Astron. Astrophys. 331, 726–736 (1998)

ASTRONOMY AND ASTROPHYSICS

The Orion Gamma-ray emission and the Orion-Eridanus bubble

Etienne M.G. Parizot

Service d'Astrophysique, CEA/DSM/DAPNIA, F-91191 Gif-sur-Yvette, France

Received 30 June 1997 / Accepted 13 October 1997

Abstract. We review the implications of the gamma-ray emission detected by COMPTEL in Orion, assuming that it is due to energetic particle (EP) interactions within the Orion clouds. We show that a series of independent arguments converge toward a model in which the EPs originate from the Orion-Eridanus bubble, located in front of the molecular cloud complex. We investigate in detail the question of energetics, introducing new indicators such as the total energy and the total mass of the EPs, and show that the average density of the EP confining region is a crucial parameter for any model of the Orion emission. Finally, we compare two extreme situations, where the EPs fill either the whole Orion-Eridanus bubble or a limited volume around the site of a recent supernova explosion in the Orion OB1 association. We conclude that the COMPTEL emission could be explained self-consistently by a hybrid solution in which a new supernova explodes within the energetic superbubble, propitious to particule acceleration. Possible generalisation to other Galactic sites is also investigated.

Key words: Gamma rays: theory – Nuclear reactions – ISM: individual objects: Orion clouds, Orion-Eridanus bubble – associations: individual: Orion OB1

1. Introduction

Bloemen et al. (1994; 1997a) have reported the detection by COMPTEL of a gamma-ray emission with unexpected intensity in the direction of the Orion molecular cloud complex. Many papers have been devoted to the origin and implications of this emission, in relation with various fields of astrophysics, such as gamma-ray line production (Bykov & Bloemen, 1994; Ramaty et al., 1995; Cowsik & Friedlander, 1995; Ramaty, 1996; Parizot et al., 1997a), spectroscopy (Bykov et al., 1996; Tatischeff et al., 1996; Ramaty et al., 1997a), spallation nucleosynthesis (Cassé et al., 1995; Bykov, 1995; Fields et al., 1996; Ramaty et al., 1996) and particle acceleration (Ip, 1995; Bykov, 1995; Miller & Dermer, 1995). Although different models have been proposed, including radiation from a distant quasar in the line of sight of Orion (Pohl, 1996), thermal emission in the accretion columns of neutron stars (Bykov & Bloemen, 1997) or electron Bremsstrahlung emission (Dogiel et al., 1997), it seems plausible that the Orion gamma-ray emission is due to non thermal processes, in which accelerated ions interact with the Orion molecular clouds to produce C and O nuclear de-excitation lines at 4.44 and 6.13 MeV, respectively. This interpretation provides a general understanding of most of the observational data, and may be regarded as the 'standard paradigm' for the Orion gamma-ray emission.

However, many questions remain to be answered, like: Where do the energetic particles (EPs) come from? What is the acceleration mechanism and what is it powered by? What are the energy spectrum and the composition of the EPs? What is their confining volume? Are there other similar sources in the Galaxy? For example, the EPs could be accelerated by multiple shock waves and magnetic turbulence in the vicinity of OB associations (Bykov & Bloemen, 1994; Bykov, 1995), in black hole accretion disks with cascading Alfvén wave turbulence (Miller & Dermer, 1995), in T-Tauri protostellar winds (Ip, 1995) or in the strong winds of massive stars (Nath &Biermann, 1994; Parizot et al., 1997b). It has also been proposed that the EPs interacting within the Orion molecular cloud complex were made of the most energetic nuclei ejected by a recent supernova (Fields et al., 1996; Cameron et al., 1995; Parizot et al., 1997c).

In this paper, we stay within the framework of the standard paradigm (EP interactions) and try to clarify the above questions. We present arguments in favour of a link between the Orion gamma-ray emission and the Orion-Eridanus superbubble, as already suggested by some authors (Bykov & Bloemen, 1994; Ramaty et al., 1997a; Parizot et al., 1997a), and pay particular attention to the energetics. Indeed, it was realised at once (e.g. Ramaty et al. 1995,1996) that the observed fluxes imply a very large power dissipation at Orion, due to the Coulomb losses of the energetic particles responsible for the gamma-ray emission. Even for the most favourable composition and energy spectrum, the EPs lose more than $2\,10^{38}$ erg s^{-1} within the Orion clouds. This represents an energy consumption of 10^{51} ergs in only $1.6\,10^{5}$ years, which requires very energetic and/or very recent events. However, precedent studies have only been interested in the energy loss rate, which is independent of the interaction region density. In this paper, we introduce other energetics indicators, such as the total energy carried by the EPs, and discuss their relevance to the study of the Orion gamma-ray

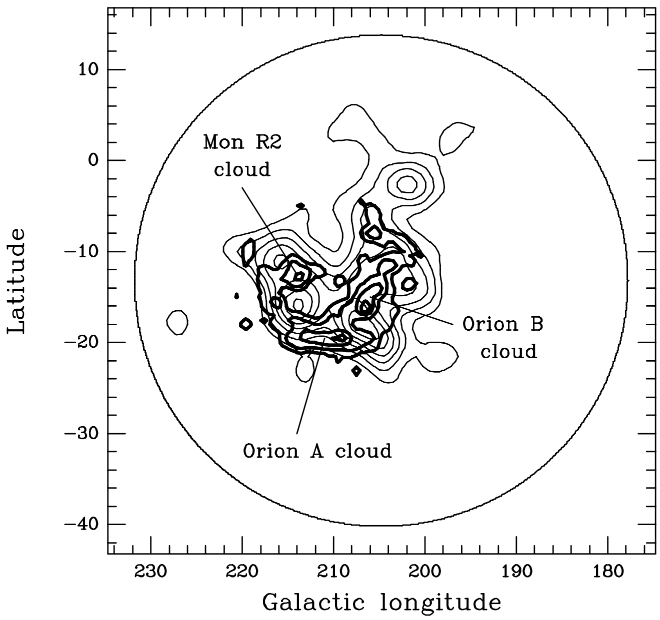

Fig. 1. Maximum likelihood map (in Galactic coordinates) of the Orion/Mon region, observed by COMPTEL in the 3–7 MeV band, with CO observations (Dame et al. 1987) superimposed (bold line). From Bloemen et al. (1997).

emission. In particular, we identify the average density of the EP confining region as a crucial parameter, and show how it can help to discriminate between specific models.

Sect. 2 provides a review of the situation, emphasizing the observational constraints which we use as arguments in the following. We also present briefly the interaction model that we use, in the framework of the standard paradigm. In Sect. 3, we address the question of the origin of the Orion EPs, and show that the Orion-Eridanus bubble gathers all the characteristics required by the different observational and theoretical constraints. We then define and discuss in Sect. 4 different energetics indicators, and apply them to the study of specific models in Sect. 5. Finally, in Sect. 6, we gather the results of the preceding sections and propose a self consistent model for the Orion gamma-ray emission. We also discuss possible generalisation to other sources.

2. General analysis

2.1. The Orion gamma-ray emission

Fig. 1 shows the 3–7 MeV maximum likelyhood ratio map obtained by COMPTEL, onboard *CGRO*, for the Orion gamma-ray emission (Bloemen et al., 1997a). The superimposed CO observations show a global correlation with the Orion/Mon R2 molecular clouds, strongly suggesting that these clouds are actually the source of the gamma-ray emission. However, we note that at smaller scales the CO and gamma-ray data show a striking anti-correlation, which has to be understood as well. While the source is clearly extended, the COMPTEL angular resolution (0.5–1°) does not allow one to exclude that it is made of several point sources spread over the emission region.

