Extended γ-ray Sources and Active Regions in the Galaxy: The Carina and Orion Complexes

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Extended γ-ray sources and active regions in the Galaxy: the Carina and Orion complexes

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The results of γ-ray observations by the COS-B satellite lend support to the suggestion that a class of γ-ray sources comprises extended sources, associated with selected active regions in the Galaxy, and in which supernova remnants and/or strong winds from young massive stars are at work. In this framework, γ-rays come either from bremsstrahlung radiation from relativistic electrons, or from π^0 decay from *in situ* accelerated relativistic protons.

Specifically, a case is made for the identification of the Carina complex with the γ-ray source 2CG288-00. By using a simplified model for the Carina complex, it is shown that, in this source, γ-rays may be the result of proton acceleration by stellar winds, followed by confinement by resonant Alfvén-wave scattering in the giant H II region NGC 3372. The confinement is efficient enough for *in situ* accelerated cosmic rays to dominate ambient cosmic rays.

The model predicts that the source should be identified with NGC 3372, with little contribution from the adjacent molecular cloud. The required proton acceleration efficiency is of the order of 10%.

In the Orion complex, the same model leads to the conclusion that the confinement is inefficient, and that, as a consequence, ambient cosmic rays dominate *in situ* accelerated cosmic rays, as observed.

1. Introduction

The latest COS-B catalogue (Swanenburg *et al.* 1981) comprises 25 localized sources of γ-ray emission above 100 MeV.

Positive identifications have been made for only two sources, which are associated with the Crab and Vela pulsars (Lichti *et al.* 1980). Two more sources are very likely identified, one with the quasar 3C273 (which we do not consider further here), the other with the nearby ρ-Oph dark cloud, or some other associated object.

To this list, one should add a *resolved* source of γ-ray emission, clearly associated with the Orion complex (Caraveo *et al.* 1980). Further, although the evidence is not yet compelling, a class of localized (unresolved) γ-ray sources may be associated with SNOBs (i.e. supernova remnants physically linked with OB-associations, Montmerle (1979*a*, *b*)). In addition, a broad, extended feature seen around $l \approx 80°$ has been associated with the Cygnus X complex (Protheroe *et al.* 1979).

Other proposals have been made for a few specific sources (see references in Montmerle 1979*a*; Kanbach 1979), including compact objects unknown at other wavelengths (Schlickeiser 1981).

Altogether, with the inclusion of the evidence of Caraveo & Paul (1979) that the diffuse galactic γ-rays come essentially from the spiral arms, it is reasonable to say that at least one class of γ-ray sources is linked with extremely young objects in the Galaxy, namely *regions of star formation* ('active regions'). This class includes, in decreasing order of certainty, the Orion complex, the ρ-Oph cloud and SNOBs. This paper discusses the evidence for the inclusion of the Carina complex.

Regions of star formation include many very different objects: *extended*, for example H II regions, molecular clouds, s.n.r., or u.v. and i.r. photon fields; and *compact*, for example stars, or their collapsed remnants. Because of their poor resolving power (error box radius *ca.* 1°) current γ-ray experiments cannot *a priori* distinguish between them. However, data obtained at other wavelengths (radio, X-ray) put strong constraints on the physics of possible compact counterparts to γ-ray sources located in regions of star formation.

Specifically, recent Einstein data obtained on such regions as Orion (Ku & Chanan 1979), ρ-Oph (Montmerle *et al.* 1981 *a*), Cygnus (Harnden *et al.* 1979), and Carina (Seward *et al.* 1979) have revealed the existence of point X-ray (0.5–4 keV) sources, with minimum X-ray luminosities of order 10^{30}–10^{32} erg s^{-1},† *all* associated with stars, at various stages of evolution (Vaiana *et al.* 1981), even pre-main sequence (T Tauri stars, Montmerle *et al.* 1981 *a*; Feigelson & De Campli 1981). Hence, to remain unseen by Einstein, a compact γ-ray source in these regions must have typically a ratio of X-ray to γ-ray luminosities $L_X/L_\gamma < 10^{-3}$. Although a Vela-like source (for which $L_X/L_\gamma \approx 10^{-5}$) is a possibility, no radio pulsar is known in these regions, and only two are definitely associated with γ-ray sources, far from any region of star formation.

Accordingly, we shall investigate what we consider currently to be the more likely possibility that γ-ray sources in active regions are *extended*. If one takes into account the fact that the Compton effect yields at most a small contribution to the γ-ray emission in such regions (Montmerle & Cesarsky 1980), one is left with two mechanisms: π^0 decay and non-thermal bremsstrahlung, both proportional to the amount of matter within the confinement volume of cosmic-ray protons or electrons, respectively. This amount is not always well known (see below).

In addition to the existing list of proposed identifications, the Carina complex appears a good candidate for identification with the γ-ray source 2CG288-00. The optical H II region NGC 3372 lies well within the corresponding COS-B error box, in a region of moderately high diffuse γ-ray emission, thus reducing the possibility of line-of-sight confusion.

We take the observed γ-ray luminosity from the Carina complex above 100 MeV to be

$$L_{\gamma,\mathrm{C}} = 5\times10^{35}\ \mathrm{erg\ s^{-1}},\dagger \tag{1.1}$$

which is obtained with $E^*_\gamma = 250$ MeV as the average energy of the photons detected by COS-B (Swanenburg *et al.* 1981), with $d_\mathrm{C} = 2.7$ kpc as the distance of the complex (Turner & Moffat 1980). The corresponding quantity for the Orion complex is (equivalent unresolved source)

$$L_{\gamma,\mathrm{O}} \approx 1.8\times10^{34}\ \mathrm{erg\ s^{-1}} \tag{1.2}$$

with $d_\mathrm{O} = 460$ pc.

By comparing the two complexes, we shall be able to draw conclusions as to the conditions required for an active region to appear as a γ-ray source.

2. THE CARINA COMPLEX COMPARED WITH THE ORION COMPLEX

The *first interpretation* to investigate is that the γ-ray emission from regions of star formation results simply from the interaction of ambient cosmic rays (protons and electrons) with the massive molecular clouds associated with them.

