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THE IMPLICATIONS OF GAMMA-RAY LINES OBSERVED FROM THE ORION COMPLEX

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ABSTRACT

The observation of intense gamma-ray line emission from the Orion complex, attributed by Bloemen et al. to de-excitation of cosmic-ray carbon and oxygen nuclei, has important implications for emission from Orion in the infrared and in high-energy gamma rays, and also for the theories of cosmic-ray origins. Some of these implications are briefly pointed out.

Subject headings: gamma rays: theory — ISM: clouds — ISM: individual (Orion Complex)

1. INTRODUCTION

Bloemen et al. (1994) have reported the detection of gamma rays from the Orion complex. These results were derived from observations with the COMPTEL instrument on the *Compton Gamma Ray Observatory* (*CGRO*). Within the energy range of 3–7 MeV, there were distinct peaks close to 4 MeV and 6 MeV, which these authors identified with the $^{12}C^*$ and $^{16}O^*$ nuclear de-excitation lines. The observed intensities were as high as $\sim 10^{-4}$ photons $cm^{-2}\ s^{-1}$, and the line widths (FWHM) were about 1 MeV, considerably broader than the calibrated instrumental resolution (FWHM) of 0.3 MeV. Bloemen et al. have interpreted their observations as indicating the source of the gamma rays to be cosmic-ray carbon and oxygen nuclei, from which Doppler broadening would match that expected if the nuclei had kinetic energies around 10 MeV $nucleon^{-1}$ and were excited in colliding with ambient hydrogen. Bykov & Bloemen (1994) went further with this model and suggested that additional gamma-ray lines should be detectable. Nath & Biermann (1994) have discussed the possible acceleration by shocks of stellar winds within Orion that could produce the required energetic nuclei. Clayton (1994) has pointed to possible connections with the production of ^{26}Al. Ramaty, Kozlovsky, & Lingenfelter (1994), while disagreeing with Clayton regarding the production of ^{26}Al, have broadened the discussion by considering implications of the lack of detection of spectral lines at energies below 3 MeV.

In this Letter, we wish to point to some additional implications that must follow from the model suggested by Bloemen et al. First, we are able to fit the observed line shape by assuming approximately equal contributions from the excitation of energetic carbon and oxygen on ambient hydrogen and helium targets, as well as the excitation of ambient carbon and oxygen targets by energetic protons and helium nuclei. Second, by comparing the observed line intensities with that of the high-energy gamma-ray continuum detected by the EGRET instrument, also on *CGRO* (Digel, Hunter, & Mukherjee 1995), we find that the spectral shape of the energetic particles in the nebula is considerably steeper than that of the cosmic rays near the solar system. Finally, we note that energetic particles responsible for the excitation of the nuclei must also, through Coulomb interactions, deposit far greater amounts of energy, considerably in excess of the observed infrared luminosity.

2. IMPLICATIONS

2.1. *Analysis of Line Shape*

Bloemen et al. (1994) have already emphasized the fact that the observed line width of about 1 MeV is considerably in excess of the detector resolution of ~ 0.3 MeV (Kanbach et al. 1989). Whereas the interaction of energetic protons, helium, etc., on target C and O nuclei will generate narrow de-excitation lines whose observed width would be limited by the instrumental resolution, the excitation of C and O projectiles in collisions with target hydrogen will lead to line widths determined essentially by the Doppler broadening for energies corresponding to the peak of the excitation cross sections, ~ 15 MeV $nucleon^{-1}$. Thus, the observed line shape is a linear combination of these two basic contributions. We consider the contributions of only energetic protons and helium particles to the excitation of target C and O since the elemental abundances expected for heavier energetic particles decrease rapidly beyond helium. For the inverse reactions, we consider only the collisions of energetic C and O nuclei on target hydrogen and helium. We have used the cross sections given by Ramaty, Kozlovsky, & Lingenfelter (1979).

