X-660-76-184

PREPRINT

NASA TM X- 71191

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(NASA-TM-X-71191) GAMMA RAY LINES FROM INTERSTELLAR GRAINS (NASA) 15 p HC $3.50 CSCL 03B

N76-33117

Unclas

G3/93 04573

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AUGUST 1976

GSFC

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GREENBELT, MARYLAND

GAMMA RAY LINES FROM INTERSTELLAR GRAINS

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ABSTRACT

We point out the existence of a hitherto unknown component of gamma-ray line emission: very narrow (FWHM $\lesssim$5 KeV) lines from interstellar grains. The prime candidate for detection is the line at 6.129 Mev from ^{16}O, but other very narrow lines could also be detected at 0.847, 1.369, 1.634, 1.779 and 2.313 Mev from ^{56}Fe, ^{24}Mg, ^{20}Ne, ^{28}Si and ^{14}N. Measurements of this line emission can provide information on the composition, size and spacial distribution of interstellar grains.

Subject headings--gamma rays - interstellar grains - cosmic rays.

*This research was supported in part by National Science Foundation grant AST 67-08178.

I Introduction

Interstellar gamma-ray line emission can result from the interaction of low-energy ($\lesssim 100$ Mev/amu) cosmic rays with constituents of the interstellar medium. The expected intensities of some of these lines and their detectability has been discussed most recently by Lingenfelter and Ramaty (1976). In the present letter we wish to point out an important component of this line emission: the very narrow gamma-ray lines emitted from interstellar grains.

Interstellar gamma-ray lines result from the deexcitation of nuclear levels, mainly in ^{12}C, ^{14}N, ^{16}O, ^{20}Ne, ^{24}Mg, ^{28}Si and ^{56}Fe. Broad lines, with a full width at half maximum (FWHM) of about 20% of the line energy, are produced by the deexcitation of cosmic-ray nuclei, while narrower lines, with FWHM of a few per cent, result from the deexcitation of gas nuclei. These two components have already been discussed by Rygg and Fishman (1973), Meneguzzi and Reeves (1975), and Lingenfelter and Ramaty (1976) for emission in the interstellar medium, and by Ramaty, Kozlovsky, and Lingenfelter (1975) for emission in solar flares.

The very narrow line component, which we shall treat here, is produced by deexcitation of interstellar grain nuclei excited by low-energy cosmic rays. Unlike the excited nuclei in gases, which retain most of their recoil energy for times much longer than the lifetimes of the excited levels, some excited nuclei in solids can lose all of their recoil energy before they emit gamma rays. The intrinsic widths of these gamma ray lines are determined only by the temperature of the solid. For grain temperatures of $\sim$15 K, the width is only about 10 ev. Larger widths, however, result from both the random and systematic motion of the grains, but these are not expected to exceed about 0.1% of the energy of the lines. These very narrow line widths not only enhance the detectability of the lines above the background, but also may permit several new astronomical investigations: namely the determination of the composition of grains and their size distributions from the relative intensities of the lines, and the study of the spacial distribution and systematic motion of grains in the galaxy from Doppler shifts of the lines. We defer detailed discussions of these exciting possibilities for future research. In the present letter we outline the physics of very narrow line production, present results of calculations on the formation of the very narrow 6.129-Mev line, and discuss the relative intensity of other lines with very narrow components.

II Discussion

The most important gamma ray lines which are expected to exhibit the very narrow component are those formed from relatively long-lived nuclear levels in abundant heavy nuclei with large excitation cross sections. Using detailed compilations of nuclear cross sections (Ramaty, Kozlovsky and Lingenfelter 1975, 1977) and the elemental abundances of Cameron (1973), we find that the strongest interstellar gamma ray lines should be at 4.438 Mev from ^{12}C and 6.129 Mev from ^{16}O. The mean lifetimes of the corresponding excited states are 5.6×10^{-14}s and 2.4×10^{-11}s, respectively (De Meijer, Plendl and Holub 1974). The expected ratio of the 4.438 and 6.129-Mev line emissivities is about 2 for $C/O \approx 0.54$.