The total flux in the 3–7 MeV band is estimated at $(1.01 \pm 0.14)\,10^{-4}\,\mathrm{ph\,cm^{-2}s^{-1}}$, while only upper limits are set at other COMPTEL energies, in the bands 0.75–1 MeV, 1–3 MeV and 7–30 MeV (Bloemen et al., 1997a). More detailed gamma-ray spectra have also been given, but they should be considered only as indicative, because of the uncomplete deconvolution and systematic uncertainties, as explained in Bloemen et al. (1997a). Nevertheless, narrow energy bin spectra show significative structures, with one main peak slightly above 4 MeV, and two lower peaks slightly below 6 and 7 MeV. These structures, together with the absence of any flux detected between 1 and 3 MeV (nor above 7 MeV), represent the best argument in favour of a non continuum, gamma-ray line emission. The proximity of the peak energies with the ^{12}C and ^{16}O de-excitation lines at 4.44 and 6.13 MeV, respectively, further tempts one to identification.

Splitting of broad gamma-ray lines has also been proposed to account for the detailed structures of the emission spectrum (Bykov et al., 1996), with possible suppression of the blue wings due to the geometry of the EP interaction region (Ramaty et al., 1997a).

2.2. The standard paradigm

The Orion gamma-ray emission is commonly attributed to de-excitation reactions of C and O nuclei, principally, following upon nuclear interactions induced by energetic particles (EPs) in the molecular cloud complex. Given the energy spectrum $N_i(E,t)$ for EPs of species i, one calculates the production rate of photons γ from the interaction $i + j \to \gamma$ as:

$$\frac{\mathrm{d}N_\gamma}{\mathrm{d}t} = \int N_i(E,t)\,v(E)\,n_j\,\sigma_{ij;\gamma}(E)\,\mathrm{d}E\,, \qquad (1)$$

where $\sigma_{ij;\gamma}$ is the cross section for the process considered, and $n_j = \alpha_j \langle n\rangle$ is the number density of element j in the interaction region (target). Here, $\langle n\rangle$ denotes the target mean density, and α_j is the abundance of element j. The total flux emitted in a given nuclear de-excitation line at energy E_γ is then obtained by summing over all the production channels, via both direct excitations and spallation reactions involving heavier nuclei.

The calculation of the emitted gamma-ray flux requires the knowledge of the energy spectrum (or phase space density) $N_i(E,t)$ for each EP species. It is generally assumed that one single spectral shape describes all the EPs, with relative abundances derived from the so-called source composition. This refers to the composition of the EPs when they leave the acceleration process. Note that it might be different from the composition of the particles entering the said process if the acceleration efficiency depends on the ion species (Ellison et al., 1981; Ellison et al., 1997; Miller & Dermer, 1995).

We note $Q_i(E,t) = \alpha_i\,\bar{Q}(E,t)$ the source spectrum, i.e. the spectrum of the EPs entering the interaction region. As the EPs propagate within the Orion clouds, their spectrum and relative abundances are affected by species–dependent Coulomb losses, according to the well-known transport equation:

$$\frac{\partial}{\partial t}N_i(E,t) + \frac{\partial}{\partial E}(\dot{E}_{\mathrm{ion},i}(E)N_i(E,t)) = Q_i(E,t) - \frac{N_i(E,t)}{\tau_i}\,, \quad (2)$$

where $\dot{E}_{\mathrm{ion},i}(E)$ is the ionisation energy loss rate of nuclei i in the target, and τ_i is their total lifetime against catastrophic losses (escape, nuclear destruction and/or decay). In the steady-state approximation, we have:

$$N_i(E) = \frac{1}{\left|\dot{E}_{\mathrm{ion},i}(E)\right|} \times \int_E^{+\infty} Q_i(E_0)\,\exp\left(-\frac{1}{\tau_i}\int_{E_0}^{E}\frac{\mathrm{d}E'}{\dot{E}_{\mathrm{ion},i}(E')}\right)\mathrm{d}E_0. \quad (3)$$

In principle, we should be able to calculate the source spectrum and the source composition from the analysis of the astrophysical conditions in the region considered. However, the acceleration processes are still poorly known, and moreover, we do not know where the acceleration takes place. All we can do is thus to use the various observational constraints as indications of the ongoing processes, and in turn propose a self consistent model.

2.3. Constraints on the EP composition

In their original paper, Bloemen et al. (1994) have indicated that the EPs responsible for the Orion gamma-ray emission must be exceptionally enriched in C and O nuclei, principally for energetics reasons. As a consequence, the gamma-ray lines are produced mainly by inverse processes, i.e. by interaction of heavy EPs (C and O) with ambient protons and α-particles. A distinctive feature of inverse processes is that they lead to broad de-excitation lines, contrary to direct processes (interaction of light EPs, i.e. p and α, with ambient C and O). The spectral analysis is not yet fully deciding, but it also seems to favour EP compositions enriched in C and O.

Another decisive argument has been presented by Ramaty et al. (1995). If the EPs were not especially poor in protons and α-particles, they would excite nuclei from Ne to Fe in the target medium, and produce gamma-ray de-excitations lines in the range 1–3 MeV, violating the COMPTEL upper limit. This is a very strong argument, since it relies only on the assumption that the Orion emission is induced by EP interactions (standard paradigm). In particular, it excludes source compositions such as that of the solar system (SS), cosmic ray source (CRS) or ejecta of supernovae (SNe) with mass $M_{in} \leq 35\,\mathrm{M}_{\odot}$ (Ramaty et al., 1996). On the other hand, very specific compositions are allowed: ejecta of a massive SN (e.g. 60 $\mathrm{M}_{\odot}$; SN60), late phase wind of a Wolf-Rayet star of spectral type WC (late-WC), pick-up ions resulting from the breakup of interstellar grains (GR) (Ramaty, 1996), mean wind of a massive star, or of a whole OB association (Parizot et al., 1997a). This suggests that the Orion gamma-ray emission is somehow related to the activity of massive stars. However, we stress that the constraint actually concerns the composition of the EPs at the end of the acceleration process, which could be different from the 'seed composition' if selective acceleration occurs. We took this possibility into account by investigating mean-wind compositions (OB) with enhancement of the metal abundances by a factor of 3 (OB+) and 10 (OB++).

2.4. Constraints on the EP spectrum

Concerning the EP source spectrum, $\bar{Q}(E)$, one can infer from observations that it is hard, up to a break energy between 10 and 100 MeV/n. Indeed, most of the energy should be concentrated in high energy particles, since nuclei with energy lower than the excitation thresholds (a few MeV/n) do not produce gamma-rays, but contribute to the power dissipated within the Orion complex, which is very high, as already mentioned. On the other hand, if the EP spectrum extended up to hundreds of MeV/n, then π^0 pions would be overproduced in the Orion clouds, leading to a continuum gamma-ray flux around 1 GeV incompatible with EGRET observations (Bloemen et al., 1994; Cowsik & Friedlander, 1995). This unambiguous argument sets an upper limit of 100 MeV/n to the EP source break energy (Ramaty et al., 1997b, for a recent and detailed account of this question).

Clearly, any complete model of the Orion gamma-ray emission should explain such a cut-off. It is worth recalling in particular that single shock wave acceleration cannot satisfy this constraint, the expected break energy being higher than $\sim 10^{12}$ eV for any reasonable set of parameters (Ellison, private communication). However, it is possible that what we call the source spectrum, i.e. the spectrum of the EPs entering the interaction region, is different from the spectrum of the EPs leaving the acceleration process. If the acceleration takes place outside the interaction region, the spectrum may be affected while the EPs find their way onto it, with leakage of the most energetic particles.

Bykov & Fleishman (1992a; 1992b) have presented a model for particle acceleration in superbubbles produced by the intense wind and SN activity of OB associations. Interestingly enough, the resulting energy spectrum is compatible with the above requirements (Bykov, 1995), and very similar to the spectra generally adopted on phenomenological grounds (Cassé et al., 1995; Ramaty, 1996). This might be thought of as an indication of the processes at work in Orion. For convenience, we shall use a similar source spectrum depending on one single parameter:

$$\bar{Q}(E) = \left(\frac{E}{E_0}\right)^{-1.5}\exp\left(-\frac{E}{E_0}\right)\,, \quad (4)$$

allowing the break energy E_0 to vary from 2 to 100 MeV/n.

