Proceedings of ICRC 2001: 2077 © Copernicus Gesellschaft 2001

ICRC 2001

Gamma-ray line shape and cosmic-ray acceleration

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Abstract. The 1.809 MeV gamma-ray line from radioactive ^{26}Al observed towards the galactic center shows a line width of $\approx$ 5 keV. If interpreted as kinematic broadening, the required velocities are ≈ 500 km/s. The acceleration of cosmic rays from the interstellar medium (ISM), is commonly assumed to take place in shock regions associated with groups of massive stars. In that case, freshly-produced ^{26}Al should be among the accelerated nuclei, and the velocity distribution of these particles is a function of the gas density, the assumed grain size, and typical separations between supernova remnants. Studies have shown that ^{26}Al embedded in these dust particles can easily reach and maintain velocities of order of 1000 km/s, and thus explain the observed width of the 1.809 MeV line. Stellar winds and supernova explosions in star forming regions can drive large, rapidly expanding superbubbles into the ISM. Shocks propagating inside the bubble accelerate dust particles and with it the ^{26}Al they contain. We discuss the resulting shape of the 1.809 MeV line.

1 Introduction

Measurements of the 1.809 MeV gamma-ray line from the decay of radioactive ^{26}Al with the imaging Compton telescope COMPTEL point to massive stars as the predominant contributors to interstellar ^{26}Al. Nuclei freshly produced in stellar interiors are expelled into the ISM by powerful stellar winds of massive stars and by the supernova explosions at the end of their lifetimes.

These energetic outflows associated with massive stars inject tremendous amounts of thermal and kinetic energy into the ISM. The decay of radioactive nuclei in these flows is thus expected to occur at non-negligible velocities, which leads to Doppler-broadening of emission lines like the 1.809 MeV line observed with the gamma-ray spectrometer GRIS (Naya et al. 1996). Different acceleration mechanisms lead to different distributions of nuclei in velocity space, which affect the shape of the corresponding lines. For example, a radiating, optically thin thermal gas leads to a Gaussian line shape, while a power-law distribution of radiating particles generates a power-law spectrum. From the study of line shapes, we can gain information about particle acceleration and radiation processes.

2 Sites and Physical Processes

2.1 Astrophysical objects

Massive stars, which provide the bulk of cosmic radioactivity (Diehl and Timmes, 1998), often form in associations containing tens or even hundreds of OB stars, and form at approximately the same time. Freshly synthesized nuclei are ejected by these stars during epochs of large mass loss in late stages of their evolution and the subsequent core collapse supernova event.

The stellar winds ($v = \mathcal{O}(1000\ km/s)$), driven by the intense ultraviolet emission, and supernova ejecta ($v = \mathcal{O}(10^4\ km/s)$) together blow bubbles into the ISM. These cavities are filled with hot ($T = \mathcal{O}(10^6\ K)$) tenuous gas because of the large input of kinetic and thermal energy from the evolving stellar population. The cavities are surrounded by a dense, cool neutral shell composed of ejecta and swept-up interstellar material. Both the bubble interior as well as the shell contain freshly synthesized material. Dust grains, which are known to form in supernovae and which incorporate radioactive nuclei, move independently of the gas because of their small interaction cross sections. Gamma-ray emission from radioactive isotopes in these environments trace some aspects of the dynamic evolution of gas and dust in young star forming regions. In particular, the shape of their emission lines provides information on the kinematic properties of these environments.

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2.2 Line broadening mechanisms

Several physical processes that occur in the environment of massive stars are possible contributors to the broadening of gamma-ray lines. The natural line width ($\mathcal{O}(\text{meV})$) can be neglected. Pressure broadening and scattering also do not play an important role because the densities in the systems under consideration are small. For Compton scattering to be important, column densities of at least 1 g/cm^2 are required. For one solar mass of ejecta confined to a volume with linear dimension of $L \approx 0.01\ pc$, Compton scattering would have to be taken into account. This may be important during the very early phase of SNR evolution, but at late times the material ist too tenuous for Compton scattering to be effective.

The most significant effects are expected from Doppler shifts, where isotropic and anisotropic velocity distributions have to be distinguished. In the anisotropic case, not only line boadening but also line shifts can occur. Consider two different situations:

- An isotropic velocity distribution of the radiating particles occurs in a thermalized system, such as the interior of a superbubble, where temperatures in excess of $T = 10^6\ K$ can be attained, or the shocked material in a SNR or unstable stellar winds. In the presence of shocks or turbulence, some fraction of the particles develop a non-thermal velocity distribution.

- If the emitting medium shows macroscopic motion, such as galactic disk rotation (Gehrels and Chen, 1996) or expanding sperical motions in stellar winds, supernova remnants and superbubble shells, the line shapes are complex and dependent on the relative orientation of observer and emitting region.

3 A model for γ-ray line shapes

3.1 Emission from an OB association

We model OB associations using the stellar evolution tracks by Meynet et al. (1994), combined with supernova simulations from Woosley et al. (1995). For the hot O, B and WR stars wind velocities range from 500 to 3000 km/s. Combined with theoretical mass loss rates, we calculate the kinetic luminosity of stellar winds. This energy together with the canonical 10^{51} ergs of kinetic energy per supernova leads to the formation of an expanding bubble, which we model numerically. While gamma-ray line emission from individual supernovae is of great interest in supernova studies (e.g. Chan and Lingenfelter, 1991), here we are concerned with the integrated line emission from radioctivities contributed by many supernovae.

In particular, we are interested in gamma-ray lines from ^{26}Al and ^{60}Fe. The yields of these nuclei in massive stars are available in the literature. To determine the time dependent release of these nuclei we assume a star formation history and an initial mass function. Stellar evolution theory thus predicts the production rate of both nuclei as a function of time. We determine the abundances of both species as a function of time and thus also their respective radioactive decay rates. This in turn provides the lightcurves of lines at 1.809 MeV (from ^{26}Al) as well as 1.173 MeV and 1.332 MeV (from ^{60}Fe). Using a Monte Carlo method for the generation of statistically sampled initial stellar mass distributions, we also evaluate the uncertainties due to the small number of stars in a typical association.

3.2 Modelling the line shape

To model the shape of gamma-ray lines emerging from a star forming region, the line broadening effects mentioned in sec. 2.2 have to be incorporated. The typical bubble interior has temperatures of $T = \mathcal{O}(10^6\ K)$, corresponding to thermal velocities of ≈ 25 km/s, which is clearly inadequate to explain the GRIS measurements. On the other hand, winds of hot stars have terminal velocities on the order of 1000 km/s, which would be adequate, and supernova ejecta are even faster. If some fraction of a freshly synthesized radioactivity can maintain such high velocities for a substantial fraction of its mean life, significant line broadening should result. We therefore intend to incorporate the effect of bulk motion into our model. We must develop a more detailed model of the kinematics of the gas inside an expanding superbubble, and we must simulate the formation and evolution of dust grains is this dynamic environment.

To model the acceleration of dust grains, the interaction between grains and shocks from SNe and colliding winds must be treated carefully (e.g. Sturner and Naya, 1999). Future gamma-ray spectrometers might allow the detection of high-velocity tails resulting from particle acceleration and thus shed light on the possibility that grains from supernovae are accelerated and reaccelerated in the highly dynamic interiors of stellar nurseries.

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