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Implications Of Gamma-ray Lines Observed From The Orion Complex. II

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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.

1 Introduction

The detection of the nuclear de-excitation gamma-ray lines of $^{12}C^*$ and $^{16}O^*$ from the Orion complex with the COMPTEL instrument on the *Compton Gamma Ray Observatory*[1] has stimulated a considerable amount of interest among the astrophysical community. The observations showed distinct peaks close to 4 MeV and 6 MeV and the intensities were as high as 10^{-4} photons $cm^{-2}s^{-1}$. A remarkable feature of these observations is that the line widths (FWHM) were about 1 MeV, considerably broader than the instrumental resolution of 0.3 MeV.[2] This fact was noticed by Bloemen et al.[1] who interpreted their observations as indicating the source of the gamma rays to be energetic C and O nuclei which got excited in collision against ambient hydrogen in the Orion complex. Nath and Biermann[3] and Cameron et al.[4] have discussed the possible origin of these energetic particles and the latter have also discussed in detail the implications of these observations to the generation of ^{26}Al in our galaxy. Of particular interest is the analysis by Ramaty et al.[5] which indicates that any plausible bombardment scheme to generate ^{26}Al produces too much ^{9}Be unless the particle spectrum is suddenly cut-off at energies below 10 MeV/nucleon, as suggested by Clayton and Jin[6]. This is unlikely since the ionization energy losses will move the particles of higher energy into this range rather rapidly. The observed line shape was analyzed by Cowsik and Friedlander[7] to show that it comprised both a narrow and a broad component, produced respectively by energetic proton and He nuclei bombarding the ambient C and O nuclei and by energetic C and O bombarding the p and He targets. In their further analyses, they also took into account the high energy gamma-ray continuum around 100 MeV detected by the EGRET instrument by Digel, Hunter and Mukherjee[8]. The findings of Cowsik and Friedlander had important implications to the energetics of the Orion complex and to the origin of cosmic rays. The purpose of the present paper is to discuss some of these implications.

2 Analysis of the line shape

The cross-sections for the excitation of C and O nuclei have been given by Ramaty, Kozlovsky and Lingenfelter[9] and these become significant beyond ~10 MeV/nucleon and go through a broad maximum at ~15 MeV/nucleon and become small beyond ~20 MeV/nucleon. Thus most of the gamma ray line generation occurs with projectiles having energies in this band. When C and O are the projectiles the de-excitation gamma rays will show a Doppler broadening corresponding to ~15 MeV/nucleon; on the other hand when they are targets bombarded by p and He projectiles, the recoil momenta are so small during the excitation process that the width of the observed gamma rays is dominated by the instrumental resolution.