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† 1 erg $s^{-1} = 10^{-7}$ W.

For the Orion complex, the available evidence, deduced from CO measurements, interstellar absorption, and γ-rays, converge to yield a total mass

$$M_{\mathrm{O}} \approx 1.5 \times 10^5 \, M_{\odot}, \tag{2.1}$$

and a γ-ray emissivity above 70 MeV

$$q_{\gamma,\,\mathrm{O}}\,(>70\ \mathrm{MeV}) = 4.3 \pm 0.6 \times 10^{-25}\ \mathrm{H}^{-1}\,\mathrm{s}^{-1} \tag{2.2}$$

(see discussion in Caraveo *et al.* 1980), a value that is consistent, above 100 MeV, with the local γ-ray emissivity

$$q_{\gamma,\,\odot}\,(>100\ \mathrm{MeV}) = 2.9 \times 10^{-25}\ \mathrm{H}^{-1}\,\mathrm{s}^{-1} \tag{2.3}$$

as deduced by Lebrun & Paul (1979) from SAS-2 data. These values include π^0 decay *and* bremsstrahlung from primary electrons.

This implies in turn a complete penetration of the molecular clouds of the complex (mostly L1630 and L1641) by cosmic rays having an energy density comparable with that in the solar neighbourhood. In that sense, the Orion complex appears as a 'passive' γ-ray source (Montmerle 1979*b*).

That this situation holds in general in the Galaxy has been recently advocated by Wolfendale (1980). However, there is evidence for an increase of the γ-ray emissivity by a factor of about five in the ρ-Oph cloud (Simpson 1979; Cassé & Paul 1980; Bignami & Morfill 1980; Paul *et al.* 1980), and possibly by a much larger factor in SNOBs (Montmerle 1979*a*). A slight increase (by a factor of about two) in the Cygnus X complex cannot be ruled out (see Protheroe *et al.* 1979).

What is the situation in the Carina complex?

First, the mass of the associated molecular cloud is not known, owing to the lack of CO measurements (used as a tracer of molecular hydrogen) in the Southern Hemisphere. The mass of the HII region has been estimated by Dickel (1974), by finding

$$R_2 = 25\ \mathrm{pc} \tag{2.4}$$

as the radius of NGC 3372, and taking $n_2 = 100\ \mathrm{cm}^{-3}$ as its average density, which yields a mass $M_2 \approx 10^5\,M_{\odot}$. By using the electron density calculated by Smith *et al.* (1978) from the thermal radio emission of the nebula, $n_2 = 250\ \mathrm{cm}^{-3}$, the previous estimate is doubled, so we have

$$10^5\,M_{\odot} \lesssim M_2 \lesssim 2 \times 10^5\,M_{\odot}. \tag{2.5}$$

Now in our framework, the γ-ray flux Φ_{γ} from a given mass M and emissivity q_{γ} at a distance d is

$$\Phi_{\gamma} \propto M q_{\gamma}/d^2, \tag{2.6}$$

from which one deduces

$$(Mq_{\gamma})_{\mathrm{C}} \approx 30\,(Mq_{\gamma})_{\mathrm{O}}. \tag{2.7}$$

The question now becomes: If $q_{\gamma,\,\mathrm{C}} = q_{\gamma,\,\mathrm{O}} = q_{\gamma,\,\odot}$, is it still possible to account for the γ-ray flux of 2CG288-00 in terms of the effect of the mass only? Were this to be the case, one should have a total mass of the Carina complex given by

$$M_{\mathrm{C}} \approx 4.5 \times 10^6\,M_{\odot} \tag{2.8}$$

(by using equation 1.3), with respect to which the mass of the HII region is negligible.

Such high masses are excluded on the basis of the results of the Columbia group (Stark & Blitz 1978; Blitz & Shu 1980); they are possible, though extreme, according to the results of the Stony Brook group (Solomon *et al.* 1980). The respective results can be given by a cumulative mass distribution function $\mathcal{N}(>M)$, presented, in a normalized form, in figure 1. The basic differences between the two groups comes from using $^{13}CO/H_2$ ratios differing by a factor of five, and a different cloud sampling, the 'Columbia clouds' being relatively nearby, the biggest 'Stony Brook clouds' being part of the 4 kpc ring.

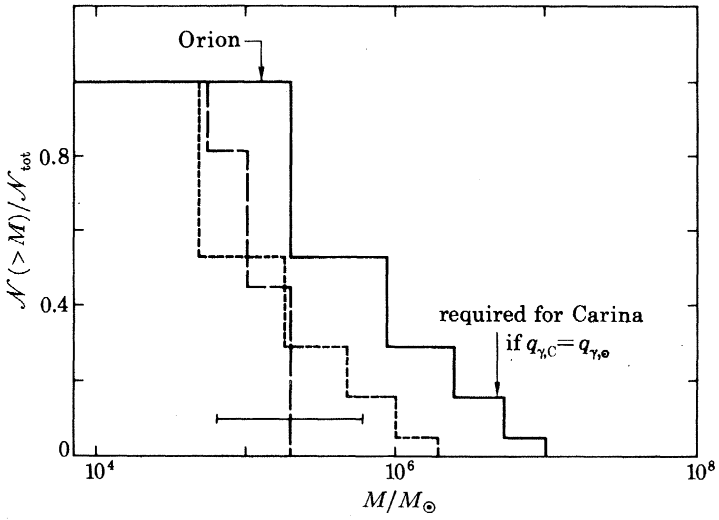

FIGURE 1. The cumulative mass distribution $\mathcal{N}(>M)$ for molecular clouds in the Galaxy, normalized to the total number of clouds observed, $\mathcal{N}_{tot}$. Two histograms have been derived from Solomon *et al.* (1980), (i) (——) by using their nominal $^{13}CO/H_2$ ratio, and (ii) (- - -) by dividing their results by five, to provide a comparison with the histogram derived from Stark & Blitz (1978) (— — —), who use a $^{13}CO/H_2$ ratio one-fifth the size. (The error bar on their results is shown.)