3. Where do the EPs come from?

The above overview allows one to draw an important conclusion: the EPs interacting in Orion represent an energetic component distinct from the ordinary Galactic cosmic rays (GCRs). Indeed: i) they are much richer in C and O, ii) they have a different energy spectrum, with a characteristic energy of order 30 MeV/n (instead of 1 GeV/n for the GCRs), and iii) their energy density is at least ten times higher (Ramaty, 1996), and probably much more (see below, Sect. 4). So, what is the origin of the Orion EPs?

3.1. Internal source?

Since the gamma-ray emission follows the Orion clouds, it may seem natural that the EPs are accelerated inside, but we show here that this is unlikely. The point is that the EPs cannot travel far from their injection site. The lifetime of C and O nuclei of a few tens of MeV/n against ionisation energy losses is rather small in a dense media. For initial energies in the energy range of interest (10–100 MeV/n), we calculated the time spent by the different nuclei above the nuclear excitation thresholds, $E_{\rm th}$, and obtained the following fit:

$$\tau_{{\rm ion},i}(E) \equiv \int_E^{E_{\rm th}} \frac{{\rm d}E'}{\dot{E}_{{\rm ion},i}(E')}$$
$$\sim (9.3\,10^3\ {\rm yr})\,\frac{A_i}{Z_i^2}\left(\frac{E}{20\,{\rm MeV/n}}\right)^{1.39}\left(\frac{n_0}{100\,{\rm cm}^{-3}}\right)^{-1}, \quad (5)$$

where n_0 is the Orion density ($\geq 100\,{\rm cm}^{-3}$) and A/Z^2 equals 1/3 for ^{12}C nuclei, and 1/4 for ^{16}O nuclei. Consequently, the EPs have only a few 10^3 years (or 10^2 years if $n_0 = 10^3\ {\rm cm}^{-3}$) to diffuse away from their injection site, and cannot go further than a distance:

$$L_i(E) \equiv \sqrt{D(E)\,\tau_{{\rm ion},i}} \sim (1.8\,{\rm pc})\,\frac{A_i}{Z_i^2}\left(\frac{D}{10^{26}\,{\rm cm^2 s^{-1}}}\right)^{\frac{1}{2}}$$
$$\times\left(\frac{E}{20\,{\rm MeV/n}}\right)^{0.7}\left(\frac{n_0}{100\,{\rm cm}^{-3}}\right)^{\frac{-1}{2}}, \quad (6)$$

where $D(E)$ is the diffusion coefficient in the Orion clouds.

Since the Orion gamma-ray source is extended, one can conclude from this low value of the diffusion length that if the EPs originate from an internal source, then there must be actually several sources. Moreover, according to Eq. (5), all of these sources have to be recent (a few thousand years). Now this seems very difficult to achieve within the standard paradigm. Indeed, the energetics is very constraining. As shall be shown in Sect. 4, the EPs lose more than 2 10^{38} ergs every second in Orion. This means that some mechanism provides as much power either to re-inject EPs at energies above the nuclear thresholds, or to reaccelerate the initial EPs so as to maintain their energy above the thresholds. Large energy release is known to accompany the activity of massive stars (strong winds of WR stars, SN explosions), but the time scales implied by Eq. 5 are too short, as there is no evidence for a SN explosion in Orion in the last 10^4 years - especially not several of them ! Neither is any currently active WR star.

Note that if reacceleration takes place within the Orion clouds, so that the EP energy never drops below the excitation thresholds, the effective time scales for nuclear interactions can be lengthened. However the lifetime of energetic C and O nuclei cannot exceed their destruction time, τ_D, which is given in Table 1 for different values of the ion energy (using inelastic cross-sections from Silberberg & Tsao, 1990). These time scales are still short if one needs several distinct sources, and again, there is not enough power in the magnetic turbulence or in stellar winds ($\sim 10^{37}$ erg s^{-1}; Brown et al., 1994) to ensure reacceleration. One should therefore think of other sources of energy, such as gravitation. Accretion on black holes or neutron stars, for example, are known to involve powers comparable to the Eddington luminosity ($\sim 10^{38}$ erg s^{-1}). Several of these objects could therefore be at the origin of the Orion gamma-ray emission, as recently suggested by Bykov and Bloemen (1997).

Table 1. Destruction time of C and O nuclei in a medium of mean density 100 cm^{-3} ($\tau_D \propto \langle n\rangle^{-1}$).

Energy	C	O
10 MeV/n	2.9 10^5 yr	2.4 10^5 yr
30 MeV/n	1.2 10^5 yr	9.4 10^4 yr
100 MeV/n	1.0 10^5 yr	8.4 10^4 yr

3.2. External source?

Apart from re-accelerating the EPs or re-injecting new ones, another possibility is to dispose of a huge reservoir of EPs to draw on. As seen from the Orion clouds, this is actually a kind of re-injection, but from the outside. One advantage of this situation is that the external source doesn't have to be active now, which would raise again the problem of energetics. It suffices that enough energy was released in the past, and that the EPs keep on reaching the Orion clouds, at the rate imposed by their diffusion from the actual source. Of course, in order that the EPs survive against energy losses and nuclear destruction until they interact with the cloud material, the reservoir has to have a low density. Now such a reservoir exists close to Orion: it is the Orion-Eridanus superbubble (see below).

An other appeal of the external source scenario is that it accounts naturally for the extension of the gamma-ray source. Indeed, if the pool of EPs is as large as (or larger than) the Orion clouds A and B, the irradiation takes place over their whole surface, resulting in the observed global correlation with the CO contours (see Fig. 1). Moreover, the detailed anti-correlation mentioned in Sect. 2.1 may find an explanation in that the small diffusion length discussed above is translated here into a small penetration length. This implies that the EPs encounter the Orion clouds only superficially. As a consequence, the gamma-ray emission is (in this scenario) proportionnal to the irradiated surface, while the CO observations are related to the total amount of matter, i.e. to the volume. The gamma-ray/CO anti-correlation would thus result from the basic surface/volume (limb/center) anti-correlation of clouds. Besides, this effect should be significanty enhanced in Orion, because of the very clumpy and filamentary structure of the molecular complex (Gentzel & Stutzki, 1989).

The surface irradiation of the Orion clouds is also required from an independent argument: the volume deposition of a power as high as a few times $10^{38}\,\mathrm{erg\,s^{-1}}$ would indeed imply an ionisation rate higher than allowed by astrochemistry (Bloemen et al., 1994; Ramaty et al., 1996; Dogiel, 1996).

Finally, Ramaty et al. (1997a) have argued that the detailed structure of the Orion gamma-ray emission spectrum may be explained by an irradiation geometry in reservoir the EP source is located outside the molecular clouds, and in front of them in the line of sight.

3.3. The Orion-Eridanus bubble

All the above arguments against an internal origin of the EPs as well as in favour of a large pool outside, and more precisely in front of the Orion clouds, find a fortunate convergence in the evocation of the Orion-Eridanus (super)bubble. It was first observed in H_α (Sivan, 1974), with shell structures extending all the way from the

arnard's loop, around the Orion clouds A and B, to 50 degrees below the Galactic plane, in the Eridanus constellation. It consists of a cavity filled with hot ionised gas and surrounded by an expanding shell of neutral hydrogen, most certainly related to the strong stellar wind and SN activity of the Orion OB1 association (Reynolds & Ogden, 1979; Burrows et al., 1993; Brown et al., 1994; Brown et al., 1995). The bubble is located in front of the Orion clouds A and B, at about 350 pc from the Sun, and $\sim$ 150 pc below the Galactic plane. Its present size ($R \sim 140$ pc) and expanding velocity ($15-20\,\mathrm{km\,s^{-1}}$) allow one to estimate its age, $\sim 5\,10^6$ years, and energy, $\sim 2\,10^{52}$ ergs, in very good agreement with theoretical expectations based on stellar evolution calculations.