In Figure 1*a*, we show our fit to the observed line shape, making the simple assumption of equal contributions of target excitation (FWHM = 6.3%) and projectile excitation (FWHM = 15%). We find a satisfactory fit which implies that, unlike the galactic cosmic rays near the solar system, the energetic particle abundances in the Orion complex are in close agreement with their ambient abundances in the same region. In other words, the H to C and H to O ratios are as $1:10^{-3}$ both for the projectile and for the target particles, in contrast to the local cosmic rays where the hydrogen is suppressed by a factor of ~ 10. In Figure 2 we show the expected spectrum deduced for exclusively projectile excitation with Doppler broadening (as suggested by Bloemen et al.), and we note that this does not reproduce the spectrum observed.

We have also explored the effect of varying the relative proportions of hydrogen to carbon and oxygen among the cosmic rays, leaving the target abundances unchanged. The results are shown in Figure 1*b*, in which we display the results of changing the H:C and H:O ratios from $1:10^{-3}$, reducing the hydrogen fraction by factors of 3 and 5. The fits to the observed spectrum are comparable to that shown in Figure 1*a*. Reducing the

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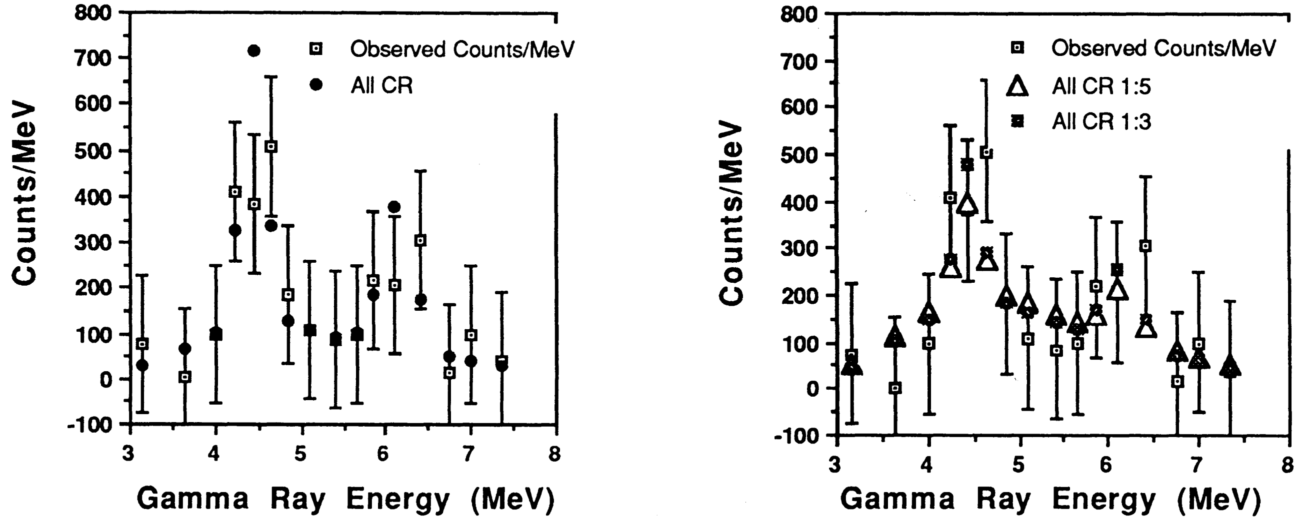

FIG. 1a

FIG. 1b

FIG. 1.—(a) Calculated gamma-ray spectrum, normalized to the observed number of photons and including contributions of cosmic-ray H, He, C, and O in the normal proportions. Instrumental FWHM of 6.3% and Doppler FWHM of 15% are assumed. (b) As in (a), but with the hydrogen reduced by factors of 3 and 5, as indicated.

hydrogen fraction lowers the peak values for the two gamma-ray lines, but we note that the observed peaks appear in the energy bins immediately above the expected values. For all of our assumed hydrogen to carbon and hydrogen to oxygen ratios, the fits are far better than are obtained with no cosmic-ray hydrogen, as shown in Figure 2. However, the question of the hydrogen/oxygen ratio in Orion and among the cosmic rays in that region is complex. Meyer et al. (1994), using observations made with the Hubble telescope, have confirmed earlier observations that the O/H ratio is only about half that of the Sun's. Reducing the hydrogen to carbon and hydrogen to oxygen ratios among the cosmic rays, if correct, would raise additional questions.