In view of the current debate, it appears premature to choose sides (see further discussion in Montmerle *et al.* 1981*b*), but from figure 1, it seems fair to conclude that there is a high probability that

$$q_{\gamma,C} > q_{\gamma,\odot} \quad \text{or} \quad q_{\gamma,C} \gg q_{\gamma,\odot}, \tag{2.9}$$

even if the exact relation cannot yet be quantitatively estimated. This is very different from the situation in the Orion complex.

Does this difference relate to physical differences between the two complexes? In our view, this is definitely so. The Carina complex includes six O3 stars, three Wolf–Rayet stars, a possible supernova remnant (s.n.r.), and the strange object η Car (see below). By contrast, the Orion complex comprises stars not earlier than O7, ionizing a relatively small Strömgren sphere (radius *ca.* 1.5 pc). Processes related to star formation are thus exacerbated in Carina, relative to Orion.

Accordingly, a *second interpretation* can be examined: the γ-ray emission from 2CG288-00 arises from non-thermal bremsstrahlung of the relativistic electrons associated with the s.n.r. (Montmerle & Cesarsky 1980). This imples $n/B_5^{1.5} = 560$ [$\mathrm{cm^{-3}\,nT^{-1.5}}$], which is possible, for reasonable values of n and B. Alternatively, cosmic-ray protons are accelerated in the s.n.r., interact

PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

with the surrounding matter, and give rise to π^0-decay γ-rays. Insufficient spectral data are available from COS-B to distinguish the two contributions, which may even be combined.

However, some doubts on the existence of this s.n.r. have been recently raised by Einstein observations (Seward *et al.* 1979). Briefly, in spite of the existence of the non-thermal hot spot detected at 30 MHz by Jones (1973) in this region (and presumably dominated at higher frequencies by the thermal bremsstrahlung from the H II region (see, for example, Goudis 1977)), no s.n.r.-type image appears in X-rays. Only stars are seen, superimposed on a diffuse background extending throughout the H II regions (see further discussion in Montmerle *et al.* 1981 *b*).

In view of this, it is of interest to examine a *third interpretation* (either alternative or complementary to the preceding one), first suggested for the ρ-Oph cloud by Cassé & Paul (1980). This interpretation is that *stellar winds* may accelerate cosmic rays, as possibly do s.n.rs, and generate γ-rays by π^0 decay in their vicinity. Various mechanisms are now being investigated (see, for example, Völk 1981; Webb & Forman 1980), with for instance a combination of first-order Fermi acceleration and Alfvén-wave scattering (see, for example, Blandford & Ostriker 1980 and references therein).

In what follows, we shall be interested mainly in the *energetics* of the suggested mechanism, as applied to the Carina complex, and comparing it with that of the Orion complex. This is obviously a first step, before the proposed mechanism is investigated in more detail.

3. Mechanical power from stellar winds

The Carina complex comprises one of the richest aggregates of very early-type stars known in the Galaxy (O3 and later). These stars are grouped in compact associations (mainly Tr 14, Tr 16) (see, for example, Turner & Moffat 1980). While in the early main sequence, these stars shed comparatively little mass, but once they have reached the supergiant stage (luminosity class I), the mass-loss rate $\dot{M}$ increases, and rates as high as the order of $10^{-6}\ M_\odot\ \mathrm{a}^{-1}$ have been derived from observations (Conti & Garmany 1980). The mass-loss rate is roughly proportional to the luminosity of the star and hence increases very rapidly with the mass (e.g. Lamers 1980). On the other hand, these stars provide most of the ionizing photons of the giant H II region (*ca.* $1.5\times10^{50}\ \mathrm{s}^{-1}$, Smith *et al.* 1978).

In addition to the O stars, the Carina complex features three Wolf–Rayet (W.R.) stars, which is unique among galactic OB-associations (see Humphreys 1978; Van der Hucht *et al.* 1981). Their mass-loss rates have been recently measured (Barlow *et al.* 1980), and are *ca.* $10^{-5}\ M_\odot\ \mathrm{a}^{-1}$.

For all these stars, the corresponding terminal velocities v_∞ are from about 2500 to 3000 km s^{-1}.

For the strange object, η Car, the case is much less clear, and mass-loss estimates range from 10^{-3} to $7.5\times10^{-2}\ M_\odot\ \mathrm{a}^{-1}$ (continuing since 1836), with a terminal velocity $v_\infty\approx 600$ km s^{-1}. (For further details, see Montmerle *et al.* (1981 *b*) and references therein.)

Using actual values for $\dot{M}$, when they are available, or values derived from empirical formulae (Lamers *et al.* 1980; Lamers 1981), when they are not, we can obtain the total mechanical power of the stellar winds, $P_\mathrm{w} = \Sigma\,\frac{1}{2}\dot{M}v_\infty^2$, for the Carina complex:

$$P_\mathrm{w}\approx 5\times10^{38}\ \mathrm{erg\ s^{-1}}, \tag{3.1}$$

the W.R. stars making up 40% of this amount and η Car contributing a minimum of 2×10^{38} erg s^{-1}.

Now, because the terminal velocities are highly supersonic, the wind drives a shock front where its pressure is balanced by the external pressure Σp_k (due to gas, cosmic rays, magnetic fields; see Cassé & Paul 1980 for details). The wind shock radius is given approximately by

$$R_{\mathrm{w}} = (\Sigma \dot{M} v_{\infty}/4\pi\, \Sigma p_k)^{\frac{1}{2}}. \tag{3.2}$$

For the Carina complex, one finds ($T \approx 10^4$ K, $n_2 = 100$ cm^{-3})

$$R_{\mathrm{w}} \approx 10 \text{ pc}. \tag{3.3}$$

Note that $R_{\mathrm{w}} < R_2$ (equation 1.3). As a result, the shock is well within the HII region, and an efficient diffusion of energetic particles may occur (see below). This is likely to be one of the necessary conditions for the above acceleration mechanism to work. (Also, R_{w} is much greater than the apparent dimensions of η Car, if interpreted as an expanding gas–grain mixture (see, for example, Cassatella *et al.* 1979). It may then not be appropriate to include it in equation (3.1), but this is of little quantitative consequence for the final conclusions.)