So we dispose of a lot of energy at the right place (close to, and in front of the Orion complex), in a medium with sufficiently low density ($\sim 10^{-2}\mathrm{cm}^{-3}$) for the possible EPs to survive until they interact with the Orion cloud material, and we dispose in addition of a natural acceleration mechanism. Indeed, superbubbles are known to convert a significant fraction of their free energy into low-energy cosmic rays, with spectra very similar to that required by the observations recalled above (Bykov &Fleishman, 1992a; Bykov &Fleishman, 1992a, Sect. 2.4).

Finally, the Orion-Eridanus bubble may provide a natural explanation for the last ingredient of the standard paradigm of the Orion gamma-ray emission: the EP composition. As discussed in detail in Parizot et al. (1997a), the potentially accelerable material in the superbubble is made of the combined wind and SN ejecta from massive stars in the OB1 association. The resulting mean-wind composition is rich in C and O, and was shown to satisfy the various observational constraints, in particular the most relevant band ratio upper limit (1–3 MeV)/(3–7 MeV). This adds to the list of converging arguments pointing to the Orion-Eridanus bubble as the acceleration site of the Orion EPs. However, we still have to turn to the question of energetics, and try to gather further informations on the timescales

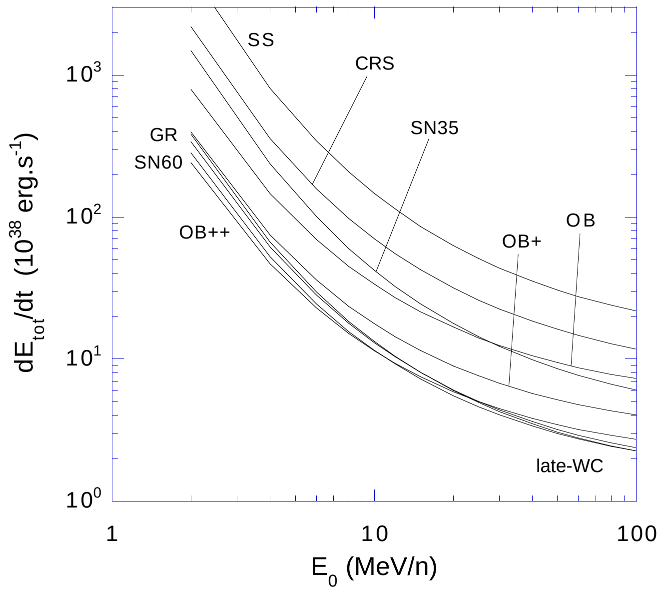

Fig. 2. Ionisation energy loss rates (in units of $10^{38}\,\mathrm{erg\,s^{-1}}$) as a function of the source break energy E_0, for different EP compositions (defined in the text).

of the different processes, as will be needed for purposes of generalisation to other astrophysical sites and possible Galactic emission.

4. The energetics

4.1. The basic indicators

As we already noted, the energetics implied by the Orion gamma-ray fluxes is very substantial. The total power deposited by the EPs is given by:

$$\frac{\mathrm{d}E_{\mathrm{tot}}}{\mathrm{d}t}\bigg|_{\mathrm{ion}} = \sum_i \int N_i(E)v(E)\langle n\rangle \frac{\mathrm{d}E}{\mathrm{d}x}\bigg|_{\mathrm{ion}}(E)\,\mathrm{d}E\,. \qquad (7)$$

Here the discrete sum is over all EP species, $\langle n\rangle$ is the mean density of the interaction region, $v(E)$ is the velocity of the particles, and $(\mathrm{d}E/\mathrm{d}x)_{\mathrm{ion}}$ is the ionisation energy loss per $\mathrm{g\,cm^{-2}}$.

Comparing Eqs. (1) and (7), we see that both the energy loss rate and the gamma-ray production rate are proportional to the target density. Thus, normalising to the COMPTEL fluxes, one obtains the total power deposited in Orion which depends only on intrinsic characteristics, namely the EP spectrum and the EP composition. Some results are shown in Fig. 2 for different compositions, and with the source spectrum of Eq. (4). We can see that the energy loss rate is lower, or equivalently, the gamma-ray production efficiency is higher for compositions richer in C and O, as well as for spectra extending up to higher energies, because i) more particles are then above the nuclear excitation thresholds, and ii) the ionisation energy losses are lower at higher energy.

Apart from the energy loss rate, it is useful to consider the total energy stored in the Orion EPs, as can be deduced from the observed gamma-ray fluxes. Given the EP phase space density

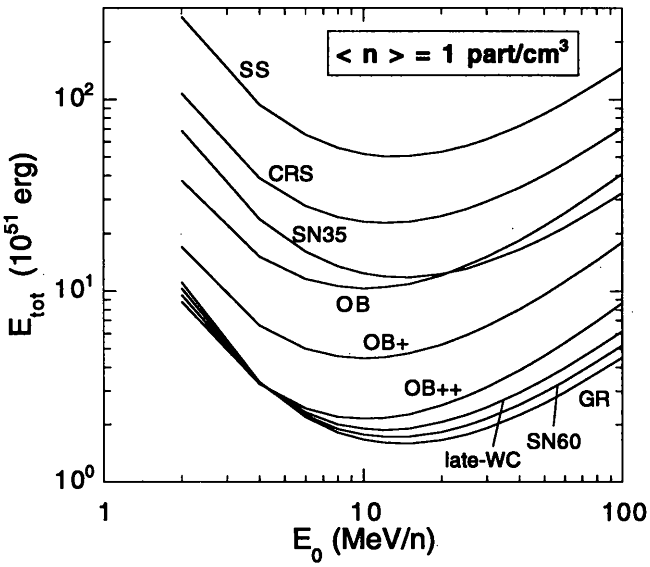

Fig. 3. Total energy stored in the Orion EPs (in units of 10^{51}erg) as a function of the source break energy E_0, for different EP compositions. The values are inversely proportional to $\langle n\rangle$. Here, $\langle n\rangle$ = 1 cm^{-3}.

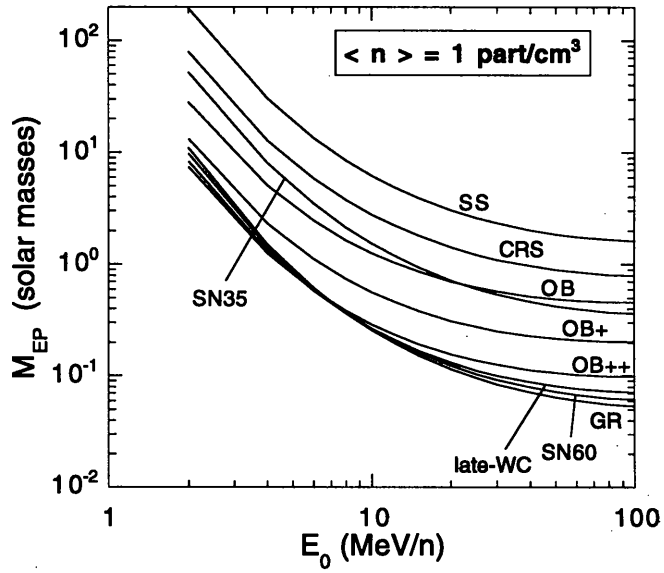

Fig. 4. Total mass of the EPs (in $M_\odot$) necessary to produce the Orion gamma-ray flux between 3 and 7 MeV, as a function of the source break energy E_0, and for different EP compositions.

$N_i(E)$, from which we calculate the gamma-ray emission rate, it is easy to sum over all the EP species and obtain the total energy involved:

$$E_{\rm tot} = \sum_i \int N_i(E)\, A_i\, E\, {\rm d}E. \tag{8}$$

Of course, $E_{\rm tot}$ depends only on intrinsic characteristics of the EPs, notably not on the target density. The values obtained after normalising to the Orion gamma-ray flux therefore depend on the mean density of the interaction region: $E_{\rm tot} \propto \langle n\rangle^{-1}$. Some results are shown in Fig. 3 for $\langle n\rangle$ = 1 cm^{-3}. Qualitatively, the total required energy decreases as E_0 increases up to 10–15 MeV/n, for the same reasons i) and ii) as put forward above in connection with ${\rm d}E_{\rm tot}/{\rm d}t$. However, $E_{\rm tot}$ increases at energies higher than 10 MeV/n, because iii) the averaged particle energy increases, and iv) the peaks of the relevant cross sections are then exceeded and the gamma-ray production efficiency decreases.

