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ABSTRACT

We propose that the very narrow (FWHM$\lesssim$10keV) gamma-ray lines observed at 1.495 and 6.695 MeV from SS433 (Lamb et al. 1983, 1984) are blueshifted 1.369 and 6.129 emissions from deexcitations of ^{24}Mg* and ^{16}O* in grains moving with the jets and inelastically excited by interactions with the ambient medium. As previously shown (Lingenfelter and Ramaty 1977), energetic particle interactions in grains produce very narrow gamma-ray lines from deexcitation of nuclear levels whose lifetimes are long enough that the excited nuclei stop before deexcitation. The presence of grains in the jets resolves hitherto discussed difficulties of inelastic-excitation models for gamma-ray production in SS433, namely the very narrow widths of the observed lines and the absence of other strong lines expected from abundant elements. The model that we propose could be distinguished from a previously proposed fusion model (Boyd et al. 1984) by gamma-ray line observations.

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I. INTRODUCTION

Lamb et al. (1983, 1984) have observed blue- and red-shifted gamma-ray lines from SS433 with the HEAO-3 high-resolution gamma-ray spectrometer. The lines with the highest statistical significance, observed at 1.495 and 6.695 MeV, are very narrow (FWHM < 10 keV) and their central energies are determined to an accuracy of a few keV (Lamb et al. 1983, 1984). Boyd et al. (1984) have interpreted these lines as blueshifted $^{15}O^{*}$ deexcitation lines of rest energies 1.380 MeV and 6.175 MeV. These two lines result from the cascade deexcitation of the 7.556 MeV level of ^{15}O, through its 6.176 MeV level, to the ground state. The ^{15}O level at 7.556 can be populated by thermonuclear fusion of ^{14}N and protons through a narrow resonance at 0.278 MeV. The ratios of the observed line energies, 1.495/6.695 ≃ 0.2233, and line intensities, $\varphi(6.695)/\varphi(1.495) \sim 0.7$, are, within observational uncertainty, the same as those expected from the ^{15}O lines, 0.2235 and 1, respectively (Ajzenberg-Selove 1981).

There is, however, an alternative identification of the observed lines. Lamb et al. (1983) orginally identified the 1.495 MeV line as a blueshifted 1.369 MeV line resulting from $^{24}Mg^{*}$, excited by inelastic collisions with protons. One of the strongest lines that is expected to accompany this line is that at 6.129 MeV from $^{16}O^{*}$ (Ramaty, Kozlovsky and Lingenfelter 1979). By a remarkable coincidence, the ratio of these two line energies, 0.2233, is almost exactly the same as that of the two ^{15}O lines and is, within observational errors, precisely equal to the ratio of the energies of the two observed blueshifted lines. Thus, we propose that the observed lines from SS433 are due to $^{24}Mg^{*}$ and $^{16}O^{*}$ in the jets, excited by inelastic interactions with ambient protons.

In both the inelastic-excitation and the fusion models, the implied blueshift is consistent with that expected at the epoch of observation from the approaching jet of SS433. As suggested by Lamb et al. (1983), a weaker line, observed at approximately 1.2 MeV, could then be the redshifted counterpart of the 1.495 MeV line produced in the receding jet. For a recent discussion of the kinematics of SS433, see Margon (1984).

The lines observed from SS433, however, cannot be produced by excitations of ^{24}Mg and ^{16}O in gas. For at proton energies above the line production threshold, recoils of the $^{16}O^*$ nuclei broaden the 6.129 MeV line to a width of ~ 100 keV which is totally inconsistent with the observed width (< 10 keV). Moreover, at such bombarding energies and for galactic abundances (Cameron 1982), the two strongest lines would be at 6.129 MeV and 4.438 MeV, and not at 1.369 MeV as observed from SS433.