For future reference, we note that, from Lamers (1981), one can estimate

$$P_{\mathrm{w,O}} \approx 5 \times 10^{37} \text{ erg s}^{-1}, \tag{3.4}$$

i.e. one order of magnitude less than Carina, essentially because of the lack of W.R. and early-type O stars.

Also,

$$R_{\mathrm{w,O}} \approx 1.2 \text{ pc}, \tag{3.5}$$

by using an average density $n_2 \approx 320$ cm^{-3}, which is deduced from the radius of the Strömgren sphere,

$$R_{2,\mathrm{O}} \approx 1.5 \text{ pc}, \tag{3.6}$$

and the spectral types of the ionizing stars.

Returning to the Carina complex, one therefore finds:

$$(L_\gamma/P_{\mathrm{w}})_{\mathrm{C}} \approx 10^{-3}. \tag{3.7}$$

Hence, there is *a priori* no energetics problem. However, while $L_\gamma/P_{\mathrm{w}} < 1$ is a necessary condition for the wind acceleration mechanism to work, it is not sufficient. Indeed, a measure of the conversion efficiency of c.r. protons into γ-rays is the 'optical depth' of the medium for *ca.* 3 GeV protons (median energy for γ-ray-producing protons, see, for example, Stecker 1973), i.e. $\langle\sigma_\gamma\rangle nL$ ($\langle\sigma_\gamma\rangle$ is the cross section for π^0-production at $E_{\mathrm{p}} \approx 3$ GeV, n is the average density, and L is the typical dimension). For Carina one finds

$$\langle\sigma_\gamma\rangle nL \approx 10^{-4} \tag{3.8}$$

if the c.r. travel in straight lines, i.e. are not *confined* in the vicinity of the acceleration region. But, if equation (3.8) holds, a measure of the acceleration efficiency is roughly

$$\eta_{\mathrm{a}} \approx \frac{L_\gamma}{P_{\mathrm{w}}} \frac{1}{\langle\sigma_\gamma\rangle nL} > 1. \tag{3.9}$$

In other words, to have a γ-ray source, it is necessary to assume some – as yet undefined – reasonably efficient confinement mechanism for cosmic rays, unless the mechanical power P_{w} is many orders of magnitude higher than the γ-ray luminosity L_γ. Clearly, this is not so in the Carina complex.

4. A MODEL FOR γ-RAY PRODUCTION

To make quantitative estimates, let us take a simplified three-component model of the Carina complex (see figure 2):

Component 1 is the molecular cloud, approximated by a cylinder of length L_1, and radius R_1, of average density n_1.

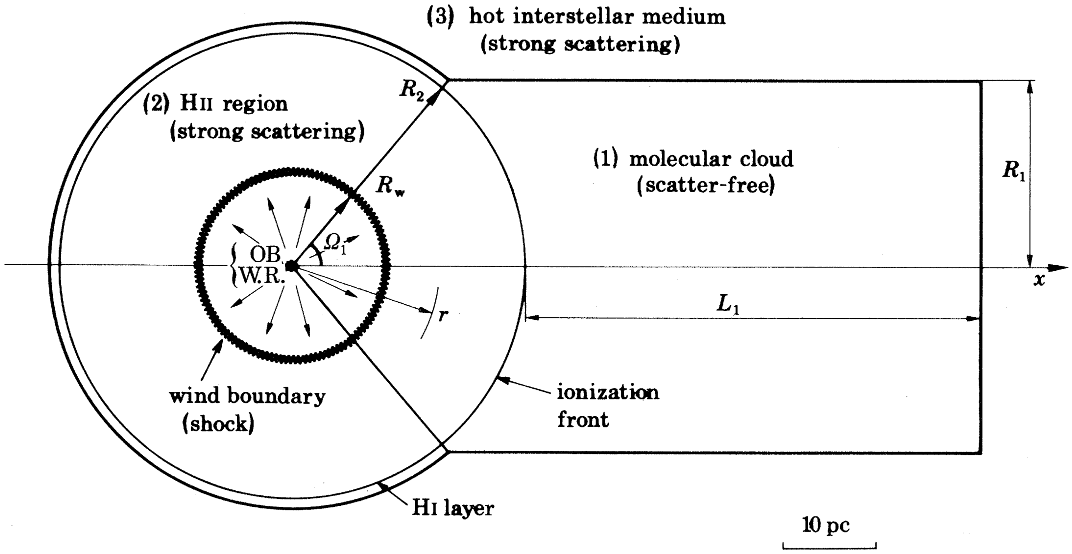

FIGURE 2. A simplified model for the Carina complex, drawn to scale (see table 1), and featuring the three components described in the text.

Component 2 is the H II region, lying at one end of the molecular cloud, approximated by a sphere of radius R_2. From the observed typical width of molecular clouds (see, for example, Blitz 1980), *ca.* 30–40 pc, one presumably has, for the Carina complex, $R_2 > R_1$. The stars that ionize the H II region are assumed to be at roughly the same location as those that provide the mass loss (O3If stars do both; W.R. stars provide little additional ionization, but a large fraction of the mass loss; by comparison, stars later than O4 provide only ionizing photons). Hence, the shock sphere and the Strömgren sphere can be taken to be approximately concentric, and the shock radius is $R_W < R_2$. The average density outside the shock is n_2.

Inside the shock, the density is much less than n_2 because of the stellar winds. The outflow of matter, of order $10^{-5}\,M_\odot\,\mathrm{a}^{-1}$, is deposited in an outer H II region of mass *ca.* $10^5\,M_\odot$; as a result, there will be no *systematic* motion of the outside matter because of the winds (equilibrium of pressures implies that the shock is stationary).

Also, from Bell (1978), it can be shown that at the energies relevant for γ-ray production, the high c.r. densities (see below) being taken into account, the shock thickness for cosmic rays is much less than R_W.