In proton induced interactions, the excitation cross sections for the $^{12}C^{*4.439}$ and $^{16}O^{*6.131}$ levels peak at proton energies of approximately 10 Mev. By nuclear kinematics, the heavy nuclei have recoil energies of a few tens of kev/amu. In solids of density $\rho \sim 1$ g cm^{-3}, such particles stop on time scales of the order of 10^{-12}s (Northcliffe and Schilling 1970; Winterbon 1975). By comparing this time with the lifetimes of the excited levels, we see that the 6.129-Mev line of ^{16}O will exhibit the very narrow component, but that the 4.438-Mev line of ^{12}C will not. Another strong interstellar line is expected at 0.511 Mev from positron annihilation; even though the width of this line can be as small as a few kev (Crannell et al., 1976), interstellar grains play no special role in its formation.

In addition to having stopping times shorter than the nuclear deexcitation times, the emission of the very narrow component also requires the existence of grains with linear sizes larger than the vector stopping distance of the recoiling nuclei. Since the average stopping distances, $\sim (10^{-4}/\rho)$ (Northcliffe and Schilling 1970; Winterbon 1975) are comparable to the linear dimensions of the grains, we expect that a significant fraction of the excited nuclei will stop in the grains. Those nuclei that escape from the grains will emit gamma rays while still in motion and hence will not contribute to the very narrow line component. However, because they have lost some energy in the grains these nuclei will produce a narrower line width than excited gas nuclei.

We have carried out Monte Carlo calculations to determine both the fraction of ^{16}O nuclei that stop in grains, and the shape of the 6.129-Mev line produced in a mixture of gas and grains irradiated by low-energy protons. We have assumed that half of the ambient oxygen is in the gas and the other half is in the grains (e.g. Morton 1975). We have used the range-energy relation of oxygen in water (Northcliffe and Schilling 1970), and we took $\rho = 1.5$ g cm^{-3} for the grains. The range of oxygen in silicates is not significantly different. We have used detailed nuclear cross sections and kinematics for the calculation of the energy and angular distribution of the recoiling nuclei. The method that we have used is similar to that of Ramaty and Crannell (1976), who have evaluated the shape of the 6.129-Mev line for the narrow component.

Observations of the reddening and obscuration of starlight by interstellar grains are consistent with equilibrium grain size distributions (e.g. Wickramasinghe 1967; Aannestad and Purcell 1973) of the form $N(a) = N_o \exp(-a/a_o)$, where the characteristic radius a_o is on the order of 0.1μ and depends only weakly on the assumed composition. Such values of a_o, although appropriate for diffuse clouds, may not be representative of most grains, however, since grains in dense, dark clouds may contain the bulk of the interstellar grain mass. Observations of the dark cloud ρ Oph (Carrasco, Strom and Strom 1973) suggest that the mean grain size increases with depth in such clouds. A similar effect is suggested from the study (Jura 1975) of the apparent dark cloud remnant VY CMa. The high opacity of dark clouds to visible radiation does not permit study of grains in the densest regions of such clouds, where the mean grain size could be even a couple of orders of magnitude larger (Greenberg 1974). Very narrow line gamma ray observations, however, may help determine the mean sizes of grains in such dark clouds, since they are transparent at gamma ray energies and the relative intensity of very narrow line components from different excited states is fairly strongly dependent on grain size. In the present calculations therefore we study very narrow line emission for grain size distributions with a range of characteristic radii a_o between 0.03 and 10μ.