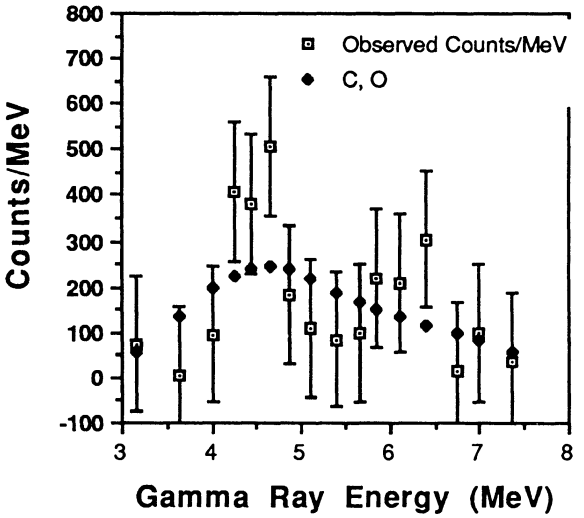

FIG. 2.—Calculated gamma-ray spectrum, normalized to the observed number of photons, but including only the contributions of cosmic-ray C and O projectiles. Instrumental FWHM of 6.3% and Doppler FWHM of 15% are assumed.

Ramaty et al. (1994) have also computed the expected gamma-ray spectrum. They assumed a proton spectrum characterized by some critical energy, E_c, being flat below E_c and decreasing as E^{-10} at higher energies. Only the instrumental line width was included, and their fit to the COMPTEL observations is not quite as good as that shown in our Figure 1 where both the Doppler broadening and the instrumental resolution have been included.

2.2. *Gamma-Ray Continuum at* ~100 MeV *and the Energy Spectrum of Cosmic-Ray Particles*

In analyzing the high-energy gamma-ray flux from the Orion complex, the following physical details are relevant. The complex is a young OB association surrounded by a tenuous plasma bubble of radius ~45 pc itself surrounded by a shell of gas of 20 pc thickness (Bykov & Bloemen 1994). At a distance of 450 pc this complex subtends an angle of 16°, much larger than the angular resolution obtainable with the COMPTEL and EGRET instruments on *CGRO*. Within the shell, there is a mean density of roughly two H atoms cm^{-3}. Thus a total of $N_\text{H} \sim 4 \times 10^{61}$ H atoms are available as targets in the complex. However, Bloemen et al. (1994) used a value of 10^5 solar masses for the Orion complex. The corresponding value of N_H is 1.25×10^{62}, and we use both values for N_H in our further calculations, though our results are not very sensitive to the choice.

Gamma rays of 100 MeV and above come primarily from neutral pions, produced by collisions of cosmic-ray particles with energies of 400 MeV nucleon^{-1} and above; the median proton energy for pion production is 1 GeV nucleon^{-1}. The gamma-ray intensity at $E \sim 100$ MeV expected from this complex is given by

$$f_\gamma(\sim 100\ \text{MeV}) = \frac{\phi q_\gamma N_\text{H}}{4\pi D^2} \approx \phi 3 \times 10^{-7}\ \text{cm}^{-2}\ \text{s}^{-1}\ . \qquad (1)$$

Here ϕ is the flux of energetic particles at ~1 GeV nucleon^{-1} in the complex, expressed in units of the cosmic-ray flux near

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the solar system, and $q_\gamma \sim 2 \times 10^{-25}$ s^{-1} is the number of gamma rays of $\sim$100 MeV generated by the cosmic-ray flux per hydrogen atom (Stephens & Badhwar 1981).

For 100 MeV gamma rays, the EGRET detector has reported a total flux of 2.8×10^{-6} photons cm^{-2} s^{-1} (Digel et al. 1995; Mukherjee 1994). Combining this with equation (1), we find $\phi = 8$ for the lower value of $N_{\rm H}$ and $\phi = 2.6$ for the higher value. In all, then, we find the gamma-ray observations require a flux within Orion of energetic particles responsible for pion production not much enhanced with respect to general cosmic-ray levels.

For the low-energy cosmic rays responsible for the gamma-ray lines, we represent the flux of energetic particles of charge Z_i by

$$f(E, Z_i) = K n_i E^{-\beta}\,, \tag{2}$$

where E is the kinetic energy of the particle in GeV nucleon^{-1}, n_i is the flux relative to that of protons, and $K \approx 0.1$ cm^{-2} s^{-1} sr^{-1} GeV^{-1} is the constant which normalizes the flux to that of the cosmic rays at 1 GeV nucleon^{-1} near Earth. (See, e.g., Oda 1988, p. 315.)