Component 3 is the hot ('coronal') interstellar medium (h.i.m.), and is assumed to be of the McKee & Ostriker (1977) type.

An H I layer, of thickness much less than R_2, separates the H II region from the interstellar medium.

Values of the parameters relevant to the Carina complex and used in the following calculations are given in table 1.

Now at the shock radius R_w, acceleration of c.r. protons is assumed to take place, giving rise to an intensity $\lambda_w I_0(p)$ [$\mathrm{cm^{-2}\,s^{-1}\,GeV^{-1}\,sr^{-1}}$], where $I_0(p)$ is the intensity normalized such that, for instance, the corresponding energy density ϵ is equal to the proton energy density in the solar neighbourhood, $\epsilon_\odot \approx 0.8\ \mathrm{eV\,cm^{-3}}$.

One has
$$I_0(p) \propto p^{-2} \tag{4.1}$$
for the acceleration mechanism of Blandford & Ostriker (1980).

TABLE 1. PARAMETERS OF THE MODEL OF THE CARINA COMPLEX

component	size pc	density cm^{-3}	temperature K	magnetic field nT
1. Molecular cloud†	$L_1 = 50$ $R_1 = 20$	$n_1 = 100$	$T_1 = 100$	1
2. HII region	$R_2 = 25$ $R_w = 10$	$n_2 = \begin{Bmatrix}100\\250\end{Bmatrix}$	$T_2 = 10^4$	1
3. Hot interstellar medium	$L_3 = 10^3$	$n_3 = 3.5\times10^{-3}$	$T_3 = 4.5\times10^5$	$\lesssim 0.1$

† The values of L_1 and R_1 were chosen to yield a mass of *ca.* $10^5\ M_\odot$ for the molecular cloud (see, for example, Blitz 1980), with higher-than-average values for L_1, R_1, and n_1 separately.

Because of confinement and losses (mainly π^0-production) of protons travelling from region i to region j, only a fraction, $\xi_{ij}(r, E)$, of the flux of protons of kinetic energy E (or momentum p) remains at a distance r from the source. This fraction will be referred to as the 'escape function' in what follows. With the notation

$$\xi_{ij}^{(i)}(E) = \text{value of } \xi_{ij}(r, E) \text{ at the downstream boundary of region } i, \tag{4.2}$$
$$\langle \xi_{ij}(r) \rangle = \text{average of } \xi_{ij}(r, E) \text{ over the proton spectrum}, \tag{4.3}$$

and assuming that, to first order, the c.r. intensity is of the form
$$J(p, r) = I(p)\, f(r), \tag{4.4}$$
one may write an approximate equation equating gains (source) and losses for protons, over the whole complex:
$$\eta_a P_w = \frac{\mathscr{E}_2}{\tau_2} + \langle \xi_{23}^{(2)} \rangle\, \eta_a P_w \left(1 - \frac{\Omega_1}{4\pi}\right) + \frac{\mathscr{E}_1}{\tau_1} + \langle \xi_{21}^{(2)}\, \xi_{13}^{(1)} \rangle\, \eta_a P_w \frac{\Omega_1}{4\pi}\, \alpha_1. \tag{4.5}$$

In equation (4.5), $\mathscr{E}_i$ is the total proton energy in region i, τ_i represents the losses (assumed to be catastrophic, approximately), Ω_1 is the solid angle in the HII region subtended by the molecular cloud (see figure 2) and corresponding to θ_1; $\alpha_1 = \pi \sin^2\theta_1/\Omega_1$ is a geometrical factor. The factor η_a is the proton *acceleration efficiency*, which is what we are seeking.

This process gives rise to a γ-ray luminosity above 100 MeV, L_γ, corresponding to an average $\langle q_\gamma \rangle$[$\mathrm{s^{-1}\,H^{-1}}$]. Approximating the total number of protons in region i by $\mathscr{E}_i/\epsilon_\odot$, one has:
$$L_\gamma \approx \langle q_\gamma \rangle\, E_\gamma^* \frac{n_1 \mathscr{E}_1 + n_2 \mathscr{E}_2}{\epsilon_\odot}. \tag{4.6}$$

Since
$$\tau_i \approx (\langle \sigma_L \rangle n_i c)^{-1}, \tag{4.7}$$
σ_L being the cross section for inelastic proton–proton collisions, one has finally
$$\eta_a P_w \approx \frac{L_\gamma \epsilon_\odot \langle \sigma_L \rangle c}{E_\gamma^* \langle q_\gamma \rangle} \frac{1}{1 - \xi_e}, \tag{4.8}$$

PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

where ξ_e is the 'escape parameter' for the whole complex:

$$\xi_e = \langle \xi_{23}^{(2)} \rangle \left(1 - \frac{\Omega_1}{4\pi}\right) + \langle \xi_{21}^{(2)}\, \xi_{13}^{(1)} \rangle \frac{\Omega_1}{4\pi} \alpha_1. \tag{4.9}$$

A numerical estimate for equation (4.8) may be obtained by assuming that $\langle \sigma_L \rangle$ and $\langle q_\gamma \rangle$ have approximately the same value as for local c.r. protons (π^0 decay, but including also bremsstrahlung γ-rays from secondary electrons, see Marscher & Brown (1978)): $\langle \sigma_L \rangle \approx 100$ mb ($10^{-26}\,\mathrm{m}^2$), $\langle q_\gamma \rangle = 2.2 \times 10^{-25}\,\mathrm{H}^{-1}\,\mathrm{s}^{-1}$. This yields

$$\eta_a \approx 43 \frac{L_\gamma}{P_w} \frac{1}{1-\xi_e}. \tag{4.10}$$

The escape factor ξ_e depends on the geometry (see equation 4.9), but more particularly on the confinement mechanism assumed. Note that, if the confinement is total ($\xi_e = 0$), then $\eta_a \approx 43\, L_\gamma/P_w$, i.e. of the order of 4% for the Carina complex. This is the optimum situation.