The resultant gamma ray spectrum is shown in Figure 1. We have averaged the spectrum over energy bins of 5 kev, comparable to the expected energy resolution of future gamma ray line detectors employing solid state devices (Metzger 1973). The solid line is the sum of the broad, narrow and very narrow components, the dashed lines represent the sum of the broad and narrow components only. All spectra are normalized to unit area under the curves. Half of the integral is under the broad component, only a portion of which is shown, since it has a FWHM of ∿1 Mev, while the other half is under the sum of the narrow and very narrow components. As can be seen, for $a_o > 0.1\mu$, the very narrow component can be resolved. The fraction of photons in a 5-kev bin around 6.129 Mev is 0.03, 0.75, 0.16 and 0.23 of the total in the three components for a_o equal to 0.1, 0.3, 1.0 and 10μ, respectively.

It is difficult to estimate the expected intensity of the 6.129-Mev line from interstellar grains because of the large uncertainties in the possible low-energy cosmic ray and ambient matter densities (e.g. Lingenfelter and Ramaty 1976). We can, however, normalize our calculations to the measurements of Haymes et al. (1975), who have reported the detection of several gamma ray spectral features from the direction of the galactic center. In particular, these authors report a broad feature at ∿4.4 Mev with intensity $\sim 10^{-3}$ photons $cm^{-2}s^{-1}$, which could be nuclear radiation from ^{12}C. Using the results given above on the ratios of the broad, narrow and very narrow components, and on the relative 4.438 to 6.129-Mev line fluxes, we find that the flux of the very narrow 6.129-Mev line from the direction of the galactic center should range from about 4×10^{-5} to 10^{-4} photons $cm^{-2}s^{-1}$ for a_o between 0.3 and 10μ. These fluxes are well above the diffuse gamma ray background, which, for a collimated detector of 0.1 str solid angle at 6 Mev, is only about 2×10^{-7} photons $cm^{-2}s^{-1}$ in a 5 kev bin around this energy (Trombka et al. 1976). Such fluxes should be observable with future satellite-borne gamma ray detectors (Jacobson 1976 private communication). The expected emission would of course be lower if some of the line emission reported by Haymes et al. (1975) were due to nuclear excitation of material surrounding the detector.

Although the very narrow component of the 6.129-Mev gamma ray line from oxygen should be the most intense line emitted by interstellar grains there are several other nuclei in interstellar grains which should also emit very narrow lines of nearly comparable intensity. These lines are listed in Table 1. The relative intensities given in this table represent the sum of the narrow and very narrow components, and are based on our compilations of nuclear cross sections (Ramaty, Kozlovsky and Lingenfelter 1977) and the abundances of Cameron (1973). The mean lifetimes are taken from Nuclear Data Group (1973), De Meijer, Plendl and Holub (1974) and De Meijer, Drentje and Plendl (1975). Since the stopping times of nuclei with kinetic energies of a few tens of kev/amu in grains is of the order 10^{-12}s, all the lines listed in Table 1 should exhibit significant very narrow components. For the iron lines, however, this component probably cannot currently be resolved from the gas component, because the latter is also quite narrow (FWHM $\simeq$ 5 kev). It should also be noted that if nearly all of the heavier nuclei (Mg, Si and Fe) in the interstellar medium are in grains but only about nalf of the O and N and possibly Ne nuclei are in grains (e.g. Morton 1975), then the relative intensities of the very narrow line component from the heavier nuclei could be as much as a factor of 2 greater than the values shown. Observations of the very narrow line component may help resolve this question, particularly in such uncertain cases as Ne.

III Summary

We have pointed out the existence of a potentially detectable very narrow component of interstellar gamma ray line emission and have presented results from calculations of the emissivity of this component in interstellar grains. Gamma ray line emission from grains results when low-energy cosmic rays interact with heavy nuclei embedded in the grains. Very narrow line emission is produced if both the stopping times and stopping distances of the recoiling heavy nuclei are shorter than the lifetimes of the nuclear levels and the sizes of the grains, respectively. The widths of these lines are determined by the motions of the grains, and are not expected to exceed about 0.1% of the energy of the lines.

The prime candidate for a line with an observable very narrow component is the 6.129-Mev line of ^{16}O. We have performed detailed calculations on the production of this line in grains using nuclear cross sections and kinematics, range-energy relations, and exponential grain size distributions. For characteristic grain radii of 0.1 to 1.0μ we find that 10 to 60% of the nuclei stop in the grains. For these stopped nuclei, the emitted gamma rays are in an energy bin narrower than 5 kev.