Both of these difficulties, however, can be resolved if the gamma-ray lines are produced in grains or other dense particles ($\rho \sim 1$ g cm^{-3}) moving with the jet velocity. Lingenfelter and Ramaty (1977) showed that energetic particle interactions in grains can produce very narrow gamma-ray lines, and that strong grain lines are expected at 6.129 and 1.369 MeV from ^{16}O and ^{24}Mg deexcitation. These gamma-ray lines are very narrow because the lifetimes of the corresponding excited levels are sufficiently long ($\gtrsim 1$ psec) that the recoiling nuclei stop before they emit gamma rays. On the other hand, the lifetime of the 4.439 MeV level of ^{12}C is too short to allow the excited ^{12}C nuclei to stop. Therefore, the recoil-broadened 4.438 MeV line would be so wide (FWHM ~ 100 keV) that it would fall below the instrumental sensitivity of the HEAO-3 detector. Furthermore, the well-known depletion of Ne and O in grains with respect to Mg, Si and Fe could explain the observed relative line intensities without having to assume arbitrary elemental abundances. Overall then, the assumption of the existence of grains in the jets allows us to use the simplest interaction model, namely that the nuclear excitations result from the interaction of the jets with the ambient medium.

II. VERY NARROW LINES FROM GRAINS

We now consider the strongest very narrow lines expected from excited nuclei that lose their recoil energy in dense particles before deexcitation. The size of these particles, which we will hereafter refer to simply as grains, must be less than ~ 1 cm to allow them to be transparent to gamma rays and greater than ~ 10^{-4} cm to stop the excited nuclei. The principal grain lines are listed in Table 1, together with the gamma-ray emission processes, mean lifetimes and principal excitation processes (Ramaty, Kozlovsky and Lingenfelter 1979).

The relative intensities of the very narrow lines depend on the excitation cross sections, the elemental abundances and the probability that the recoiling nucleus will stop before emitting gamma rays. The cross sections, σ, given in Table 1 are for an interaction energy of 33 MeV, corresponding to the velocity (V=0.260c, Margon 1984) of the ambient protons in the rest frame of the jets. These cross sections are from Ramaty, Kozlovsky and Lingenfelter (1979), with corrections inferred from the measurements of Dyer et al. (1981) at energies less than 23 MeV.

We assume that essentially all the heavier, less volatile elements, Mg, Si, Fe, etc., are in the grains with the relative abundances of Cameron (1982), and that the more volatile lighter elements are depleted, such that in the grains C, N and O are reduced by a factor f relative to the Cameron (1982) abundances and there is essentially no H, He, Ne or S. Such abundances (Table 1) are consistent with studies (e.g. Morton 1975) of gas depletion in the interstellar medium. We treat the factor f as a free parameter, which we expect to be about 1/2 or less.

The probabilities that the recoiling nuclei stop in the grains before emitting gamma rays were calculated in detail (Ramaty, Kozlovsky and Lingenfelter 1979). For grains larger than a few times 10^{-4} cm, these probabilities are essentially unity for all the lines listed in Table 1, except the 4.438 MeV line for which it is vanishingly small.

From these cross sections, abundances and stopping probabilities, we calculate the relative intensities of the grain lines listed in Table 1. As can be seen, the two strongest lines are at 6.129 and 1.369 MeV. The observed ratio, $\phi(6.695)/\phi(1.495) \sim 0.7$, implies that the $^{16}O/^{24}Mg$ ratio in the grains is ~ 4, or that f ~ 0.17. Such a fraction is consistent with the locking of O in grains due to the formation of chemical compounds with Mg, Si and Fe.

In addition to the observed lines, the inelastic-excitation model also predicts lines at 0.847, 0.931, 1.317, 1.634 and 1.779 MeV with intensities about 1/2 that of the 1.369 MeV line. The relative intensities of the 0.847 and 1.779 MeV lines, however, depend on the Fe and Si abundances. But, independent of the abundances, there should be 1.634 MeV emission from Ne produced by ^{24}Mg spallation. Norman and Bodansky (1984) have suggested that the intensity of the 1.634 line relative to that of the 1.369 MeV line should be ~ 0.85, based on the cross sections of the reactions $^{24}Mg(p,p')^{24}Mg^*$ and $^{24}Mg(p,x)^{20}Ne^*$ at 33 MeV, and that this high ratio would seem to rule out inelastic-excitation at such an energy since the 1.634 MeV line was apparently not seen. However, as we show in Table 1, the ratio of these lines depends also on the abundance of ^{28}Si, because of the strong contribution of ^{28}Si spallation to the 1.369 MeV line. Therefore, the apparent absence of the 1.634 MeV line is not an argument against the inelastic-excitation model.

