticism that we could just as easily do a more accurate volume integral on a medium-sized computer instead of the approximations (1) and (2), which we do on personal microcomputers. We first showed that approximating the true volume integral by the cylinder of radius a plus a flat disk for $a < x < b$ introduces less than 1% error into the results. Because this result is so compact and useful, we show it here. Consider $\sigma(R)$ to be a constant because ρ is everywhere constant for a thickness $h = \sigma/\rho$. Then the exact integral can be done analytically, giving

$$\frac{df}{dl} = \frac{\rho h}{4\pi}\left[1 + \ln\left(\frac{b}{h}\right) + \ln\left(2 \sin \frac{\alpha}{2}\right)\right], \tag{3}$$

whereas our approximation scheme yields

$$\frac{df}{dl} = \frac{\rho h}{4\pi}\left[\cos \frac{\alpha}{2} + \ln\left(\frac{b}{h}\right) + \ln\left(2 \tan \frac{\alpha}{2}\right)\right], \tag{4}$$

which differ by less than 1% for $b/h \approx 10^2$. This good agreement will not be disturbed by letting $\rho h = \sigma(R)$ instead of a constant value, but the integrals (1) and (2) are of useful simplicity. Second, one may criticize approximating $\rho(z)$ by a constant value for $|z| < h/2$ and zero beyond, rather than by a Gaussian or an exponential z-distribution. We examined this by assuming an exponential scale height such that

$$2 \int_0^\infty \rho_0 \exp(-2z/h) dz = \sigma_\odot$$

and showed that the flux from $r < a$, which is already no more than a few percent of the total, differs by only a few percent from that of the constant-density disk. A final question is the arbitrariness of taking $\alpha = 42°$ simply because of the *HEAO 3* FWHM, considering that the magnitude of α does determine the scale for our separation at $x = a$. For example, a disk of half-thickness $h/2 = 70$ pc (i.e., molecular clouds) and a 42° aperture defines the near zone as a radius $a = 182$ pc. Although taking $\sigma_\odot =$ constant over such a dimension is reasonable, one may wonder how much the magnitude of df/dl is influenced by the latitude aperture α. It is a simple matter to use either equation (3) or equation (4) to show that for $\alpha = 40°$ a change $\Delta\alpha = \pm 10°$ alters df/dl by ± 5%.

In short, if radioactivity is continuously distributed in the galactic disk, the use of the sum of equations (1) and (2) to obtain its angular distribution df/dl is quite adequate. Indeed, the physical errors of a non–cylindrically symmetric distribution or of nonconfinement to a disk introduce more uncertainty than does our simple geometrical representation.

III. MODEL DISTRIBUTIONS OF ^{26}Al EMISSIVITY

To obtain a better quantitative understanding of the ^{26}Al flux for different physical assumptions, we evaluated df/dl and the present interstellar isotopic ratio for the following specific distributions of ^{26}Al activity:

Case A.—Assuming $\sigma(R) \propto \sigma_{CO}$. The idea is that $\sigma(^{26}\text{Al})$ represents current star formation and that the CO surface density is its indicator. We examined other indicators (e.g., H II regions, supernova remnants) but found them (as have others) to be not as accurately mapped as the CO intensity and not in any case obviously different from σ_{CO}.

Case B.—Superposing on case A an additional gradient in $\sigma(^{26}Al)$ by assuming it to be a secondary nucleosynthesis product [viz., $^{25}Mg(p, \gamma)$] on seed nuclei (viz., initial Mg) having the same metallicity gradient as oxygen.

Case C.—Measuring $\sigma(^{26}Al)$ by the distribution of visual surface brightness, which amounts to assuming an ejection rate for ^{26}Al proportional to the current light output.

Case D.—Taking $\sigma(^{26}Al)$ proportional to the total mass density of gas, H I plus H_2, as if its synthesis simply depends on the total gas density, independent of measures of active star formation.

Case E.—Taking $\sigma(^{26}Al)$ proportional to the rate of occurrence of novae per unit area of disk novae on the assumption that novae are its sources. Only this angular distribution and its associated isotopic composition will be greatly different from the others.