For our present purposes, it is sufficient to note that σ_e, the cross section for excitation, peaks at $\sim$15 MeV nucleon^{-1} with a value of $\sim$200 mb and has a full width of $\Delta E \approx 10$ MeV nucleon^{-1}. Then I_γ, the flux of gamma rays from the complex expected at Earth, is given with sufficient accuracy by

$$I_\gamma \approx \frac{f(E, Z_i)\sigma_e \Delta E N_{\rm H} C_{\rm C,O}}{D^2}\,. \tag{3}$$

Using $I_\gamma \sim 10^{-4}$ cm^{-2} s^{-1} and $C_{\rm C,O}$ the abundance of carbon and oxygen relative to hydrogen $\approx 10^{-3}$, we derive $f \approx 2.5 \times 10^6$ cm^{-2} s^{-1} sr^{-1} GeV^{-1}, using $N_{\rm H} = 4 \times 10^{61}$. If instead we use $N_{\rm H} = 1.25 \times 10^{62}$, derived from 10^5 solar masses, we obtain $f \approx 8 \times 10^5$ cm^{-2} s^{-1} sr^{-1} GeV^{-1}.

Assuming that the energy spectrum given in equation (2) is valid between 15 MeV nucleon^{-1} and 1 GeV nucleon^{-1} (as required for pion production), we can now compute the slope β. We derive a value for $\beta \approx 3.6$, regardless of which value we use for $N_{\rm H}$. This steep increase in the cosmic-ray flux in Orion toward low energies should be contrasted with the near constancy and even a decrease of the flux below 0.5 GeV nucleon^{-1} in galactic cosmic rays.

Changing the hydrogen to carbon and hydrogen to oxygen proportions, as done earlier, produces a change in β, the slope of the assumed spectrum. Reducing the hydrogen by factors of 3 and 5 yields $\beta = 3.2$ and 3.1, respectively, still appreciably steeper than is observed close to Earth.

2.3. *Ionization Energy Loss by Particles*

Turning our attention to the energy budget of the Orion complex, we note that the luminosity in gamma-ray lines is $\sim 2 \times 10^{34}$ ergs s^{-1}, with a comparable luminosity in photons above 100 MeV. To calculate the energy deposited through ionization in the gas present in the Orion complex, we adopt an empirical fit to the ionization loss formula valid at low energies,

$$j(E, Z_i) = -bZ_i^2 E_i^{-0.81}\,, \tag{4}$$

where $b = 4 \times 10^{-6}$ ergs cm^2 g^{-1} and E is the energy expressed in GeV nucleon^{-1} for a particle of charge Z_i. Thus, the total energy deposited through ionization in the Orion complex amounts to

$$\begin{aligned} J &= \sum_i 4\pi \frac{N_{\rm H}}{A} m_{\rm H} \int_{E_m}^{\infty} j(E, Z_i) f(E, Z_i) dE \\ &= \sum_i 4\pi \frac{N_{\rm H} b}{A} m_{\rm H} n_i Z_i^2 K \int_{E_m}^{\infty} E^{-(\beta+0.81)} dE \\ &\approx \sum_i \frac{4\pi N_{\rm H} m_{\rm H} b \eta_i Z_i^2 K}{3.4A} E_m^{-3.4} \\ &\approx 1.6 \times 10^{39} \text{ ergs s}^{-1} \quad (\text{for } N_{\rm H} = 4 \times 10^{61})\,, \end{aligned}$$

or

$$\approx 5 \times 10^{39} \text{ ergs s}^{-1} \quad (\text{for } N_{\rm H} = 1.25 \times 10^{62})\,, \tag{5}$$

for cosmic rays with a minimum energy E_m of 0.01 GeV nucleon^{-1}. The efficiency for production of gamma-ray lines by energetic particles is thus $\lesssim 10^{-5}$ when compared to ionization loss, most of which goes into heating the medium through ionization and other coulombic interactions. Against this heat input of $\sim(1.6\text{–}5) \times 10^{39}$ ergs s^{-1}, we note that the infrared luminosity of the complex is about 4×10^{38} ergs s^{-1}.