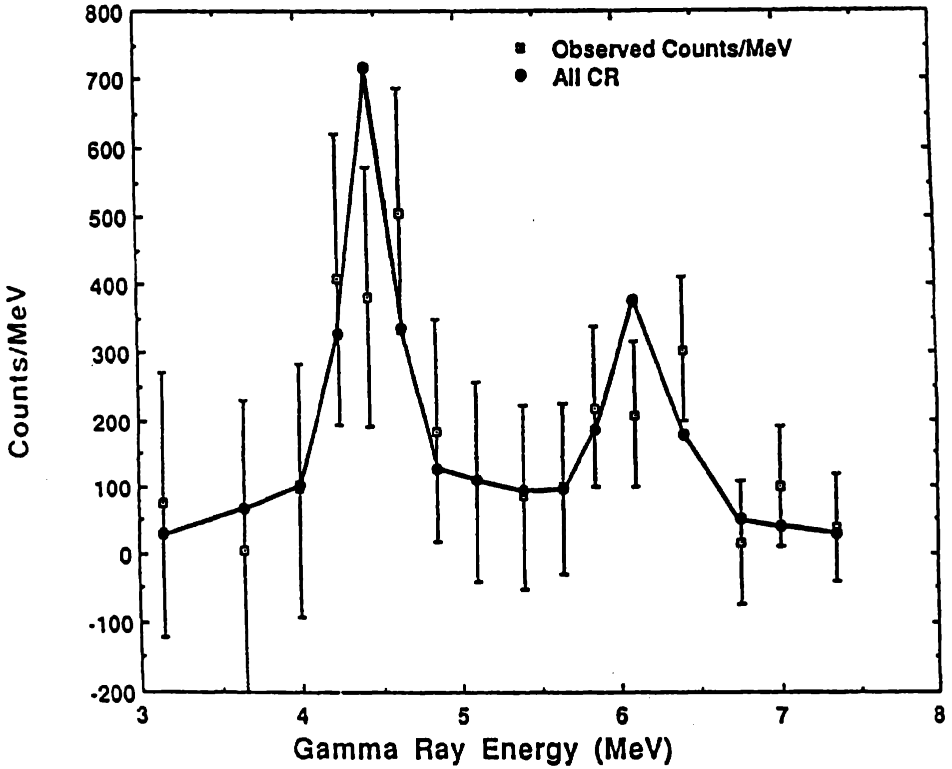

Fig. 1. The line shape computed assuming equal contributions from C and O acting as projectiles and as targets is compared with observations. The error bars appear to be $\sim 2\sigma$ and the contribution of the p and He projectiles generating the narrow component can not be reduced by more than a factor of ~2.

In Figure 1, we show a fit to the observed data assuming equal contributions from both these channels. We have also assumed equal abundances of C and O, each of which are down with respect to H by 10^{-3} . What this fit implies is that the intensity of low energy hydrogen nuclei in the nebula is 1000 times that of C and O nuclei. This is in contrast with the corresponding ratio in galactic cosmic rays of $\sim 10^{2}$ at ~1 GeV/nucleon. It seems that the error bars shown in Figure 1 represent two standard deviations and consequently the intensity of the energetic protons in the nebula can not be lowered by more than a factor of ~2. It is possible to construct specific models, based on the effect of ionization loss, which will yield the high ratio at ~15 MeV/nucleon while maintaining the cosmic-ray value of ~100 at ~1 GeV/nucleon.

3 Spectrum of projectiles

Digel et al.[8] have reported a total flux of 2.8 x 10^{-6} photons $cm^{-2}s^{-1}$ at $E_\gamma \geq 100$ MeV from the Orion complex. Since the rate of production of these gamma rays by cosmic rays is well known (see for e.g. Badhwar and Stephens[10]) the relative intensities of low and high energy projectiles in the nebula can be estimated. This estimate indicates that the spectrum is very steep $\sim kE^{-\beta}$ with $\beta \approx 3.6$, E being the kinetic energy per nucleon of the projectiles. The coefficients k can be fixed if we can estimate the total mass of gas in the complex. Taking a value of 10^5 M⊙ given by Bloemen et al. the value of k pertaining to the nebular region was estimated. It is convenient to express this as a ratio ϕ with respect to its value k at ~1 Gev/nucleon near the solar system ($k \approx 0.1$ cm^{-2}s^{-1}sr^{-1}GeV^{-1}; see Oda[11]); we estimate $\phi \approx 3$. Thus the total energy in cosmic rays contained within the nebula is

$$U(> 10\ \mathrm{MeV}) \approx 10^{53}\ \mathrm{erg} \tag{1}$$

$$U(> 1\ \mathrm{Gev}) \approx 10^{51}\ \mathrm{erg} \tag{2}$$

Such an enormous amount of energy in the nebula suggest the possibility of the occurrence of one or several massive supernova outbursts within it.

4 Ionization energy lost by the particles

At low energies the rate of energy lost by charged particles through coulombic interactions with the medium increases so that we may expect substantial energy to be deposited in the nebula by the particles which are responsible for the production of the gamma-ray lines. In fact, the dominant contribution to the rate of energy deposition comes from the protons responsible for the narrow core of the observed line profile. Adopting a convenient empirical fit to the ionization energy loss formula

$$j(E,Z) = bZ^2E^{-0.81} \tag{3}$$

where $b = 4 \times 10^{-6}$erg cm^{2}g^{-1} when E is expressed in GeV nucleon^{-1}. Summing over the contribution of all the particles, we find the rate of deposition of energy in the nebula to be

$$I = 4 \times 10^{39}\mathrm{erg\ s^{-1}} \tag{4}$$

Notice that this energy deposition rate exceeds considerably the infrared luminosity of the nebula, L(IR) $\approx 4\ 10^{38}$ erg s^{-1}. The ionization energy deposition rate is comparable or slightly larger than the estimated luminosity of the 56 O and B stars in the nebula. Thus any mechanism that accelerates these particles responsible for gamma-ray emission must be highly efficient; otherwise, the energy balance within the nebula would be upset. In any case, the ionization energy loss by the particles must contribute significantly to the IR-luminosity of the nebula. Conversely, other such extended sources of intense infrared emission would be prime candidates for sources of gamma-ray lines.

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