a) *Case A*

Consider the ^{26}Al surface density to be proportional to that of CO molecules, which will bring out most of the features of the set of calculations. Extensive surveys of the galactic plane have been made in the $J = 1 \rightarrow 0$ transition of CO at 2.6 mm (Scoville and Solomon 1975; Burton *et al.* 1975; Gordon and Burton 1976; and the review of Burton 1976). The radial distribution found by Burton *et al.* (1975), which is typical of all surveys, is shown in Figure 2. Because other indicators of current star formation correlate so well with this CO distribution, we use an analytic fit to it to test the assumption that ^{26}Al results from current star formation. The form fitted to the data was suggested by Stecker and Jones (1977):

$$\sigma(R) = c\left(\frac{R}{10\ \text{kpc}}\right)^{A} \exp\left(-B\,\frac{R}{10\ \text{kpc}}\right), \qquad (5)$$

where c is a normalization constant that will be chosen to match the observed ^{26}Al flux level and R designates the galactocentric distance (Fig. 1*a*). A least-squares fit to the data in Figure 2 gives $A = 7.3$ and $B = 13.7$, and is shown as the solid curve in Figure 2. This functional form for $\sigma(R)$ is more suitable for use in the integral of equation (1). If $\sigma_\odot$ is the rate per unit area of 1.809 MeV γ-ray emission at $R = R_\odot = 10$ kpc (Ovenden and Byl 1983), the constant is then $c = \sigma_\odot e^{13.7}$ for this parametric fit.

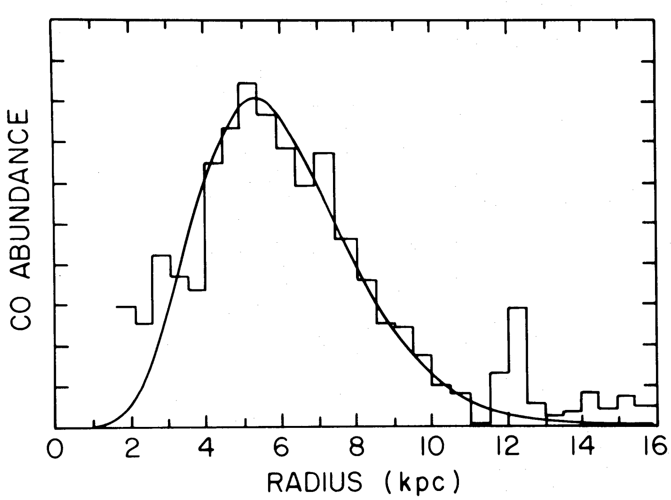

FIG. 2.—The radial distribution of CO from Burton *et al.* (1975) and analytic fit (*solid line*). The data are in arbitrary units related to antenna temperature. We assume that the surface density has a similar profile and use only the relative values.

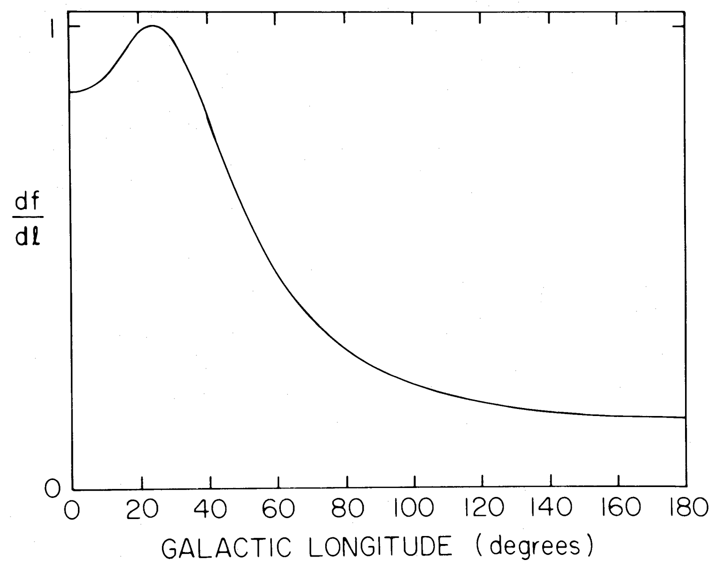

FIG. 3.—The differential γ-ray flux at 1809 keV under the assumption that the surface density of ^{26}Al is proportional to that of CO. The flux is plotted against galactic longitude and is normalized to unity at $l = 25°$. Note that the flux is symmetric with respect to $l = 0°$ under the assumption of axial symmetry.

To estimate an isotopic composition in the interstellar medium we must also normalize to the total amount of interstellar gas. In order to be specific we will regard the molecular cloud production of ^{26}Al as being added to the molecular phase, which must then be diluted by the ^{26}Al–free H I phase if one wishes an average isotopic ratio in bulk. The relative masses of H_2 and H I phases enter into such an average, and we note that there is still uncertainty in the conversion of CO observations to H_2 densities (Blitz and Shu 1980; Liszt, Xiang, and Burton 1981). It is also not obvious that ^{26}Al ejected in a molecular cloud must join the molecular phase. That is a question of mixing dynamics, as is the question whether H_2 and H I phases can mix in the 10^6 yr Al lifetime. On the basis of recent surveys Sanders (1983) determines $\sigma_{gas}(R_\odot) = 7\ M_\odot\ pc^{-2}$, of which 4 $M_\odot\ pc^{-2}$ is in molecular form and 3 $M_\odot\ pc^{-2}$ is H I. Ultraviolet observations by the *Copernicus* satellite indicate that the total density for the solar neighborhood is similar but that only 20%–25% is in molecules (Jenkins 1976; Bohlin, Savage, and Drake 1978). We will take Sander's estimate as being probably a better azimuthal average at $R_\odot$. The distribution of Figure 2 then amounts to $4 \times 10^9\ M_\odot$ of molecular gas.