Nuclear interactions in O, Mg, Si and Fe also produce positrons. We estimate that at 33 MeV about 1.8 positrons should be produced for each 1.369 MeV photon. The width of the 0.511 MeV line, however, will depend on the temperature and density of the annihilation site.

III. ABSOLUTE LINE LUMINOSITIES, ENERGY LOSS, GRAIN TEMPERATURE AND X-RAY PRODUCTION

We now investigate the energetics of the gamma-ray line emission. Considering for simplicity the instantaneous interaction rate between the jet grains and the ambient gas, the expected luminosity in the very narrow 1.369 MeV line is given by

$$L(1.369\ \mathrm{MeV}) = \left[N_{Mg}\ \sigma_{Mg} + N_{Si}\ \sigma_{Si}\right] V\ n_H\ E_\gamma, \qquad (1)$$

where N_{Mg} and N_{Si} are the total numbers of Mg and Si nuclei in the grains, n_H is ambient hydrogen density, and $E_\gamma = 1.369$ MeV. Using the values of σ and the abundances given in Table 1, we obtain

$$L(1.369\ \mathrm{MeV}) \simeq 3.3\mathrm{x}10^{34}\ n_H(M_{gr}/M_\odot)\ \mathrm{erg/sec}, \qquad (2)$$

where $M_{gr}/M_\odot$ is the total mass of the grains in solar masses and n_H is in cm^{-3}. This nuclear deexcitation radiation is accompanied by Coulomb energy loss, bremsstrahlung and a variety of other radiations which provide further constraints on the model.

The Coulomb energy loss, $\dot{W}_C$, is due to ambient protons and electrons traversing the grains and gas in the jets with energies of 33 MeV and 18 keV, respectively, in the jet rest frame. Taking the bulk of the jet gas to be hydrogen of mass M_{gas}, we obtain

$$\dot{W}_c \simeq V n_H \{[(\frac{dE}{dx})_{p,gr} + (\frac{dE}{dx})_{e,gr}] M_{gr} + [(\frac{dE}{dx})_{p,H} + (\frac{dE}{dx})_{e,H}] M_{gas}\}, \quad (3)$$

where the four expression for dE/dx are energy loss rates per g cm^{-2} of protons and electrons in grain material and hydrogen. From Barkas and Berger (1964) and Berger and Seltzer (1964) we find

$$\dot{W}_c \simeq 6.7 \times 10^{38}\, n_H\, (M_{gr} + 2.6\, M_{gas})/M_\odot \text{ erg/sec.} \quad (4)$$

Combining equations (2) and (4), and substituting the observed average blueshifted 1.369 MeV luminosity (~ 10^{37} erg/sec, Lamb et al. 1983), we obtain $\dot{W}_c \simeq 2 \times 10^{41} (1 + 2.6\, M_{gas}/M_{gr})$ erg/sec. This large Coulomb energy loss must be compensated by continuous acceleration, since otherwise the jets would slow down and the Doppler shift would change with time, contrary to the observation of an essentially constant blueshift and very narrow line for a period of several days (Lamb et al. 1984). Such constancy of the jet velocity may be maintained in condensed material by line-locking (Pekarevich, Piran and Shaham 1984).

The minimum $\dot{W}_c \simeq 2 \times 10^{41}$ erg/sec, obtained when $M_{gas} << M_{gr}$, exceeds the Eddington luminosity of a solar mass compact object by about 3 orders of magnitude. Therefore, $\dot{W}_c$ should be released primarily as mass motion in the jets. Letting the Coulomb energy loss equal the jet kinetic energy flow, $\dot{W}_c \simeq (\dot{M}_{gr} + \dot{M}_{gas})\, V^2/2$, and assuming that $\dot{M}_{gr}/\dot{M}_{gas} \simeq M_{gr}/M_{gas}$, we find that $\dot{M}_{gr} \simeq 10^{-4}\, \varepsilon\, M_0/y$, where ε is a numerical factor between 1 and 2.6, depending on M_{gas}/M_{gr}.