Similarly, we calculate the total mass of the EPs necessary to produce the Orion gamma-ray flux:

$$M_{\rm EP} = \sum_i \int N_i(E)\, A_i\, m_{\rm p}\, {\rm d}E\,, \tag{9}$$

Again, $M_{\rm EP}$ is inversely proportional to $\langle n\rangle$. We show the results in Fig. 4.

4.2. The importance of the confining region average density

Comparing Figs. 2 and 3, it appears that what we may consider as the most energetically favourable spectrum actually depends on what we wish to minimise: the power deposited by the EPs, or their total energy. Up to now, ${\rm d}E_{\rm tot}/{\rm d}t$ was the only energetic indicator to be considered. Spectra extending up to high energies were then favoured, because the deposited power, and consequently the energy consumption rate, are about 4.5 times lower for E_0 = 100 MeV/n than for E_0 = 10 MeV/n. However, Fig. 3 shows that, on the other hand, the total energy required in the form of EPs, $E_{\rm tot}$, is 3 to 4 times higher (depending on the composition) for high values of the source break energy than for low values. Now this may be very discriminating. Indeed, if the average density of the EP confining region (including the interaction region) is $\langle n\rangle$ = 1 cm^{-3}, as in Fig. 3, then the total energy required in the case when the EPs have a mean-wind (OB) composition is greater than 10^{52} erg - equivalent to 10 supernovae ! Even with the most extreme composition (GR), more than 2 10^{51} ergs are required. To this extent, the prefered spectra would certainly be those with a low source break energy ($\sim$ 10 MeV/n). Furthermore, if the confining average density were that of the Orion-Eridanus superbubble ($\langle n\rangle$ = 10^{-2} cm^{-3}), the energy required would still be 100 times higher, which is just excluded, for obvious reasons. The mean density thus appears to be a very important parameter.

Combining both energetics indicators, the total EP energy, $E_{\rm tot}$, and its time derivative, ${\rm d}E_{\rm tot}/{\rm d}t$, we calculate the energy exhaustion time scale, defined by:

$$\tau_{\rm ex} = \frac{E_{\rm tot}}{{\rm d}E_{\rm tot}/{\rm d}t}\,. \tag{10}$$

The results are shown in Fig. 5, for $\langle n\rangle$ = 1 cm^{-3} ($\tau_{\rm ex} \propto \langle n\rangle^{-1}$). Again, it appears that what we may consider as the most energetically favourable composition depends on the constraints we set ourselves. For example, given an ambient average density $\langle n\rangle$, the available EP energy will be consumed quicker if the EPs have the late-WC composition than if they have the mean-wind (OB) one. This is just the contrary of what we would conclude considering only the energy loss rate ${\rm d}E_{\rm tot}/{\rm d}t$ (see Fig. 5), and

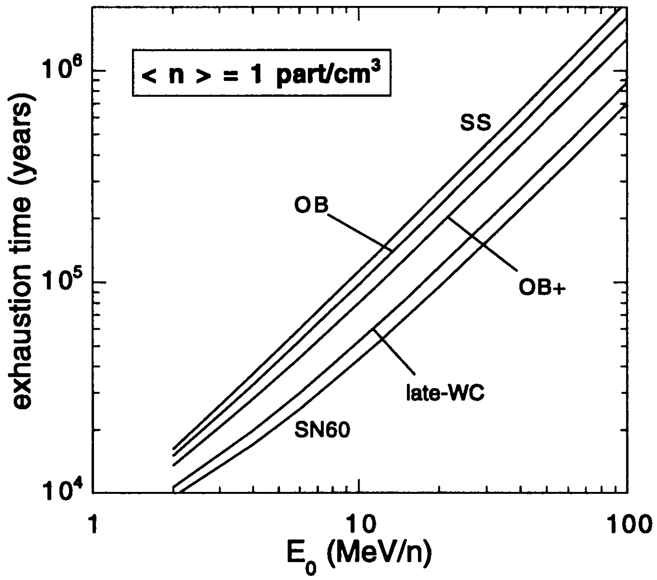

Fig. 5. Time for the complete consumption of the EP energy as a function of the source break energy E_0, for different EP compositions.

giving ourselves an initial EP energy, $E_{\rm tot}$. This apparent paradox is again due to the important role of $\langle n\rangle$. Given $E_{\rm tot}$, the late-WC composition indeed allows for a lower value of $\langle n\rangle$, which in turn lengthens the EP exhaustion time $\tau_{\rm ex}$.

To be more quantitative, we give the following fit for $\tau_{\rm ex}$, in the case of a mean-wind composition:

$$\tau_{\rm ex} \sim (1.0\,10^5\ {\rm yr}) \left(\frac{E_0}{10\,{\rm MeV/n}}\right)^{1.27} \left(\frac{\langle n\rangle}{1\,{\rm cm}^{-3}}\right)^{-1} . \qquad (11)$$

Taking $100\,{\rm cm}^{-3}$ as the Orion mean density, we have $\tau_{\rm ex}$ = 1-2 10^3 yr, which is very short as compared to the mean time separating two SN explosions in the Orion OB1 association, evaluated around 5 10^5 years (Cowie et al., 1979). This suggests that the average density of the EP confining region is much lower than that of the Orion clouds themselves, favouring again an external source scenario in which the EPs originate from the low density Orion-Eridanus bubble, and penetrate only superficially into the dense molecular complex.

It emerges from the foregoing that a rigourous study of the Orion energetics should take into account not only the energy loss rate, but also the total energy of the EPs. Moreover, the mean density of the region in which the EPs are confined appears to be a crucial parameter. However, it intervenes in two opposite ways: $\langle n\rangle$ should not be too small, so that the total EP energy is not unreasonably high; but in the other hand, $\langle n\rangle$ should not be too high, because one would then encounter difficulties with the exhaustion time $\tau_{\rm ex}$, which is extremely short. The question which arises is then: are these two constraints compatible?

We show in the following that not only they are compatible within a small range of confining average densities, which is quite remarkable in itself, but the allowed values of $\langle n\rangle$ are just what we would expect in an external source model involving the Orion-Eridanus bubble.

5. Toward a solution of the Orion gamma-ray emission puzzle

5.1. The superbubble model

In Sect. 3, we were led naturally to consider the Orion-Eridanus superbubble as the source of the Orion EPs. However, the preceding section emphasized possible difficulties related to the energetics, so we now turn to the detailed analysis of specific models. We collect the results and display the parameters of different models in Table 2, and we sketch out in Fig. 6 the idealised picture that we use for the Orion-Eridanus region. In particular, we assume that the surface of the Orion clouds facing the superbubble is $S \sim R^2$ = (45 pc)×(45 pc) $\sim$ 2000 pc^2 (Gentzel & Stutzki, 1989), and that the EPs fill the volume $V_{\rm SB} \sim 10^{62}\,{\rm cm}^3$, with a total energy of $\sim$ 2 10^{52} ergs (see Sect. 3.3). This is the gist of what we call the 'superbubble model' (SB).

As discussed in Parizot et al. (1997a), the natural EP composition in this model is the averaged wind composition of a whole OB association (OB). We learn from Figs. 2 and 3 that if E_0 = 10 MeV/n, then $\langle n\rangle$ = $0.52\,{\rm cm}^{-3}$ and ${\rm d}E_{\rm tot}/{\rm d}t$ = 3.4 10^{39} erg s^{-1}. The corresponding energy exhaustion time is 1.9 10^5 years, which is much too short as compared to the age of the bubble ($\sim$ 5 10^6 years). It reaches 8.7 10^5 years if the EP spectrum extends up to 100 MeV/n (see Table 2), but this is still too short. Moreover, the required confining average density is then $\langle n\rangle$ = 2.1 cm^{-3}, which implies that the total mass irradiated by the EPs is $\sim$ 1.2 10^5 M$_\odot$, i.e. $\sim$ 40% of the mass of the Orion clouds. The EPs thus have to penetrate up to $\sim$ 40 pc inside the clouds, which is in opposition with our conclusions of Sect. 3. To be specific, such a penetration length requires a diffusion coefficient of 7 10^{28} cm^2 s^{-1}, which is much higher than expected in the Orion clouds (most certainly lower than 10^{27} cm^2 s^{-1}; Bykov, private communication).