The integration of equation (1) was performed numerically using Newton-Cotes quadratures, at 1° intervals around the galactic plane. The longitudinal angular distribution is plotted for case A in Figure 3, normalized to unity in the direction of maximum flux (in this case $l = 25°$), the maximum path through the CO ring. The anticenter flux is of course small for this mapping of $\sigma(^{26}Al)$.

To evaluate the coefficient $\sigma_\odot$ requires normalizing this angular distribution to the *HEAO 3* data; but because they were not able to report a detailed distribution, the procedure is somewhat ambiguous. For the purposes of this paper it should not be inappropriate to compare the total flux from our angular distribution for the central 42°, namely,

$$F_0 = \int_{339}^{21} \frac{df}{dl}\, dl \approx \frac{2\pi}{360} \sum_{339}^{21} \frac{df}{dl} = 0.87\ \sigma_\odot$$

for case A, with an *HEAO 3* estimate. Mahoney *et al.* (1984) give both the angular distribution assumed by them in order to extract the flux and the normalization of that distribution at $l = 0$, $df/dl = 4.8 \times 10^{-4}$ cm^{-2} s^{-1} radians^{-1}. We integrate that distribution from $l = 339°$ to $l = +21°$ to obtain $F_0 = 3.42 \times 10^{-4}$ cm^{-2} s^{-1}. Equating the two gives the case A surface density at $R = R_\odot$, namely, $\sigma_\odot(A) = 3.93 \times 10^{-4}$ cm^{-2} s^{-1}. Similarly, from the anticenter direction ($l = \pi$) the flux within 42° is

$$F_\pi = \frac{2\pi}{360} \sum_{l=159}^{201} \frac{df}{dl} = 0.15\ \sigma_\odot\ ,$$

which is less by the factor $F_0/F_\pi = 5.8$ than that toward the center. The angular distribution is in this sense unlike the one that Mahoney *et al.* (1982, 1984) actually used to extract the flux in that the high-energy γ-radiation which they used does not have such a small anticentral value.

Because the *HEAO 3* shield is partially transparent to γ-rays at all angles, it can be argued that the better determined quantity is the total count rate, the differential flux integrated around the whole galactic plane. If we normalize our distributions by setting this quantity equal to the corresponding integral of the high-energy γ-ray distribution, the implied surface densities of ^{26}Al are very similar to those computed here, except for the centrally concentrated nova distribution, where the difference is a factor of 2.

For a given $\sigma(R)$ we can calculate the total galactic production rate,

$$Q = \int_0^{15} 2\pi R\sigma(R)dR = 2\pi\sigma_\odot e^B R_\odot^2 \int_0^{1.5} r^{A+1} e^{-Br} dr\ ,$$

for distributions parameterized as in equation (5). We have denoted $R/R_\odot$ by r. For the match to σ_{CO} this yields $Q = 1.12 \times 10^{46}\ \sigma_\odot$ (cm^{-2} s^{-1}) s$^{-1} = 4.4 \times 10^{42}$ s^{-1}. The total production Q implied by the observed flux is insensitive to the assumed $\sigma(R)$.

Taking the case A result $\sigma_\odot(A) = 3.93 \times 10^{-4}$ cm^{-2} s^{-1} to equal $N_\odot(^{26}\mathrm{Al})/\tau(^{26}\mathrm{Al})$ at the solar radius then yields $N_\odot(^{26}\mathrm{Al}) = 1.29 \times 10^{10}$ atoms cm^{-2} of ^{26}Al. Taking the total surface density (H_2 + H I) to be $\sigma(R_\odot) = 7\ M_\odot$ pc^{-2}, and assuming that the solar mass fraction of aluminum $X_\odot(^{27}\mathrm{Al}) = 6.6 \times 10^{-5}$ (Cameron 1982) also holds in today's interstellar medium, results in $N_\odot(^{27}\mathrm{Al}) = 2.15 \times 10^{15}$ atoms cm^{-2} of ^{27}Al. Then the local isotopic ratio $^{26}\mathrm{Al}/^{27}\mathrm{Al} = 6.0 \times 10^{-6}$ results for the average over both phases. This important ratio is about a factor of 3 smaller than the estimate by Clayton (1984), primarily because he used a less massive interstellar medium, whereas our case A dilutes the ratio $^{26}\mathrm{Al}/^{27}\mathrm{Al} = 1.05 \times 10^{-5}$ in the H_2 clouds (assuming mixing of the ejecta into the molecular phase but not into the atomic gas) with a ^{26}Al–free H I gas amounting to an extra 3 $M_\odot$ pc^{-2}. For comparison with meteoritic data perhaps the isotopic ratio in the CO clouds is more relevant of the two, but they differ only by the factor 7/4.