We estimate that the Coulomb energy loss in the grains will heat them to a temperature high enough to drive off the more volatile compounds but not the most refractory materials, particularly MgO. The equilibrium temperature of the grains, T, can be estimated by letting the rate at which energy is deposited in them, 2×10^{41} erg/sec, equal $\sigma T^4 A$, where A is the total surface area of the grains. This area can be calculated from the mass of grains involved in nuclear excitation at any one time and the area-to-mass ratio of the grains, $A/M_{gr} = 3/\rho r \simeq 10^4$ cm^2/gm, assuming a density $\rho \sim 3$ gm/cm^2 and a radius $r \sim 10^{-4}$ cm. Such a size and density are large enough that the thermal emission will be essentially blackbody and the bulk of the recoiling, excited Mg and O will stop in the grains to emit very narrow gamma-ray lines. The mass of grains in the emission region depends on $\dot{M}_{gr}$, estimated above, and the length of the emission column, which could be 4 days travel distance or more, based on the length of flaring (Seaquist et al. 1982) If we take ~ 4 days and $\dot{M}_{gr} \sim 2.6 \times 10^{-4}\ M_\odot$/yr, we find a mass of $\sim 3 \times 10^{-6}\ M_\odot$ corresponding to a radiating area of 6×10^{31} cm^2 and an equilibrium temperature of ~ 2750°K, significantly below the 3125°K melting temperature of MgO. We emphasize, however, that the relative line intensities given in Table 1 are for grains that consist not only of Mg and O but also C, Si and Fe.

The ambient electrons and protons traversing the grains and gas in the jets produce a bremsstrahlung luminosity $\lesssim$ 18 keV of

$$L_x \simeq 2\, V n_e \left[\left(\frac{dE}{dx}\right)_{r,gr} M_{gr} + \left(\frac{dE}{dx}\right)_{r,H} M_{gas}\right] \simeq 2\times10^{35}\, n_H\, (M_{gr} + 0.3\, M_{gas})/M_\odot \text{ erg/sec.} \quad (5)$$

Combining equations (2) and (5) and substituting the observed line luminosity, we find $L_x(\lesssim 18 \text{ keV}) \simeq 1\times10^{38}\,(1 + 0.3\, M_{gas}/M_{gr})$ erg/sec. These X rays must be substantially attenuated since the minimum bremsstrahlung of 10^{38} erg/sec exceeds the observed $\lesssim$ 18 keV luminosity (~ 10^{36} erg/sec, Marshall et al. 1979) by about a factor of 100.

The X rays, as well as the the gamma rays, could be attenuated or absorbed in both the ambient medium and the jets. We first estimate the attenuation in the ambient medium. We assume that the characteristic path length is comparable to the length of the gamma-ray emitting portion of the jets, which we approximate by $\ell \approx V M_{gr}/\dot{M}_{gr}$. From equation (2), with $L(1.369\ \mathrm{MeV}) \approx 10^{37}$ erg/sec and $\dot{M}_{gr} \approx 10^{-4}\ M_\odot$/year, we find a column depth $\ell\, n_H \approx 7\times10^{23}\ \mathrm{cm}^{-2}$. For such a value, the ambient medium is quite transparent to 1.5 MeV gamma rays, $\tau \approx 0.1$, but for X rays, it has an optical depth of $\tau \approx 1$ at ~ 10 keV for Cameron (1982) abundances, and it could be much more opaque if the heavy element abundances were enhanced.