The only way to take advantage of the huge energy in the bubble is thus to lower the energy consumption rate by using an EP composition richer in C and O (in order to allow for a lower $\langle n\rangle$ and increase $\tau_{\rm ex}$). However, the most favoured late-WC composition (see Fig. 2) doesn't appear to be realistic, since it corresponds to the extreme late phase wind of a massive WR star (Ramaty et al., 1995) which represents only a negligeable fraction of the stellar wind ejecta. The same is true for the SN60 composition (Parizot et al., 1997a).

The superbubble model thus requires a selective acceleration mechanism capable of enhancing C and O abundances in the EPs so as to provide an effective composition similar to the late-WC. In that case, and with E_0 = 100 MeV/n (model SB′h; see Table 2), one obtains ${\rm d}E_{\rm tot}/{\rm d}t$ = 2.2 10^{38} erg s^{-1}, and $\tau_{\rm ex}$ = 2.9 10^6 years. This energy exhaustion time is marginally compatible with the age of the bubble. Concerning the total mass of the EPs, we find M_{EP} = 0.23 M$_\odot$, that is $\sim 10^{-3}$ the mass of the superbubble. Such an acceleration efficiency is compatible with theoretical estimates (Bykov & Fleishman, 1992b; Bykov & Bloemen, 1994). Finally the average density of the confining region, $\langle n\rangle$ = 0.31 cm^{-3}, implies that the total irradiated mass is $\sim$ 2 10^4 M$_\odot$, i.e. $\sim$ 7% of the Orion mass. This is compatible with the penetration length calculated from Eq. (6),

Table 2. Parameters and energetics indicators of different models: SB = superbubble, WR = Wolf-Rayet (+ indicates an enhancement of the metal abundances due to a selective acceleration), and SN = supernova. Labels 'l' and 'h' stand for low and high source break energy.

model	$E_{\rm tot}$ (erg)	composition	E_0 (MeV/n)	$\langle n \rangle$ (cm^{-3})	d$E_{\rm tot}$/dt (erg s^{-1})	$\tau_{\rm ex}$ (yr)	$M_{\rm EP}$ (M$_\odot$)
SBl	$2\,10^{52}$	OB	10	0.52	$3.4\,10^{39}$	$1.9\,10^{5}$	2.4
SBh	$2\,10^{52}$	OB	100	2.1	$7.3\,10^{38}$	$8.7\,10^{5}$	0.22
SB′l	$2\,10^{52}$	late-WC	10	0.10	$1.2\,10^{39}$	$5.3\,10^{5}$	2.7
SB′h	$2\,10^{52}$	late-WC	100	0.31	$2.2\,10^{38}$	$2.9\,10^{6}$	0.23
WRl	10^{51}	OB	10	10	$3.4\,10^{39}$	$9.3\,10^{3}$	0.12
WR+l	10^{51}	OB+	10	4.5	$1.8\,10^{39}$	$1.8\,10^{4}$	0.13
WR++l	10^{51}	OB++	10	2.2	$1.1\,10^{39}$	$2.9\,10^{4}$	0.13
WRh	10^{51}	OB	100	41	$7.3\,10^{38}$	$4.3\,10^{4}$	0.011
WR+h	10^{51}	OB+	100	18	$4.0\,10^{38}$	$7.9\,10^{4}$	0.011
WR++h	10^{51}	OB++	100	8.7	$2.7\,10^{38}$	$1.2\,10^{5}$	0.011
SNl	10^{51}	SN60	10	1.8	$1.3\,10^{39}$	$2.4\,10^{4}$	0.15
SNh	10^{51}	SN60	100	5.2	$2.4\,10^{38}$	$1.3\,10^{5}$	0.012

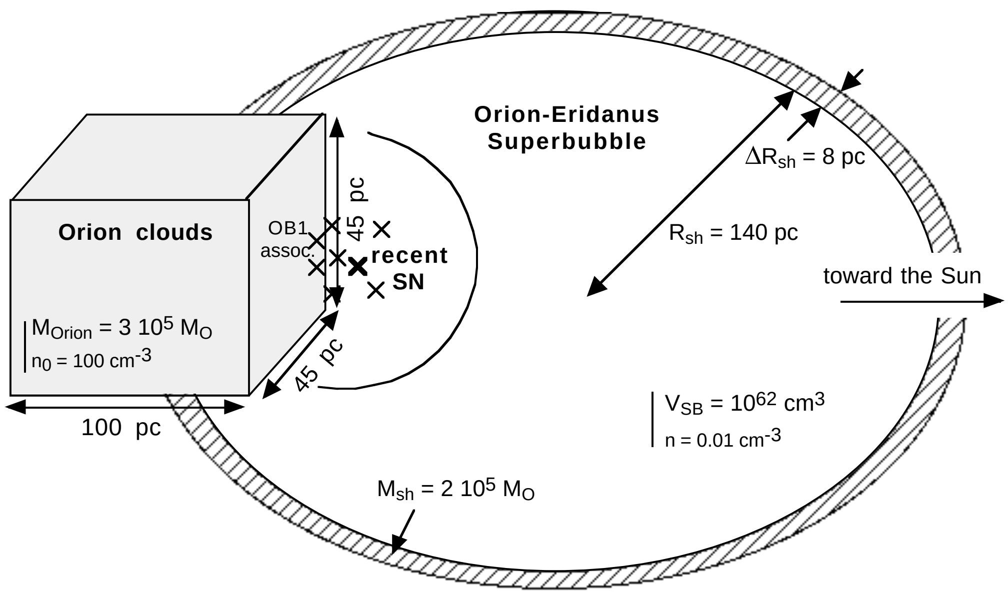

Fig. 6. Idealised sketch of the Orion-Eridanus region, specifying the relevant characteristics and parameters.

provided that the diffusion coefficient in the Orion clouds is $D \sim 1.8\,10^{27}\,\mathrm{cm^2 s^{-1}}$.

The superbubble model then seems to provide a possible, but rather marginal solution. The required values of the parameters ($\tau_{\rm ex}$ and D) are indeed extreme, and a chemically selective acceleration is needed, which is not expected within the superbubble acceleration mechanism proposed by Bykov & Fleishman. Moreover, if the EPs responsible for the Orion gamma-ray emission actually fill the whole Orion-Eridanus bubble, the supershell surrounding it should also be a source of gamma-rays. Indeed, the mass of the shell is approximately equal to that of the Orion clouds, i.e. $M_{\rm sh} = 2.3 \pm 0.7\,10^5\,\mathrm{M_\odot}$ (Brown et al., 1995), and its column density seems to be high enough to stop most of the EPs. Using a shell radius $R_{\rm sh}$ = 140 pc, and a shell thickness $\Delta R_{\rm sh}$ = 8 pc (Reynolds & Ogden, 1979), we obtain an average density $n \sim M_{\rm sh}/(4\pi R_{\rm sh} \times \Delta R_{\rm sh} \times \langle m \rangle) \sim 4\,\mathrm{cm^{-3}}$. Eq. (6) then gives a penetration length of 7.9 pc for particles of 100 MeV/n, and a diffusion coefficient $D = 10^{26}\,\mathrm{cm^2 s^{-1}}$. The thickness of the shell is thus just enough for the EPs to interact with its material, in the very same way as with the Orion clouds.