This same set of quantities can now be calculated in exactly the same way for $\sigma(^{26}\mathrm{Al})$ distributions corresponding to cases B, C, D, and E. The results are summarized in Table 1.

b) Case B

Because the ^{26}Al nucleosynthesis is believed to depend upon seed Mg (and other intermediate nuclei), it is sensible to assume a ^{26}Al yield (per unit of star formation) that is proportional to the metallicity. To measure the effect of such considerations quantitatively, we take a star formation rate identical with that of case A ($\psi \propto \sigma_{CO}$) but add an additional gradient to the ^{26}Al yield. Of all the abundance gradients studied, the O/H ratio probably has the most secure data, so we employ $d[\log(\mathrm{O/H})]/dR = -0.07$ kpc^{-1} between 4 and 15 kpc (Shaver *et al.* 1983; see also Torres-Peimbert and Peimbert 1977; Peimbert 1979). Taking that to represent the metallicity yields $Z(R) = Z_\odot \exp\ [0.16(10 - R)]$. Accordingly, our procedure here is to multiply our assumed star formation rate in case A by the extra factor $\exp\ [0.16(10 - R)]$. Note that this is not a physical model but only a way of evaluating the effect of the gradient on a fixed gradient in the star formation rate. In an actual physical model one would in addition have to consider how the metallicity gradient affects σ_{CO}, and how σ_{CO} actually translates into a star formation rate. We ignore all such physical considerations because the proper way to treat them appears to be unknown. We also note that the gradient would have a larger effect if we took the nitrogen gradient $d[\log(\mathrm{N/H})]/dR = -0.14$ kpc^{-1} (Peimbert 1979), but Shaver *et al.* (1983) have recommended a smaller value for this gradient as well.

Having said all that, we find that calculations exactly analogous to that previously described give an average central flux per radian of $F_0 = 1.45\ \sigma_\odot$. The intensity at the anticenter, $F_\pi = 0.14\ \sigma_\odot$, is smaller than the central value by a factor of 10.4. The surface density at the solar position for this case (case B) is then $\sigma_\odot(B) = 2.35 \times 10^{-4}$ cm^{-2} s^{-1}, just 60% of the case

TABLE 1

SUMMARY OF RESULTS

^{26}Al DISTRIBUTION	df/dl ($\sigma_\odot$ radians^{-1})								$\sigma_\odot$[a] (photons cm^{-2} s^{-1} $\times 10^4$)	$(^{26}\mathrm{Al}/^{27}\mathrm{Al})_\odot$[b] ($\times 10^6$)	Q (10^{42} photons s^{-1})
	$l = 0°$	$l = 25°$	$l = 60°$	$l = 90°$	$l = 135°$	$l = 180°$	$F_0/\sigma_\odot$	$F_\pi/\sigma_\odot$			
A. CO	1.13	1.31	0.59	0.39	0.24	0.21	0.87	0.15	3.93	6.0	4.4
B. CO plus gradient	1.84	2.14	0.69	0.32	0.21	0.19	1.45	0.14	2.35	3.60	4.7
C. Disk light	0.71	0.79	0.48	0.35	0.29	0.26	0.56	0.19	6.12	9.36	5.0
D. Total ISM mass	0.74	0.87	0.47	0.32	0.26	0.23	0.58	0.17	5.95	9.10	5.5
E. Novae	6.57	1.05	0.46	0.33	0.21	0.18	2.32	0.13	1.47	2.25	4.4

[a] The quantity $\sigma_\odot$ is the azimuthally averaged surface rate of ^{26}Al decay at $r = R_\odot$.

[b] The isotope ratio is averaged overall in interstellar phases. The ratio in one phase can be roughly twice as great if H_2 and H I phases do not mix in ^{26}Al lifetime.

A value. Accordingly, the solar isotopic ratio $^{26}Al/^{27}Al$ is also reduced to 60% of its case A value by the metallicity gradient. For this distribution, the total galactic production rate implied by the γ-ray observation is $Q = 4.7 \times 10^{42}$ photons s^{-1}.

c) *Case C*

Another interesting assumption for the current rate of ^{26}Al nucleosynthesis is to take it to be proportional to the light output from stars. Simple models of the light distribution in galaxies yield excellent fits to the observed star counts for a large range of stellar luminosities (e.g., Bahcall and Soneira 1980). The surface brightness of spirals can be fitted with a combination of an exponential for the disk component, $B(R) \propto e^{-R/h}$, and a de Vaucouleurs profile (developed for ellipticals) for the spheroidal component, $B(R) \propto \exp\{-7.67[(R/R_E)^{1/4} - 1]\}$, as discussed, for example, by de Vaucouleurs (1959), Freeman (1970), and Kormendy (1977). For our Galaxy the space density of stars in the spherical component is normalized to 1/800 of that of the disk component at $R = R_\odot$. The standard value for h is 3.5 kpc for the Galaxy. We use $R_E = 3.3$ kpc for that parameter because several authors, including de Vaucouleurs (1977), find $R_E = R_\odot/3$.

