Gamma-Ray Line Emission from Superbubbles

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ABSTRACT We present an evolutionary model for $\gamma$-ray line emission from superbubbles based on shock acceleration of metal-rich stellar ejecta. Application to the Orion OB1 association shows that $\gamma$-ray lines at the detection threshold of the SPI spectrometer aboard of INTEGRAL are expected, making this region an interesting target for studies of the interaction of supernova shocks with the interstellar medium.

KEYWORDS: gamma-ray lines; superbubbles; OB associations; mean wind composition; Orion.

1. INTRODUCTION

The claim for a detection by COMPTEL (Bloemen et al. 1994) of an intense flux of 3-7 MeV gamma-rays from the Orion molecular complex, attributed most naturally to $^{12}$C and $^{16}$O de-excitation lines, has led many authors to re-consider the nature and impact of energetic particles (EPs) in the interstellar medium (ISM). Although re-analysis of COMPTEL data suggests now that the observed emission was an instrumental artefact (Bloemen, these proceedings), the former “detection” raised the question about the possible existence of a low-energy, C and O enriched cosmic-ray component. Indeed, independent of the COMPTEL result, new observations relating to the Be and B abundances in the early Galaxy support the existence of such a component (e.g. Gilmore et al. 1992; Duncan et al. 1992; Cassé et al. 1995). A mechanism revived to explain low-energy C and O rich cosmic-rays has been the acceleration of particles in a superbubble resulting from the intense energetic activity of an OB association inside a molecular cloud (Bykov & Bloemen 1994; Parizot 1998). Strong stellar winds and supernova (SN) explosions fill the superbubble with both energy and enriched material to be accelerated by the numerous secondary shocks and by magnetic turbulence resulting from the interaction of shock waves (from winds and SNe) with each other and with dense clumps inside the bubble (Bykov & Toptygin 1990; Bykov & Fleishman 1992). The resulting energy spectrum is expected to be very hard ($\propto E^{-1}$) up to a cut-off energy, $E_0$, of $\sim 100$ MeV/n. As for the chemical composition of the EPs, it is clearly related to the composition of stellar winds and SN ejecta, although some contamination by swept-up and/or evaporated material is likely to occur.

In this paper we calculate the $\gamma$-ray line emission associated with such a sce-
nario. As we believe that the Orion complex associated with the Orion-Eridanus superbubble represents the most favoured target for a detection, we normalise our results to the distance of Orion (450 pc) and the stellar content as inferred from observations of the Orion OB1 association (Brown et al. 1994).

2. BASIC INGREDIENTS OF THE MODEL

The first step in our model calculation consists in the evaluation of the enrichment of the superbubble by stellar winds and SN ejecta as a function of bubble age. For this purpose we follow the evolution of a coevally formed OB association, characterised by an IMF of slope $\Gamma$. The enrichment is calculated using the stellar yield compilation of Portinari et al. (1998) who combined the Padova stellar evolutionary models with SN models of Woosley & Weaver (1995). Additionally, yields for the production of radioactive $^{26}$Al have been taken from Meynet et al. (1997), Woosley & Weaver (1995), and Woosley et al. (1995). To determine the parameters of the superbubble “blown” by the association, we derive the time dependent mechanical luminosity of the OB association from the evolutionary tracks of the Padova group. Using this luminosity, we solve the dynamical equation for a spherical, homogeneous bubble (e.g. Shull & Saken 1995). The characteristic density and temperature of the bubble interior is dominated by the “mass loading” from evaporated gas off the shell. This mass loading dilutes the bubble interior with ambient ISM material which we assume to have solar composition. We calculate the conductive mass evaporation from the shell into the bubble by solving the equation of classical, unsaturated conductivity (e.g. Shull & Saken 1995). Even if we disposed of reliable stellar evolutionary tracks giving the composition of the winds and the SN ejecta, we would still have to evaluate the mixing of the ejecta with the evaporated ISM. To avoid such a hazardous attempt, we consider two extreme scenarios, in which the EPs are made of the stellar ejecta alone (models P), or a perfect mixture of the ejecta and the evaporated ambient material (models D).