Very narrow lines should also be emitted at 0.847 and 1.238 Mev from ^{56}Fe, at 1.369 Mev from ^{24}Mg, at 1.634 from ^{20}Ne, at 1.779 Mev from ^{28}Si, at 2.313 Mev from ^{14}N. The intensities of these lines range from about 20 to 50% of the very narrow

6.129-Mev line intensity. Their detection would give unique information on the composition, size and spacial distribution of interstellar grains.

Acknowledgements. We wish to acknowledge valuable discussions with R. Bussard, J. Cohen, M. Jura, B. Kozlovsky, J.C. Ling, B.J. Teegarden, and J. Willet.

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TABLE 1

PHOTON ENERGY (MeV)	PHOTON EMISSION MECHANISM	PRODUCTION MODES	MEAN LIFETIME (SEC)	RELATIVE INTENSITIES
0.847	$^{56}Fe^{*0.847} \longrightarrow g.s$	$^{56}Fe(p,p')\,^{56}Fe^{*}$	6.7×10^{-12}	0.3
		$^{56}Fe(p,n)\,^{56}Co \longrightarrow {}^{56}Fe^{*}$	9.6×10^{6} (ϵ, e^{+})	
1.238	$^{56}Fe^{*2.085} \longrightarrow {}^{56}Fe^{*0.847}$	$^{56}Fe(p,p')\,^{56}Fe^{*}$	6.9×10^{-13}	0.15
		$^{56}Fe(p,n)\,^{56}Co \longrightarrow {}^{56}Fe^{*}$	9.6×10^{6} (ϵ, e^{+})	
1.369	$^{24}Mg^{*1.369} \longrightarrow g.s$	$^{24}Mg(p,p')\,^{24}Mg^{*}$	1.75×10^{-12}	0.3
1.634	$^{20}Ne^{*1.634} \longrightarrow g.s$	$^{20}Ne(p,p')\,^{20}Ne^{*}$	1.2×10^{-12}	0.5
1.779	$^{28}Si^{*1.779} \longrightarrow g.s$	$^{28}Si(p,p')\,^{28}Si^{*}$	6.8×10^{-13}	0.15
2.313	$^{14}N^{*2.313} \longrightarrow g.s$	$^{14}N(p,n)\,^{14}O \longrightarrow {}^{14}N^{*}$	102 (e^{+})	0.4
		$^{16}O(p,x)\,^{14}O \longrightarrow {}^{14}N^{*}$		
3.853	$^{13}C^{*3.854} \longrightarrow g.s$	$^{16}O(p,x)\,^{13}C^{*}$	1.08×10^{-11}	0.1
6.129	$^{16}O^{*6.131} \longrightarrow g.s$	$^{16}O(p,p')\,^{16}O^{*}$	2.4×10^{-11}	1.0

Figure Caption

Figure 1. The spectrum of 6.129 Mev gamma ray line emission, q, from ^{16}O, excited in low energy cosmic ray interactions with interstellar gas and grains, assuming equal fractions of oxygen in the gas and grains, and a grain size distribution such that the number of grains with a radius between a and da is $N(a)da = N_o \exp(-a/a_o)da$. The emission from grains is the difference between the solid and the dashed curves.