As a conclusion, the model (SB′h) predicts a gamma-ray emission from the Orion-Eridanus supershell with an integrated flux of the same order of magnitude as that of Orion, and possibly even higher, since i) the whole shell is irradiated, while only a fraction of the Orion clouds is (small penetration length), and ii) in average, the shell is closer to the observer than the Orion clouds (providing a factor of ~ 1.7 on the flux). This prediction actually represents an observational test of the superbubble model.

5.2. The single supernova model

We now turn to an alternative solution, more local, both spatially and temporally, involving one single SN in the OB1 association, exploding outside, but close to the Orion clouds (see Fig. 6). This model is suggested and supported by observation: Cowie et al.

(1979) interpreted UV data in terms of a SN explosion some $3\,10^5$ years ago, and more recently Burrows et al. (1993) claimed for the observational evidence (based on X-ray data) for a SN explosion occuring $\sim 8\,10^4$ years ago in Orion OB1. Ramaty (1996) already refered to the latter as the possible source of the Orion EPs, while Bykov and Bloemen (1994) also assumed implicitely a similar model. In the following, we analyse in detail this 'single supernova model' and examine its parameters, notably the average density of the EP confining region.

As above, we assume that the surface of the Orion clouds facing the bubble is $S \sim R^2 \sim 2000\,\mathrm{pc}^2$, but now the EPs fill a volume $V \sim R^3 \sim 2.5\,10^{60}\,\mathrm{cm}^3$, and have a total initial energy of 10^{51} ergs. Since the Orion density n_0 is much larger than that of the bubble, the average density $\langle n \rangle$ of the confining region is related to the EP penetration length L by:

$$\langle n \rangle \sim n_0 \frac{L}{R} \quad \text{, or} \quad L \sim (0.45\,\mathrm{pc}) \times \langle n \rangle \,. \tag{12}$$

We first assume that the EPs have a mean-wind composition (model WR). As indicated in Table 2, if E_0 = 10 MeV/n, the confining average density is $10\,\mathrm{cm}^{-3}$, which requires a penetration length of $\sim$ 4.5 pc. The diffusion coefficient must then be $\sim 2\,10^{28}\,\mathrm{cm}^2\mathrm{s}^{-1}$, which is very high for the dense Orion clouds. Moreover, the energy exhaustion time scale is $\sim\,10^4$ years, about a factor of 10 smaller than the presumed age of the last SN explosion. Finally, the total mass of the EPs is $0.12\,\mathrm{M}_\odot$ in this model, i.e. $\sim 0.5\%$ of the swept up mass, which implies a very high acceleration efficiency. For a high value of the source break energy (model WRh), τ_{ex} and M_{EP} have more reasonable values, but the required value of D is still high ($1.4\,10^{28}\,\mathrm{cm}^2\mathrm{s}^{-1}$).

As shown in Table 2, compositions enhanced in C and O (models WR+ and WR++) provide much better results. For E = 100 MeV/n, the energy exhaustion time and the total mass of the EPs are consistent with the model expectations, and we obtain $D \sim 7\,10^{26}\,\mathrm{cm}^2\mathrm{s}^{-1}$. However, the use of C-O enhanced compositions is hard to justify theoretically. While the enhancement is natural in the framework of single shock wave acceleration (Ellison et al., 1997), the latter does not provide any break in the energy spectrum (in the energy range of interest). Now such a cut-off is firmly required by the observations (Sect. 2.4). On the other hand, the acceleration mechanism proposed by Bykov and Fleishman (1992a; 1992b) does provide a cut-off in the spectrum, but no particular enhancement of the metal abundances. The above solution therefore seems to be hard to justify within a fully self-consistent model.

However, the single supernova model allows for another possibility, which consists in accelerating the supernova ejecta themselves (model SN). For a $60\,\mathrm{M}_\odot$ SN, the ejecta composition (SN60) was already shown to be roughly compatible with the most constraining band ratio upper limit, (1–3 MeV)/(3–7 MeV) (Ramaty, 1996). We further show in Table 2 that the energetics is fitting as well. If E_0 = 100 MeV/n, we have $\tau_{\mathrm{ex}} = 1.3\,10^5$ years and $M_{\mathrm{EP}} = 0.012\,\mathrm{M}_\odot$, i.e. $\sim 5\,10^{-4}$ times the mass swept up by the SN expanding shell. These values are exactly what is expected from observation and theoretical considerations. As for the required penetration length, we obtain $L = 0.45 \times 5.2 \sim 2.3$ pc, which corresponds to a diffusion coefficient $D = 2\,10^{26}\,\mathrm{cm}^2\mathrm{s}^{-1}$, also in good agreement with the expectations.

In order to stress the coherence of the model, it may be enlightening to reverse the argument in the following way. Suppose that you are quite stroke by the convergence of arguments of Sect. 3 and you wish to investigate the single supernova model for the Orion gamma-ray emission, which is otherwise well supported by observations (recent SN explosion). You will then assume that the ejecta (or a mixture of SN ejecta and ambient wind materials) are accelerated up to a few MeV/n, and diffuse toward the Orion clouds where they produce nuclear excitations. Assuming a reasonable diffusion coefficient within the clouds, it is easy to obtain the average density of the volume occupied by the EPs. You can then ask three questions, independently of the phenomenological study which has already been performed (broad band ratio, line profile, etc.), assuming that the EPs do produce the Orion fluxes: 1) how much energy is carried by the EPs? 2) What is their total mass? And 3) how long can the process last? Note that the answers could a priori be anything. But here is what they are: 1) 10^{51} ergs, i.e. the kinetic energy of a supernova; 2) $10^{-2}\,\mathrm{M}_\odot$, i.e. $5\,10^{-4}$ times the swept up mass; and 3) 10^5 years, i.e. the age of the last supernova in Orion !

6. Conclusion and discussion

In this paper, we have analysed the implications of the Orion gamma-ray emission within the basic assumption that it is due to C and O de-excitation lines produced by interactions of energetic particles (EPs) with the Orion molecular cloud complex. In the framework of this standard paradigm, we have shown that the EPs interacting in Orion cannot be considered as part of the ordinary Galactic cosmic rays, and we therefore addressed the question of their origin. We presented a series of arguments against an acceleration site within the Orion clouds themselves, including geometrical considerations (small diffusion/penetration length), time scales (absence of several energetic events in the last thousands of years), and energetics (not enough power in Orion to compensate the EP energy losses). In addition, we presented independent arguments in favour of an external source of the Orion EPs, based on source geometry (global correlation with the Orion clouds, and detailed anti-correlation with CO observations), EP confining region average density (low enough for the EPs to survive against energy losses and nuclear destruction), astrochemistry (no intense volume irradiation), and gamma-ray spectroscopy (line splitting with blue wing suppression).

All these arguments seem to converge and designate the Orion-Eridanus bubble, located in front of the Orion clouds, as the actual source of the Orion EPs. This is further supported by four important and independent arguments. First, the Orion-Eridanus bubble is known to contain a lot of energy, resulting from the wind and SN activity of the Orion OB1 association. Second, the superbubbles related to OB associations are known to provide a powerful acceleration mechanism. Third, the energy spectrum of the accelerated particles calculated from this mechanism has just the shape required phenomenologically by the observed gamma-ray spectrum. And fourth, the very particular EP composition (required again by the Orion gamma-ray spectrum) finds a natural explanation in the superbubble model, as reflecting the wind composition of evolved massive stars.

Following these general indications, we investigated a few models, paying particular attention to the energetics. To this purpose, we introduced and discussed new energetics indicators, emphasizing the role of the average density of the EP confining region. We identified two distinct and opposite models providing a possible solution of the Orion gamma-ray puzzle: the superbubble model (SB), in which the EPs fill the whole superbubble volume, and the single supernova model (single-SN), in which the EPs are made of the ejecta of a recent supernova accelerated close to the Orion clouds. Both scenarii, however, require rather extreme parameters. The SB model requires a chemically selective acceleration mechanism, and an energy exhaustion time scale only marginally compatible with the age of the superbubble. Note that we have proposed an observational test of this model, which predicts an integrated supershell emission similar to that of Orion. Concerning the single-SN model, all the parameters are well fitting, but a very efficient acceleration is required, with conversion of tens of percents of the SN kinetic energy in EPs. Moreover, the SN ejecta themselves have to be accelerated, which is hard to conceive from an isolated supernova.