The disk component of many spirals appears to have a central hole where the spheroid begins to dominate. We take it as likely that the Galaxy does also, and represent the disk light with the function (Kormendy 1977) $B(R) = B_0 \exp[-R/h - (\beta/R)^n]$, where β is the approximate inner radius of the disk and $n = 3$ defines the sharpness of the cutoff. On the basis of dynamical models Ostriker and Caldwell (1979, 1983) suggest $\beta \approx 3$ kpc. We adopted this form for $B(r)$ for the disk and again integrated equation (1) with the assumption $\sigma(^{26}\mathrm{Al}) \propto B(R)$. The resulting value is $\sigma_\odot = 6.1 \times 10^{-4}$ cm^{-2} s^{-1} with a center/anticenter ratio $F_0/F_\pi = 2.9$, noticeably smaller than cases A or case B because the light is not as concentrated toward the central regions as the CO is. The total galactic emission $Q = 5.0 \times 10^{42}$ s^{-1} is again not much different from the other cases, however. Other results of case C are in Table 1.

d) *Case D*

For this representation we assume that the production rate of ^{26}Al is proportional to the total surface density of gas, $\sigma(H_2) + \sigma(\text{H I})$, even though there is not so much evidence of recent star formation in the H I phase. We treat the H I gas in a very simple way for this exercise, taking its surface density $\sigma(\text{H I}) = 3\ M_\odot$ pc^{-2} at all locations between 3 and 15 kpc. Our arbitrary truncation at $R = 15$ kpc can be thought of as reflecting the assumption that no ^{26}Al exists beyond $R = 15$ kpc because there is negligible recent nucleosynthesis at great galactocentric distance. Again we emphasize that this is not a physical model but an apparently reasonable assumption for probing the angular distribution. The results, given in Table 1, show this distribution to be more like the surface brightness distribution of case C than the CO distributions.

e) *Case E*

Clayton (1984) argued that supernova nucleosynthesis cannot maintain a ratio as high as observed, $^{26}Al/^{27}Al \gtrsim 5 \times 10^{-6}$, and that the common nova (Clayton and Hoyle 1976; Arnould *et al.* 1980; Wallace and Woosley 1981) presents a better source for ^{26}Al. Nothing in the foregoing calculations changes Clayton's conclusion. Accordingly, we too wish to pattern $\sigma(^{26}\mathrm{Al})$ after the nova distribution.

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 $l = 0°$, with half 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 $b \approx 0°$, 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 as $d(\log D)/dR = -0.22$ kpc^{-1} and $d(\log D)/dz = -2.4$ kpc^{-1}, where R is galactocentric distance and z is distance perpendicular 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 dwarfs 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 $d(\log D)/dR = -0.81$ kpc^{-1} for $1 < R < 2.4$ kpc and $d(\log D)/dR = -0.16$ for $2.4 < R \leq 17$ kpc. There is some uncertainty as to the density of novae very near the center of M31, since 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. We 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 (1955) may have used too large a value for interstellar absorption (Sharov 1963) in obtaining his radial gradient, and Schmidt-Kaler (quoted in Plaut 1965) finds that the radial gradient is $d(\log D)/dR = -0.18$ kpc^{-1} in the Galaxy, very similar to that at the corresponding position in M31.

Adopting the radial distribution in M31 observed by Sharov (1971) leads to the following representation for $\sigma(^{26}\mathrm{Al})$:

$$\begin{aligned} \sigma &= 228\ \sigma_\odot\ , && R < 1\ \text{kpc} \\ &= 1.4 \times 10^3\ \sigma_\odot e^{-1.87R}\ , && 1 < R < 2.4\ \text{kpc} \\ &= 40.4\ \sigma_\odot e^{-0.37R}\ , && 2.4 < R < 15\ \text{kpc}\ , \end{aligned}$$

which is normalized to $\sigma_\odot$ at $R_\odot = 10$ kpc. The z-distribution is such that the great majority, even in the central bulge, should have been in the 42° FWHM view of the *HEAO 3* instrument while it was scanning the galactic plane, except within about 235 pc of the Sun, where the scale height is ~181 pc (Payne-Gaposchkin 1957). The same will not be true for the 3°5 × 11°