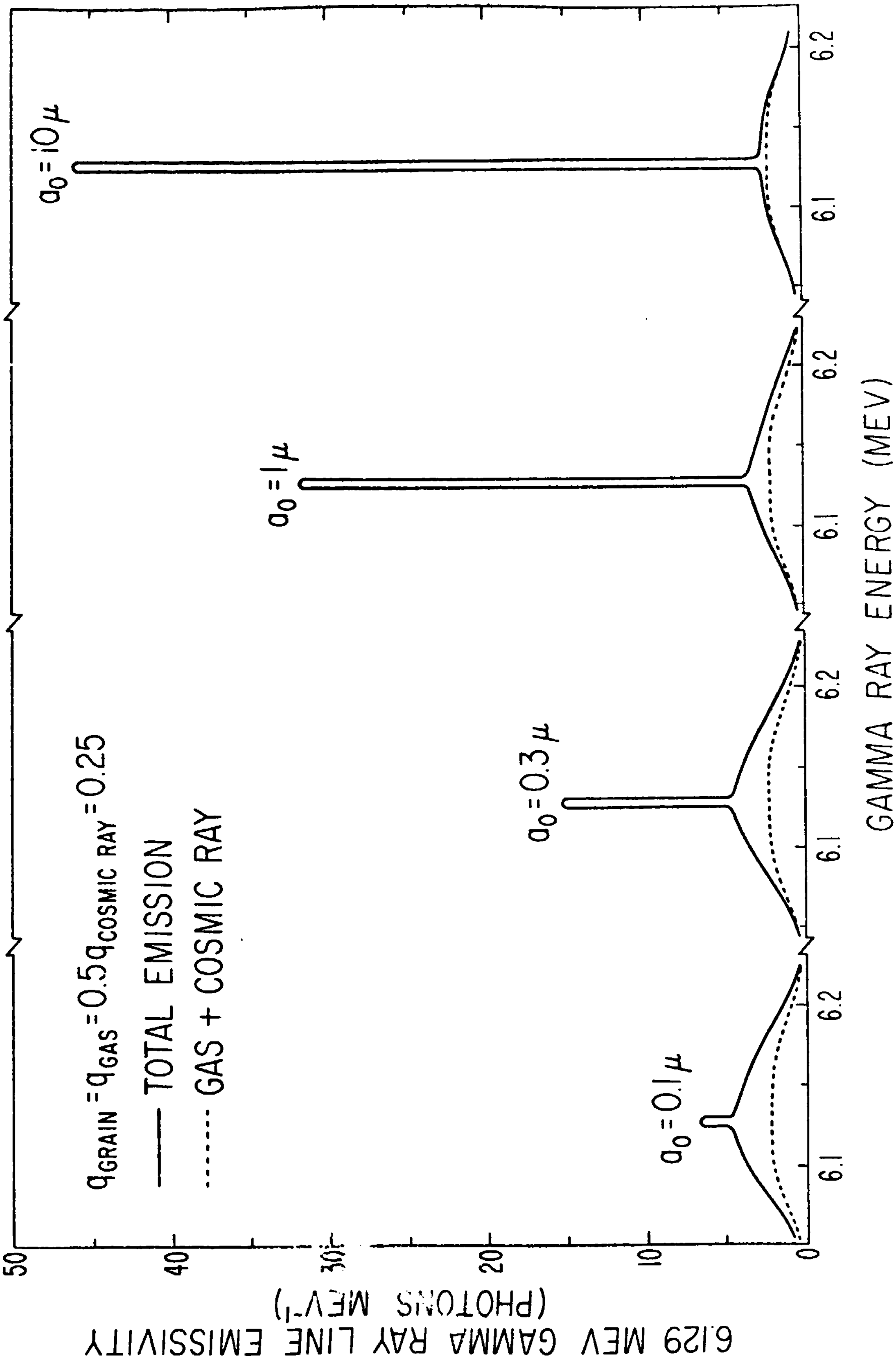
$q_{GRAIN} = q_{GAS} = 0.5 q_{COSMIC\ RAY} = 0.25$
—— TOTAL EMISSION
------ GAS + COSMIC RAY
$a_0 = 0.1\mu$
$a_0 = 0.3\mu$
$a_0 = 1\mu$
$a_0 = 10\mu$
6.1
6.2
GAMMA RAY ENERGY (MEV)
0
10
20
30
40
50
6.129 MEV GAMMA RAY LINE EMISSIVITY (PHOTONS MEV^{-1})

FIGURE 1