These might be seen as definitive arguments against the standard paradigm for the Orion gamma-ray emission (i.e. EP interaction models). However, one may remember the wealth of converging arguments recalled above, and argue that while both SB and single-SN scenarii seem rather extreme, an intermediate solution could provide a very natural explanation of the COMPTEL observations. Indeed, the Orion-Eridanus bubble, with its hot, low density material, large-scale plasma motions and multi shock waves structure, still undoubtedly provides a very energetic environment, propitious to the acceleration of suprathermal particles. Besides, there is strong evidence for a SN explosion in the last 10^5 years. The ejecta of this supernova were eventually injected at high energy inside the favourable bubble, and it is quite reasonable to assume that they were accelerated very efficiently, together with ambient high temperature and/or suprathermal material, benefiting from the energy of the new supernova as well as the 'background energy' of the preceding massive stellar winds and SN explosions responsible for the Orion-Eridanus bubble.

According to this general picture, the Orion gamma-ray line emission would thus be the natural consequence of the conjunction of two basic ingredients: an energetic superbubble involving colliding stellar winds and SN explosions, and a recent W-R strong wind and supernova explosion reheating the surrounding material and injecting new accelerable nuclei within the system. Now such a situation is typical of OB associations, and should therefore be found in other astrophysical sites. For example, the Rosette, in Monoceros, is a well known OB association–molecular cloud pair, with approximately the same mass as Orion, and ~ 5 times more luminous (Williams & McKee, 1997). Its distance (~ 1600 pc) is larger than that of Orion, but it may contribute to the gamma-ray flux detected by COMPTEL. Indeed, it is quite striking that the Mon OB1 and OB2 cloud–association pairs are very well correlated with the part of the COMPTEL emission map that doesn't match with the Orion/Mon R2 clouds (Bloemen et al., 1997a, see their Fig. 1).

In order to generalise to the whole Galaxy, we estimate that the duration of the Orion-like emission is about 10^5 years, to be compared with the $5\,10^5$ years separating two SN explosions in a typical OB association. The mechanism then appears to be intermittent, occuring during about 20% of the OB association and superbubble lifetime. Equivalently, 20% of the Galactic OB associations should currently radiate in MeV gamma-rays. This allows us to evaluate the Galactic diffuse emission at the Orion energies: Williams and McKee (1997) evaluate that there are currently ~ 200 Orion-like objects (i.e. OB associations of the same luminosity coupled with molecular clouds of the same mass) in the Galaxy, and ~ 50 Rosette-like association-cloud pairs. Taking 20 % of 200, we get ~ 40 Orion-like objects in the Galaxy, providing us with a flux of $2\,10^{-5}\,\mathrm{ph\,cm^{-2}s^{-1}}$ if the sources are, say, uniformely distributed along a ring at 5 kpc from the Galactic center. Of course, this has to be considered as a very rough estimate. But such a diffuse emission may well be observed in the future, and perharps already was (Bloemen et al., 1997b). It should be noted that if the shape of the ORION gamma-ray spectrum is actually due to broad line splitting with blue wing suppression (anisotropic interaction model), then the diffuse Galactic emission should have a different spectrum, because in average the cloud and the bubble do not have any prefered orientation with respect to the observer. This is a distinctive prediction, as compared to the neutron star model in which the apparent redshift in the C line is from gravitational origin, and is thus intrinsic.

Acknowledgements. I wish to thank warmly Michel Cassé for stimulating discussions. I am deeply indebted also to Reuven Ramaty, Andrei Bykov and Don Ellison for their pertinent comments on the details of the model.

References

Bloemen H., Bykov A.M., Bozhokin S.V., et al., 1997a, ApJ 475, L25
Bloemen H., Bykov A.M., Bozhokin S.V., et al., 1997b, in C. Winkler, T.-L. Courvoisier, and P. Durouchoux (eds.), The Transparent Universe, ESA SP-382, pp 71–74, ESA Publications Division
Bloemen H., Wijnands R., Bennett K., et al., 1994, A&A 281, L5
Brown A.G.A., de Geus E.J., de Zeeuw P.T., 1994, A&A 289, 101
Brown A.G.A., Hartmann D., Burton W.B., 1995, A&A 300, 903
Burrows D.N., Singh K.P., Nousek J.A., Garmire G.P., Good J., 1993, ApJ 406, 97
Bykov A.M., 1995, Space Sci. Rev. 74, 397
Bykov A.M., Bloemen H., 1994, A&A 281, L1
Bykov A.M., Bloemen H.: 1997, submitted
Bykov A.M., Bozhokin S.V., Bloemen H., 1996, A&A 307 L37
Bykov A.M., Fleishman G.D., 1992a, MNRAS 255, 269
Bykov A.M., Fleishman G.D., 1992b, Sov. Astron. Lett. 18(2), 95
Cameron A.G.W., Hoeflich P., Meyers P.C., Clayton D.D., 1995, ApJ 447
Cassé M., Lehoucq R., Vangioni-Flam E., 1995, Nat 373, 318

Cowie L.L., Songaila A., York, D.G., 1979, ApJ 230, 469
Cowsik R., Friedlander M.W., 1995, ApJ 444 L29
Dame T.M., Ungerechts H., Cohen R.S., et al., 1987, ApJ 322, 706
Dogiel V.A., 1996, Nuovo Cimento C 19, 671
Dogiel V.A., Freyberg M.J., Morfill G.E., Schoenfelder V., 1997, Proc. of the 4th COMPTON Symposium
Ellison D.C., Drury L.O'C., Meyer J.-P., 1997, ApJ in press
Ellison D.C., Jones F.C., Eichler D., 1981, J.Geophys. 50, 110
Fields B.D., Cassé M., Vangioni-Flam E., Nomoto K., 1996, ApJ 462, 276
Gentzel R., Stutzki J., 1989, A&AR 27, 41
Ip W.-H., 1995, A&A 300, 283
Miller J.A., Dermer, C.D., 1995, A&A 298 L13
Nath, B.B., Biermann, P.L., 1994, MNRAS 270
Parizot E.M.G., Cassé M., Vangioni-Flam E., 1997a, A&A in press
Parizot E.M.G., Lehoucq R., Cassé M., Ellison D., 1997b, in C. Winkler, T.-L. Courvoisier, and P. Durouchoux (eds.), The Transparent Universe, ESA SP-382, pp 93–96, ESA Publications Division
Parizot E.M.G., Lehoucq R., Cassé M., Vangioni-Flam E., 1997c, in C. Winkler, T.-L. Courvoisier, and P. Durouchoux (eds.), The Transparent Universe, ESA SP-382, pp 97–100, ESA Publications Division
Pohl M., 1996, A&AS 120 C, 457
Ramaty R., 1996, A&AS 120, 373
Ramaty R., Kozlovsky B., Lingenfelter R.E., 1995, ApJ 438 L21
Ramaty R., Kozlovsky B., Lingenfelter R.E., 1996, ApJ 456, 525
Ramaty R., Kozlovsky B., Lingenfelter R.E., 1997a, in C. Winkler, T.-L. Courvoisier, and P. Durouchoux (eds.), The Transparent Universe, ESA SP-382, p. 75, ESA Publications Division
Ramaty R., Kozlovsky B., Tatischeff V., 1997b, Proc. of the 4th COMPTON Sympsium
Reynolds R.J., Ogden P.M., 1979, ApJ 229, 942
Sivan J., 1974, A&AS 16, 163
Tatischeff V., Cassé M., Kiener J., Thibaud J.-P., Vangioni-Flam E., 1996, ApJ 472, 205
Williams J.P., McKee C.F., 1997, ApJ 476, 166

This article was processed by the author using Springer-Verlag LaTeX A&A style file *L-AA* version 3.