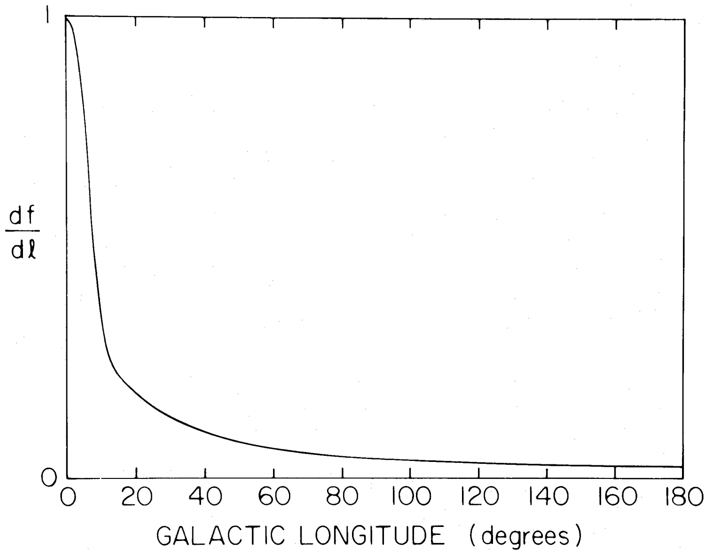

FIG. 4.—The differential γ-ray flux vs. longitude under the assumption that the surface density of ^{26}Al is proportional to the surface density of novae. The flux is normalized to unity in the direction of the galactic center.

field of view of the OSSE experiment on GRO, presenting some considerations for its background subtraction technique.

The resulting angular distribution is shown in Figure 4, and its properties are included in Table 1. The flux within $\pm 21°$ of $l = 0$ is $F_0 = 2.32\ \sigma_\odot$, and the corresponding anticenter flux is $F_\pi = 0.13\ \sigma_\odot$, a factor of 18 smaller than the central flux. The galactic production is

$$Q = \int 2\pi R\sigma(R)dR = 3.0 \times 10^{46}\ \sigma_\odot\ (\mathrm{cm^{-2}\ s^{-1}})\ \mathrm{s^{-1}}\ .$$

Equating F_0 to the *HEAO 3* observation $F_0 = 3.4 \times 10^{-4}$ cm^{-2} s^{-1} fixes $\sigma_\odot = 1.47 \times 10^{-4}$ cm^{-2} s^{-1}. The isotopic ratio $^{26}\mathrm{Al}/^{27}\mathrm{Al} = 2.25 \times 10^{-6}$ at $R = R_\odot$ is the smallest of the cases considered. The total production rate $Q = 4.4 \times 10^{42}$ s^{-1} requires 3.14 $M_\odot$ of nova-produced ^{26}Al per $\tau(^{26}\mathrm{Al}) = 1.04 \times 10^6$ yr. If the average nova ejects $10^{-4}\ M_\odot$ of matter having $X(^{26}\mathrm{Al}) = 2.5 \times 10^{-4}$ (Hillebrandt and Thielemann 1982) a nova rate of 120 yr^{-1} is indicated, which is greater than the often quoted value 40 yr^{-1} (Allen 1973) but not completely implausible. Arhipova and Mustel (1975) estimate that if all galactic novae brighter than 3 mag are discovered and if the mean absolute magnitude is $M = -7.3$ mag, the lower limit is 50 yr^{-1} for a uniform disk distribution. If, however, the galactic novae are distributed as in M31, with an increasing density near the galactic center, the minimum frequency would be much higher under the same assumptions. Clayton (1984) pointed out that if the surface concentration of Mg in the prenova exceeds solar concentration, the required rate will be proportionately reduced.

It should also be noted that the γ-ray flux expected from the distribution of Sharov (1971) does not differ greatly in longitude from that of a point source at the galactic center. Mahoney *et al.* (1984) also fitted their *HEAO 3* data to a point source at the galactic center which resulted in a positive detection at only the 2.2 σ 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 observations of a γ-ray line expected from another radioactive nucleus produced in novae, ^{22}Na. In explosive hydrogen burning, two proton captures and a beta-decay convert ^{20}Ne to ^{22}Na, which beta-decays with a mean lifetime of 3.75 yr, emitting a γ-ray at 1.275 MeV. Mahoney *et al.* (1982) placed an upper limit of 4.4×10^{-4} photons cm^{-2} s^{-1} radians^{-1} on this line.