5. COSMIC-RAY CONFINEMENT BY ALFVÉN WAVE SCATTERING

Since the distribution of magnetic fields inside HII regions or molecular clouds is unknown, we shall assume a '*minimal confinement hypothesis*', i.e. that the sole confinement mechanism is resonant Alfvén-wave scattering (see, for example, Wentzel 1974), and that the magnetic field lines are *radial* in the HII region, and *longitudinal* in the molecular cloud, with a continuity across the ionization front (see figure 3). Any other configuration will lead to longer path-lengths, hence to more efficient confinement, and hence to a smaller value of ξ_e.

The propagation of c.r. protons from the source will then be governed by radial diffusion in the HII region and longitudinal diffusion in the molecular cloud. There will be no convection term, since we assume no systematic motion of the matter.

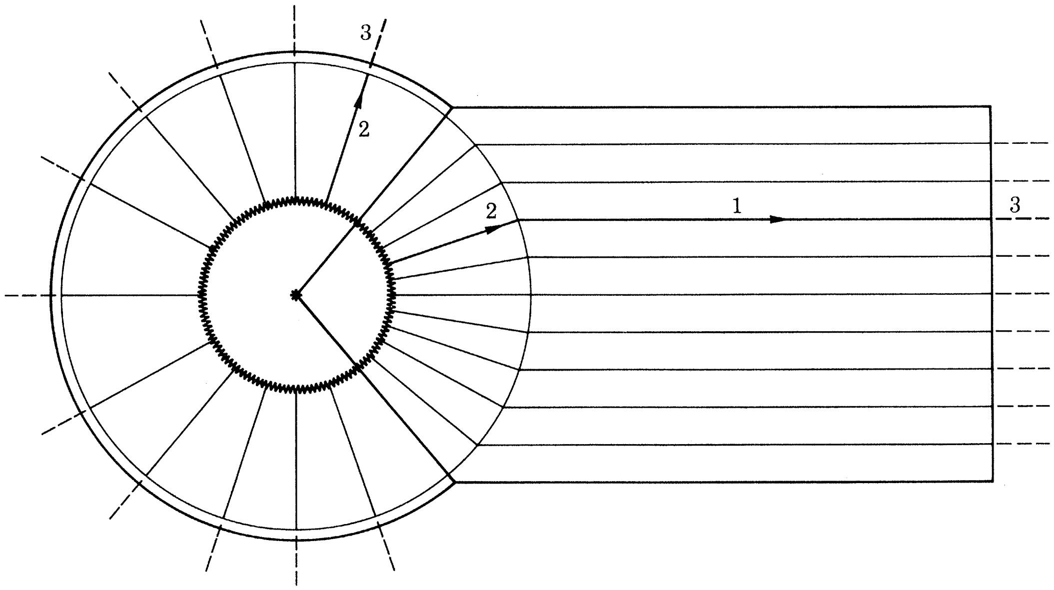

FIGURE 3. The magnetic configuration corresponding to the 'minimal confinement hypothesis'. Cosmic-ray protons, accelerated at the wind boundary (see also figure 2) stream along the field lines from the HII region (2) out to the hot interstellar medium (3), either directly, or passing through the molecular cloud (1).

Under these conditions the c.r. proton density $N_i(E, r)$ (or $N_i(E, x)$ if more appropriate; in $\mathrm{GeV^{-1}\,cm^{-3}}$) will be given by the diffusion equation

$$D_i \nabla^2 N_i + N_i/\tau_i = 0 \quad (i = 1, 2, 3), \tag{5.1}$$

on the further assumption that enough time has elapsed since the birth of the source (i.e. of the dominant mass-losing stars) so that $\partial N_i/\partial t = 0$ (see below). D_i is the diffusion coefficient appropriate to region i, τ_i is the characteristic loss time (HII region and molecular cloud), or escape time (in the h.i.m., since $n_3 \ll n_1$ or n_2, so that inelastic losses are negligible). In reality, the values of D_i depend not only on energy but also on the space variables. As a first approximation, however, the D_i will be taken as being weakly energy-dependent only (more on this later).

The boundary conditions are:

(*a*) The flux at shock is given (in practice its value is fixed by the wind energy, via the efficiency η_a).

(*b*) The cosmic ray density at infinity is equal to zero. It is possible to add a uniform c.r. component of energy density $\epsilon_\odot$ everywhere, not created by the source; but as we shall see, in the Carina complex $\epsilon \gg \epsilon_\odot$, and hence ambient c.r. can be neglected.

A sketch of the calculation follows (details will be published elsewhere). The scale height relevant to the problem in region i is:

$$\delta_i = (D_i\,\tau_i)^{\frac{1}{2}}. \tag{5.2}$$

The flux of c.r. protons will be governed by a *streaming velocity* $v_{\mathrm{s},\,i}$, computable from the quasi-linear theory of Alfvén-wave scattering (see below), so that

$$D_i = v_{\mathrm{s},\,i}\,\delta_i \tag{5.3}$$

since the diffusion is one-dimensional. From equation (5.3), one has then

$$\delta_i = v_{\mathrm{s},\,i}\,\tau_i \tag{5.4}$$

and

$$D_i = v^2_{\mathrm{s},\,i}\,\tau_i. \tag{5.5}$$

The condition that $\partial N_i/\partial t = 0$ then translates into $\varDelta_1/v_{\mathrm{s},\,i} + \varDelta_2/v_{\mathrm{s},\,2} \ll T_{\mathrm{OB}}$, where T_{OB} is the age of the mass-losing OB-association, which will be also taken as the escape time in region 3 (h.i.m.), τ_3, and $\varDelta_i$ is the size of region i.

The computation of the streaming velocities $v_{\mathrm{s},\,i}$ requires care. Indeed, depending on the relevant physical conditions, the damping mode for Alfvén waves varies, essentially depending on the ratio $v_{\mathrm{A},\,i}/v_{\mathrm{sound},\,i}$ (where $v_{\mathrm{A},\,i}$ is the Alfvén velocity in region i) and on the state, neutral or ionized, of the medium.