Changing the proportion of hydrogen to the heavier nuclei among the cosmic rays has a significant effect on this result too. For reductions in the hydrogen by factors of 3 and 5, the corresponding ionization losses are 1.6×10^{38} ergs s^{-1} and 8×10^{37} ergs s^{-1}. For the larger values of $N_{\rm H}$, the ionization losses need to be increased by a factor of 3.

Thus, it appears that the ionization heating by energetic particles might well make a dominant contribution to the luminosity of the complex, depending sensitively on the relative proportions of hydrogen and the heavier nuclei. We note that a reduction in the hydrogen flux must be compensated by an increase in the carbon and oxygen fluxes, and their Z^2 contributions to the ionization heating diminish the overall change. The customary view is that the visual and IR luminosity of the complex is powered by the nearby 56 high-luminosity O and B stars (Genzel & Stutzki 1989). However, even a generous estimate of their combined luminosity amounts to about 4×10^{39} ergs s^{-1}, and only a fraction of this will be intercepted and absorbed by the complex. Keeping in mind that the gamma-ray line shape demands approximately equal contributions from proton and C + O projectiles, there is no easy way to avoid the large energy input into the complex via ionization, and this exceeds the observed infrared luminosity and perhaps is close to the luminosity of the OB stars.

3. DISCUSSION

As is shown by our analysis and the results displayed in Figures 1 and 2, interpretation of the observed gamma-ray line shapes requires inclusion of the effects of proton and helium cosmic rays. When we combine this result with the detection of high-energy gamma rays by the EGRET experiment, we conclude that the energy spectrum of cosmic rays within the Orion complex is far steeper than among the general galactic cosmic rays. This steep spectrum will have important consequences for theories of the origin of cosmic rays, for it is very difficult to sustain a steep energy spectrum in the presence of significant energy losses. The evaluation of those energy losses, through ionization, shows that the cosmic rays may be a major contributor to the infrared luminosity of Orion, contrary to the general belief that it is the OB stars alone that are responsible.

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The importance of our comparison between the cosmic-ray ionization loss ($L_{\rm ion}$) and the observed IR luminosity must be underscored by noting that our estimates of the ionization loss are lower limits that are sensitive to the value assumed for E_m, the lower energy limit used in calculating the total ionization energy loss; $L_{\rm ion}$ varies typically as $E_m^{-3.4}$. Our assumption of 10 MeV nucleon^{-1} is the most conservative possible, as this is virtually the lowest energy that must be present among the cosmic rays for the gamma-ray line production. If, however, the cosmic-ray spectrum extends below 10 MeV nucleon^{-1}, as would reasonably be expected, then the necessary ionization losses increase.

If the energetic particles are indeed responsible for heating and resulting emission in the infrared, the problem of the energetics is merely shifted to finding efficient mechanisms for the production of the fast particles. Further, if the process of particle generation is not very efficient, then how is the rest of the energy radiated away and at what wavelengths? Detailed spectroscopic studies should be able to tell whether the excitation of the nebula is indeed due to energetic particles, which can generate highly excited and ionized states of atoms, or that it is the UV radiation from the stars which tend to ionize only the outer shells.

We are left, in the end, with several unanswered questions. Repeated observations by the COMPTEL instrument are needed in order to define the line shapes more precisely, for, as has been shown, the further analysis is sensitive to the proportions of hydrogen and carbon and hydrogen and oxygen. At the same time, observations by EGRET are also needed in order to improve the definition of the cosmic-ray energy spectrum. The shape of the low-energy gamma-ray spectrum can allow limits to be set on the proportions of the lighter cosmic-ray components, while the relative intensities of low- and high-energy gamma rays constrain the models for cosmic-ray production. Gamma-ray observations may well yield information on the sources of the cosmic rays.

In all, it is therefore clear that, with the advent of high-quality instruments like COMPTEL, the gamma-ray line shape becomes a very sensitive diagnostic tool to study the composition of energetic particles and the ambient medium far from the solar system. The observations of Bloemen et al. have provided a new and probably unique probe of the properties of cosmic rays in distant regions.

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