For two radioactive isotopes produced in the same events, the ratio of the γ-ray fluxes from the two is just equal to their production ratio, if the events responsible for them occur at a constant rate. For novae the production rate is $P = X_e M_e R_N$, 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 4 years is similar to that over the last 10^6 years, the ratio of the fluxes of ^{22}Na and ^{26}Al γ-rays is

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

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

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

These estimates would predict a steady state flux of 3×10^{-7} photons 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 results similar to those of Hillebrandt and Thielemann (1982), one model, a two-zone model which considers convection, predicts $[X_e(^{22}\mathrm{Na})]/[X_e(^{26}\mathrm{Al})] = 0.08$. Thus a flux from ^{22}Na only a factor of 10 smaller than that of ^{26}Al, $F_0(^{22}\mathrm{Na}) \approx 3.4 \times 10^{-5}$ photons cm^{-2} s^{-1} from 42° centered on the galactic center, results from this model. Since novae are so strongly peaked toward $l = 0°$, the flux within 11° (i.e., OSSE's wider dimension aligned along the plane [Kurfess *et al.* 1983] centered on $l = 0$ would be 1.8×10^{-5} photons cm^{-2} s^{-1}—approximately the OSSE threshold—and this assumes that the latitude extent of the source is within 3°.5 (OSSE's narrow dimension), which is most likely not the case. Probably only a fraction of the emission from novae lies this close to the plane, particularly near $l = 0°$.

Still, increased ^{22}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., abundances greater than solar $X(^{20}\mathrm{Ne})$]. Because there exist great uncertainties in nova models and in 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 (2×10^{-5} cm^{-2} s^{-1}), would not be especially informative, since it is only at the extremes of the models for nova production of ^{22}Na that the predictions reach that limit.

IV. DISCUSSION

Our main purpose has been to evaluate angular distributions of ^{26}Al γ-radiation for several different assumptions about its production and to estimate more closely the isotopic composition of Al in the interstellar medium. Figures 3 and 4 showed the contrast between $\sigma(^{26}\mathrm{Al}) \propto \sigma_{\mathrm{CO}}$ and $\sigma(^{26}\mathrm{Al}) \propto \sigma(\mathrm{novae})$, respectively, and characteristics of these and three other angular distributions (cases B, C, and D) are also listed in Table 1. Cases C ($\sigma \propto$ brightness) and D ($\sigma \propto$ H_2 + H I) have smaller asymmetries between center F_0 and anticenter F_π fluxes than do the two cases illustrated. Our thesis is that the detection of interstellar ^{26}Al (Mahoney *et al.* 1982, 1984) is an astounding discovery because of profound implications for nucleosynthesis in exploding objects, and that only the angular distribution of this radiation can lead to the identity of its source. Although the *HEAO 3* and *Solar Maximum Mission* experiments have not yet reported enough angular resolution to decide among source models, our distributions may be of help in future data analysis tests or in the planning of GRO observations. With regard to the *HEAO 3* data we would only add that their actual telescope has nonzero transmission at all angles, whereas our model calculations have been for an idealized telescope with sharp angular boundaries defined by a wedge ($\Delta l = 1°$ for the angular distribution df/dl, and $\Delta l = 42°$ for comparison with *HEAO 3 F*) in longitude and a square-transmission acceptance for a latitudinal wedge $\propto$(42° for *HEAO 3*). Their data analysis is in reality obfuscated not only by the very low count rates but also by the transmission and instrumental background of their detector.

Each of the five distributions in Table 1 yields $\sigma_\odot(^{26}\mathrm{Al})$ concentration in the interstellar gas and dust at $R_\odot$, which is easily mapped throughout the disk by the assumption for $\sigma(R)$. Despite noticeable differences in angular distribution, the local decay (and production) rate would seem, for the cases considered, to lie within a factor of 2 of $\sigma_\odot = 3 \times 10^{-4}$ cm^{-2} s^{-1}. If the interstellar medium contains 7 $M_\odot$ pc^{-2} near $R_\odot$ with solar composition, the isotopic ratio today, averaged over H_2 and H I phases, is $^{26}\mathrm{Al}/^{27}\mathrm{Al} = 5 \times 10^{-6}$ to within a factor of 2. This isotopic ratio is about 3 times smaller than the value calculated by Clayton (1984), primarily because the total interstellar medium is more massive than the value he used and because the ^{26}Al–rich portions (CO or novae) are of diminishing significance at $R = R_\odot$ in comparison with interior values. Let us concentrate in our concluding remarks on fascinating implications of this Al isotopic ratio.