In the neutral medium (region 1), the waves are damped by collisions between charged and neutral particles (Kulsrud & Cesarsky 1971). If the medium is ionized, there are two possibilities. If $v_{\mathrm{A},\,i} > v_{\mathrm{sound},\,i}$, the damping takes place via wave–wave interactions and decay into sound waves (Wentzel 1974). If $v_{\mathrm{A},\,i} < v_{\mathrm{sound},\,i}$, this damping mechanism is no longer possible; one has to resort to saturated nonlinear damping of coupled beat waves (Cesarsky & Kulsrud 1980). This applies in the HII region (region 2) and in the h.i.m. (region 3).

In each case, the streaming velocity can be expressed as:

$$v_{\mathrm{s},\,i} = v_{\mathrm{A},\,i} + \Delta v_i \tag{5.6}$$

with

$$\Delta v_i = f_i(p;\ T_i, n_i, B_i, L_i\, n_{\mathrm{c.r.}}), \tag{5.7}$$

$n_{\mathrm{c.r.}}$ being the density of c.r. with momentum greater than p.

In Δv_i is included a characteristic length L_i, measuring the c.r. proton gradient in the scattering region i. For regions 1 and 2:

$$L_i = \delta_i. \tag{5.8}$$

For region 3, one may take

$$L_3 \approx 1\ \mathrm{kpc} \tag{5.9}$$

(Cesarsky & Kulsrud 1980).

Hence, for regions 1 and 2, $v_{\mathrm{s},i}$ and δ_i will be the solutions of the system

$$\left.\begin{aligned} v_{\mathrm{s},i} &= v_{\mathrm{A},i} + f_i(\ldots, \delta_i), \\ \delta_i &= v_{\mathrm{s},i}\,\tau_i. \end{aligned}\right\} \tag{5.10}$$

The solution depends on the proton momentum p and on the number density of protons of momentum greater than p to the power $-\frac{1}{4}$ to $-\frac{1}{3}$. Because of losses and geometry, the number density of protons depends on the space variable, but with the same exponent, hence justifying the neglect of this dependence of the diffusion coefficient in the first approximation, as stated above. For a kinetic energy $E_{\mathrm{p}} \approx 3$ GeV (median energy for γ-ray production), typical numerical values are, with the values of table 1:

$$\left.\begin{array}{llll} \langle v_{\mathrm{s},1}\rangle \approx 2000\ \mathrm{km\ s^{-1}} & \delta_1 \approx 1\ \mathrm{kpc} & \tau_1 \approx 4\times10^5\ \mathrm{a}, & \\ \langle v_{\mathrm{s},2}\rangle \approx 40\ \mathrm{km\ s^{-1}} & \delta_2 \approx 20\ \mathrm{pc} & \tau_2 \approx 4\times10^5\ \mathrm{a} & (n_2 = 100\ \mathrm{cm^{-3}}), \\ \langle v_{\mathrm{s},2}\rangle \approx 70\ \mathrm{km\ s^{-1}} & \delta_2 \approx 12\ \mathrm{pc} & \tau_2 \approx 2\times10^5\ \mathrm{a} & (n_2 = 250\ \mathrm{cm^{-3}}), \\ \langle v_{\mathrm{s},3}\rangle \approx 50\ \mathrm{km\ s^{-1}} & \delta_3 \approx 1\ \mathrm{kpc} & \tau_3 \approx 2\times10^6\ \mathrm{a}. & \end{array}\right\} \tag{5.11}$$

(Note: the numerical value for $\langle v_{\mathrm{s},1}\rangle$ assumes a degree of ionization of about 10^{-4} in the molecular cloud; the exact value is of no quantitative consequence, since $v_{\mathrm{s},i} \gg v_{\mathrm{s},2}$ or $v_{\mathrm{s},3}$.)

Hence, one has

$$\left.\begin{aligned} D_2 &\lesssim D_3, \\ D_1 &\gg D_2 \text{ or } D_3. \end{aligned}\right\} \tag{5.12}$$

The escape functions are

$$\xi_{ij}(r, E) = -D_i\,\frac{\partial N_i(r, E)}{\partial r}\,\Sigma_i(r) \Big/ \left[-D_i\,\frac{\partial N_i(r_i, E)}{\partial r}\,\Sigma_i(r_i)\right], \tag{5.13}$$

where $\Sigma_i(r)$ is the surface at r crossed by the particle flux $-D_i\,\partial N_i/\partial r$ per unit surface; r_i is the upstream boundary of region i ($r_1 = R_2$, $r_2 = R_{\mathrm{w}}$, $r_3 = R_2$ or $R_2 + L_1$, see figure 2), r_j the corresponding downstream boundary.

The functions $N_i(r, E)$, solutions of the diffusion equations (5.1), are found by continuity of N_i and $-D_i\partial N_i/\partial r$ at r_i and r_j.

Using the approximations (5.12), one finds:

(*a*) for $R_{\mathrm{w}} < r < R_2$,

$$\left.\begin{aligned} \xi_{23}(r, E) &= \frac{r+\delta_2}{R_{\mathrm{w}}+\delta_2}\,\mathrm{e}^{-(r-R_{\mathrm{w}})/\delta_2}, \\ \xi_{21}(r, E) &= \frac{(r+\delta_2)\,\mathrm{e}^{-(r-R_2)/\delta_2} + (r-\delta_2)\,\mathrm{e}^{(r-R_2)/\delta_2}}{(R_{\mathrm{w}}+\delta_2)\,\mathrm{e}^{\Delta_2/\delta_2} + (R_{\mathrm{w}}-\delta_2)\,\mathrm{e}^{-\Delta_2/\delta_2}} \end{aligned}\right\} \tag{5.14}$$

(with $\Delta_2 = R_2 - R_{\mathrm{w}}$);

(*b*) for $R_2 \leqslant x \leqslant R_2 + L_1$,

$$\xi_{13}(x, E) \approx \frac{1+\tau_{\mathrm{c},3}(L_1-x)/\tau_1}{1+\tau_{\mathrm{c},3}(L_1)/\tau_1}. \tag{5.15}$$

In (5.15) the change of configuration (from region 2 to region 1, i.e. from spherical to axial symmetry (figure 2)) has been neglected. Also, $\tau_{\mathrm{c},3}(x)$ is the crossing time required to travel a distance x (in the molecular cloud) at the (downstream) streaming velocity $v_{s,3}$, which is therefore the effective streaming velocity for region 1. The time taken for a proton to diffuse from R_w to R_2+L_1 is thus about 10^6 a, which is less than T_{OB}; this justifies taking $\partial N_i/\partial t = 0$.