We now estimate the opacity of the jets assuming cylindrical geometry such that $\tau \approx \sigma n R \approx \sigma\dot{M}/\pi A V R$, where R is the radius of the jet, A is the mean atomic mass and σ is the mean absorption cross section (Plechaty, Cullen and Howerton 1975). For the minimum opacity, corresponding to $M_{gas} << M_{gr}$ and $\dot{M}_{gr} \approx 10^{-4}\ M_0/y$, we obtain optical depths across the jets of $\tau \approx 1.4\times10^{10}/R$ at 1.5 MeV and $\tau \approx 1.8\times10^{13}/R$ at 10 keV, where R is the radius in cm. Thus, for the jets to be transparent to gamma rays, R must exceed ~ 10^{10} cm. At such a value of R, the X-ray opacity is so large that the bremsstrahlung would only be ~ 10% of that observed. Thus, the expected X-ray bremsstrahlung is consistent with observations.

IV. CONCLUSIONS

We have studied the origin of the recent HEAO-3 gamma-ray line observations of SS433. Although no independent confirmation of these observations has yet been reported, the correlation of the gamma-ray emission with radio flaring and the agreement of the gamma-ray source direction with the known direction of SS433 are good arguments that the observed lines (Lamb et al. 1983, 1984) are indeed from SS433. Strong additional support for this identification is provided by the fact that a single jet velocity, appropriate to the epoch of the gamma-ray observation, can accurately account to a precision of a few tenths of a precent for the line energies of the two observed blueshifted lines in terms of rest energies predicted by theory.

We suggest that the gamma-ray line emission results from the inelastic excitation of ^{24}Mg and ^{16}O in grains moving with the velocity of the jets and interacting with the ambient gas in the acceleration region. This model provides an alternative identification of the observed lines to that of the p-^{14}N fusion proposed by Boyd et al. (1984). Since both models predict additional gamma-ray lines at differing energies, observations should clearly distinguish between them.

The essential ingredient of the inelastic-excitation model is the presence of dense particles in the jets. The possibility of highly clumped or condensed matter in the jets was also suggested recently by Pekarevich, Piran and Shaham (1984), if line locking is responsible for the acceleration. Much further study is needed, however, to show how these particles are produced, how long they survive in the jet environment, and what role they might have in the unsolved acceleration mechanism.

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TABLE 1
VERY NARROW LINE EMISSION

Photon Energy (MeV)	Emission Process	Mean Life (psec)	Excitation Process	σ(mb)	Abundance	Line Flux
0.847	$^{56}Fe^{*0.847}\rightarrow g.s$	9.7	$^{56}Fe(p,p')^{56}Fe^{*}$	150	1.0	0.5
0.931	$^{56}Fe^{*0.931}\rightarrow g.s$	13	$^{56}Fe(p,pn)^{55}Fe^{*}$	180	1.0	0.6
1.317	$^{56}Fe^{*1.317}\rightarrow g.s$	1.4	$^{56}Fe(p,pn)^{55}Fe^{*}$	150	1.0	0.5
1.369	$^{24}Mg^{*1.369}\rightarrow g.s.$	1.8	$^{24}Mg(p,p')^{24}Mg^{*}$	180	1.0	
			$^{28}Si(p,x)^{24}Mg^{*}$	90	1.1	1.0
1.634	$^{20}Ne^{*1.634}\rightarrow g.s.$	1.2	$^{20}Ne(p,p')^{20}Ne^{*}$	90	~ 0	
			$^{24}Mg(p,x)^{20}Ne^{*}$	150	1	0.5
1.779	$^{28}Si^{*1.779}\rightarrow g.s.$	0.7	$^{28}Si(p,p')^{28}Si^{*}$	90	1.1	0.4
4.438	$^{12}C^{*4.439}\rightarrow g.s.$		$^{12}C(p,p')^{12}C^{*}$	70	13f	
		0.06	$^{16}O(p,x)^{12}C^{*}$	80	22f	~ 0
6.129	$^{16}O^{*6.131}\rightarrow g.s.$	24	$^{16}O(p,p')^{16}O^{*}$	50	22f	
			$^{20}Ne(p,x)^{16}O^{*}$	60	~ 0	4.0f

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