The second step of our calculation consists of accelerating the enriched material within the superbubble assuming a constant acceleration rate during a time $\tau_0$ following each SN explosion. The EP spectrum is thus normalised so that the energy injection rate $\dot{E}$ is equal to $E_{SN}/\tau_0$, where $E_{SN} \equiv 10^{51} \text{ erg}$ is the SN energy. To calculate the time scale $\tau_0$, we assume that each new supernova influences and provides energy to a region of size $L$ around its explosion site, in which particles are accelerated with an efficiency $\eta \sim 10^{-3}$ (Bykov and Fleishman 1992; Parizot 1998). Further assuming that the extension of the region in which particles are accelerated increases as $L = v_A t$, where $v_A \simeq 200 \text{ km/s}$ is the Alfvén velocity, we find that the total energy injected in the form of EPs after time $t = \tau_0$ is $E_{EP} = \eta n_b \frac{4}{3} \pi v_A^3 \tau_0^3 \langle E \rangle$, where $\langle E \rangle$ is the mean EP energy, averaged over the assumed spectrum, and $n_b$ is the density of the superbubble interior. Equating $E_{EP}$ to $E_{SN}$, we obtain an estimate for $\tau_0$, which we then use to normalise the EP spectrum and thus the $\gamma$-ray fluxes. For typical values of $\langle E \rangle = 100 \text{ MeV/n}$ and $n_b = 10^{-2} \text{ cm}^{-3}$, we obtain $\tau_0 \sim 10^5 \text{ years}$, corresponding to an acceleration power of $\sim 3 \times 10^{38} \text{ erg/s}$. As
argued by Bykov and Fleishman (1992), the energy spectrum of the EPs depends on their feedback over the magnetic turbulence and the shock waves system inside the bubble. Any detailed calculation of this spectrum being out of the scope of this paper, we consider here the cut-off energy, $E_0$, as a free parameter with values in the range $3 - 3000$ MeV/n.

3. APPLICATION TO ORION AND DISCUSSION

The evolution of the Orion-Eridanus superbubble composition and the predicted $\gamma$-ray line emission is summarised in Fig. 1. On the one hand we populated the IMF using Monte Carlo samples that are compatible with the present Orion population (Brown et al. 1994). On the other hand we studied the academic case of an ‘analytic’ stellar population where the IMF is densely populated by ‘fractional’ stars. While the latter case provides the average $\gamma$-ray line emission, the Monte Carlo sampling gives us the possible scatter around this average.

Our models predict 4.44 and 6.13 MeV $\gamma$-ray line fluxes of the order of a few $10^{-5}$ ph cm$^{-2}$s$^{-1}$, i.e. around the expected threshold of SPI for broadened lines (Jean 1996). We want to emphasise that this value is only an order of magnitude estimate due to the intrinsic uncertainties in our simplified model. Nevertheless, the result indicates that Orion is still an interesting target for the observation of $\gamma$-ray excitation lines due to its proximity and star formation activity. Our model predicts an $^{26}$Al production around $10^{-4} M_\odot$, corresponding to 1.809 MeV line fluxes of $\sim 6 \times 10^{-6}$ ph cm$^{-2}$s$^{-1}$. This is compatible with the upper limit of COMPTEL (Oberlack et al. 1995), and again is at the detection threshold of SPI. In particular, the observation of either the 1.809 MeV line or the excitation lines (or both) will severely constrain the model parameters and hence provide important information about shock induced particle acceleration.

Among the most interesting observables is the $^{12}$C*/$^{16}$O* line ratio. For ejecta mixed with the evaporated ISM, the ratio is always very close to the solar value.
\( \sim 0.76 \) for \( E_0 = 100 \text{ MeV/u} \). For pure ejecta, this ratio may deviate significantly from the solar value, with values depending on the presence of a very massive star \((M \geq 50M_\odot)\) in the association (like in simulation MC1). However, \(^{12}\text{C}*/^{16}\text{O}^*\) is also very sensitive to the cut-off energy \(E_0\) due to the different energy dependencies of the excitation cross sections (cf. Fig. 2). Additionally, for \(E_0 < 20 \text{ MeV/n}\) the acceleration time scale \(\tau_0\) becomes too long, and hence the injection power too small, for significant \(\gamma\)-ray line emission. The ambiguity of interpreting a given line ratio from the 3D-space of parameters \((E_0, \text{association age}, \text{dilution})\) may be removed by jointly studying additional line ratios, e.g. LiBe*/\(^{16}\text{O}^*\) (where LiBe* refers to the so-called Li-Be feature around 450 keV). We will discuss the expected correlations in a separate paper where we also give more detailed information about the modelling procedure (Parizot & Knödlseder 1999, in preparation).

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