Using equation (4.9), and the values of table 1 and of (5.11), one finds

$$\left.\begin{array}{lll} \xi_{23}^{(2)} \approx 0.71, & \xi_{21}^{(2)} \approx 0.85 & (n_2 = 100\ \mathrm{cm^{-3}}), \\ \xi_{23}^{(2)} \approx 0.48, & \xi_{21}^{(2)} \approx 0.66 & (n_2 = 250\ \mathrm{cm^{-3}}), \\ \xi_{13}^{(1)} \approx 0.30. & & \end{array}\right\} \tag{5.16}$$

Hence
$$\xi_c \approx 0.64, \quad \eta_a \approx 12\,\% \quad (n_2 = 100\ \mathrm{cm^{-3}}) \tag{5.17}$$

and
$$\xi_c \approx 0.56, \quad \eta_a \approx 10\,\% \quad (n_2 = 250\ \mathrm{cm^{-3}}). \tag{5.18}$$

The acceleration efficiencies η_a given by equations (5.17) and (5.18) are not small, but are not implausibly high, especially in view of recent work on shock wave acceleration which points to the possibility of having a high acceleration efficiency (30%, 50% or more) in certain conditions.

If one now compares the γ-ray luminosity produced in the HII region alone, $L_{\gamma,2}$, with that produced in the molecular cloud, $L_{\gamma,1}$, one obtains

$$\frac{L_{\gamma,2}}{L_{\gamma,1}} \approx \frac{(1-\xi_{23}^{(2)})\,(1-\Omega_1/4\pi)+(1-\xi_{21}^{(2)})\,\Omega_1/4\pi}{(1-\xi_{13}^{(1)}\,\alpha_1)\,\xi_{21}^{(2)}\,\Omega_1/4\pi}, \tag{5.19}$$

or, within the framework of our model of the Carina complex,

$$3 \lesssim \frac{L_{\gamma,2}}{L_{\gamma,1}} \lesssim 7. \tag{5.20}$$

In other words, the *γ-ray emission from the* HII *region dominates*, and *the exact value of the mass of the molecular cloud then becomes irrelevant*, unless the mass ratio (HII region)/(molecular cloud) is very small.

As for the c.r. proton energy density implied by the value of ξ_c, it can be shown to be ($n_2 = 100\ \mathrm{cm^{-3}}$)

$$\epsilon_w \approx 150\,\epsilon_\odot \tag{5.21}$$

at the shock (R_w), and
$$\epsilon_2 \approx 30\,\epsilon_\odot \tag{5.22}$$

at the ionization front (R_2). These are fairly high values, but nevertheless correspond to c.r. pressures not greater than about 10–40% of the gas pressure over the whole volume. The HII region can then be viewed as a leaky 'cosmic-ray bubble' (Montmerle 1980).

Pending a confirmation by exact numerical calculations, and owing to the approximations made, the above figures should be taken only as first-order estimates, for now. They nevertheless give a fair insight into the physics involved.

6. CONCLUSIONS

To see how general the foregoing results may be, let us now return the Orion complex. Assume that c.r. protons are made there with the same acceleration efficiency as in the Carina complex, and are also confined by Alfvén-wave scattering only. One then predicts, using the values of R_2, R_w, etc. and the wind kinetic power derived in §3, a γ-ray luminosity due to this sole process given by

$$L_{\gamma,O}(\text{predicted}) \approx 8.3\times 10^{33}\ \text{erg s}^{-1}, \tag{6.1}$$

derived from an escape factor $\xi_{e,O} \approx 0.95$. Hence,

$$L_{\gamma,O}\ (\text{predicted}) \approx 0.45 L_{\gamma,O}(\text{observed}). \tag{6.2}$$

In other words, c.r. protons possibly accelerated at the wind boundary in the Orion HII region (M42) are not trapped efficiently enough to make a γ-ray source: *ambient cosmic rays dominate.* A possible weak enhancement at the location of M42 should be looked for, however.

Inasmuch as a c.r. source may be revealed only as a γ-ray source (although the converse is not true), one sees that an efficient confinement of the particles near their source is necessary for a detectable γ-ray source. Alfvén-wave scattering operates efficiently *only in giant* HII *regions like Carina.*

Again, this favours very active regions of star formation, which have both strongly *ionizing* stars and strongly *mass-losing* stars (or s.n.rs, in another context.) Also, such γ-ray sources are not expected to be numerous on a galactic scale: only the Cygnus region is known to contain also an O3 star (see also the preliminary results of a general study of OB-associations in the Galaxy, Montmerle *et al.* 1980*a, b*; Cassé *et al.* 1980). In the whole Galaxy (see, for example, Georgelin & Georgelin 1976) at most about ten such regions may exist.

It is interesting to note that Strong (1977) proposed the identification of CG135+1 (now 2CG135+01) and CG189+1 (Hermsen *et al.* 1977) with the HII regions W3 and NGC 2175, respectively, pointing out a possible connection either with the nearby s.n.rs HB3 and IC443, or with the ionizing young stars. These identifications, however, cannot be supported within the framework of stellar-wind acceleration, because the (known) mass loss is too small to energize enough c.r. production. Undetected s.n.r. inside the HII regions may be at work, for instance, as suggested by Montmerle (1979*a*) for IC1805 (2CG135+01). Further observational work is still needed to clarify the situation.

Finally, it can be emphasized that the present model makes a *definite observational prediction* for regions of star formation like Carina: the dominant γ-ray emission must come from the HII region itself. Future experiments, having an improved resolving power (such as the Franco–Soviet experiment 'Gamma 1', to be launched in 1983) may help to test this prediction.

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