The estimated isotopic ratio $^{26}\mathrm{Al}/^{27}\mathrm{Al} = 5 \times 10^{-6}$ lies squarely between and distinctly separate from two ratios of very great interest. Clayton (1984) argued at length that supernova nucleosynthesis cannot maintain an average value much in excess of $^{26}\mathrm{Al}/^{27}\mathrm{Al} = 1 \times 10^{-7}$, a factor of 50 too small; thus his conclusion, that the observed ^{26}Al is not a product of distributed supernova nucleosynthesis, remains secure. From that conclusion he argued that any live ^{26}Al in the solar cloud at the time of its collapse to form our system should logically be regarded as the result of the nonsupernova sources of ^{26}Al, and that the concept of a "supernova trigger," or a "supernova injection," should be discontinued. A prior advocate of that picture, A. G. W. Cameron, has recently come to the same conclusion (Cameron 1984*a*, *b*). Whereas Clayton (1984) argued that novae are the best source, Cameron (1984*a*) argues that the hydrogen-burning shell in double-shell red giants constitutes another, perhaps preferable, source (Norgaard 1980). Either or both of these sources may be capable of creating ^{26}Al within a molecular cloud without disrupting that cloud, and without facing the obstacles to mixing with the cloud that had caused Clayton (1981, 1982*a*) to believe that ^{26}Al injected into the hot low-density medium could not be admixed with the parent cold cloud, causing him to doubt the supernova trigger concept on those grounds. So it is that several different lines of reasoning appear now to have converged upon the discard of the supernova trigger origin of ^{26}Al.

Cameron's (1984*a*) suggestion that ^{26}Al is produced in the hydrogen-burning envelopes of asymptotic giant branch (AGB) stars raises the question of their distribution. If the most effective producers are reasonably massive AGB stars, say 4–8 $M_\odot$, their distribution would not differ noticeably from that appropriate to supernova nucleosynthesis. If, on the other hand, the important stars are AGB stars subsequent to helium flash, 1–2 $M_\odot$, say, their spatial distribution may resemble that of solar-type stars and come from progenitors that formed early in galactic history. This distribution probably resembles the brightness distribution $B(R)$ outside the spiral arms where new stars dominate, so that it may look more like case C.

Even though $^{26}\mathrm{Al}/^{27}\mathrm{Al} = 5 \times 10^{-6}$ is too big for supernova nucleosynthesis, it is too small to account for the excess Al-correlated ^{26}Mg, designated by ^{26}Mg*, found in many meteoritic inclusions, namely, $^{26}\mathrm{Mg}^*/\mathrm{Al} = 5 \times 10^{-5}$ (Lee, Papanastassiou, and Wasserburg 1977). That is, it does not appear likely that a ratio $^{26}\mathrm{Al}/^{27}\mathrm{Al} = 5 \times 10^{-5}$ could have been the average concentration at $R = R_\odot$ when the solar system formed. We envision no reasonable model of galactic evolution that would allow this isotopic ratio to decline by a factor of 10 between a time 4.6×10^9 years ago and today. In this case, all the old puzzles about this large amount of excess ^{26}Mg in meteoritic samples remain. One must take one of two positions: either some events associated with solar birth caused an enhancement of ^{26}Al in the solar cloud, or the ^{26}Al was not actually alive in the Allende samples themselves, but only in a precursor component of Al-rich interstellar dust. The latter position (e.g., Clayton 1982*a*) has been advocated by one of us (D. D. C.) for 10 years, even predicted before the ^{26}Mg excess was established to be correlated with Al, and is in this picture just one of many aspects of "cosmic chemical memory" (Clayton 1982*b* and references therein). Although this picture remains attractive in many ways, we will not defend it further here because it sometimes appears to be a contentious minority view. To take the other point of view, a live concentration $^{26}\mathrm{Al}/^{27}\mathrm{Al} = 5 \times 10^{-5}$ in the collapsing solar cloud seems to require prior ejection within the cloud, either from novae or from red giants, in such a way that hydrodynamic flows cause the ejecta to admix with the solar matter. This position is argued with some detail by Cameron (1984*a*, *b*). The net consequences for meteoritic science of the *HEAO 3* observations of ^{26}Al and of Clayton's (1984) analysis of those observations would thus seem to be that supernovae are not implicated in the ^{26}Al problems, but that the average level of interstellar $^{26}\mathrm{Al}/^{27}\mathrm{Al}$ is still not large enough to account for a live ^{26}Al explanation of Allende inclusions, so that either some other ejection event enriched the presolar cloud or the excess ^{26}Mg correlation with Al is a fossil.

We await measurements of the angular distribution of ^{26}Al γ-rays by Gamma-Ray Observatory as the best means of identifying its true origin. That angular distribution can also evaluate the other possible explanation, that the solar system exists with a 10^5 year old supernova remnant whose core nucleosynthesis debris fills a large solid angle centered about 15 pc from the Sun (Clayton 1984). Distinguishing this case from the nova distribution could be tricky.

This research was supported primarily by NASA DPR S-10987C for the OSSE spectrometer for Gamma-Ray Observatory as funded by subcontract N00014-83-C-2162 from the Naval Research Laboratory, but also in part by NASA grant NSG-7361 and by the Robert A. Welch Foundation. We express our gratitude to W. A. Mahoney and W. A. Wheaton for conversations about the *HEAO 3* experiment and to G. Share for discussions of the *Solar Maximum Mission* confirmation of the existence of the ^{26}Al line flux.

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