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COSMIC RAY ACCELERATION BY STELLAR WINDS AND SELF-CONFINEMENT IN GIANT HII REGIONS

T. Montmerle, C.J. Cesarsky

Section d'Astrophysique, Centre d'Etudes Nucléaires de Saclay, France

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1. THE CONTEXT OF COSMIC-RAY ACCELERATION BY STELLAR WINDS IN HII REGIONS

It has been suggested independently by Dorman (1979 ; ref.1) and Cassé and Paul (1980 ; ref.2) that stellar winds may play an important role in the acceleration of galactic cosmic rays ; the interactions of these particles with the surrounding matter may give rise to γ-ray sources (ref.2), either by π° decay following high energy p-p collisions or by bremsstrahlung radiation from relativistic electrons (primary or secondary). (For further details on γ-ray emission processes, see Stecker 1975 ; ref.3.)

According to Weaver et al. (1977 ; ref.4), the region behind the stellar wind shock, filled with a hot, tenuous gas, forms a bubble which expands gradually into the interstellar medium. For typical conditions, the radius R_s of the shock is > 5 pc, while the radius R_w of the wind bubble is > 10 pc.

Let $K_u(E)$ and $K_d(E)$ be the diffusion coefficients of cosmic rays of energy E in the upstream and downstream regions on either side of the shock. Particles diffusing between the two sides of the shock are accelerated by a first-order Fermi mechanism (Axford, 1981 ; ref.5, and references therein). As long as the diffusion lengths $\ell_{u,d} \sim K_{u,d}/w_s$ are small compared to R_s, the curvature of the shock can be neglected (e.g. Webb et al. 1981 ; ref.6). Now the wind terminal velocity w_s is typically $\sim 3.10^8 cm.s^{-1}$; since the shock is quasi-stationary, the wind bubble is like an "inverted" young supernova, in which matter flows from the inside to the outside. Given the high level of turbulence which is probably present on both sides of the shock (Cesarsky and Lagage, 1981 ; ref.7), we make the optimistic estimate :

$$K_{u,d}(E) = (1/3)\, r_{u,d}(E)\, v$$

where $r_{u,d}$ are the upstream and downstream Larmor radii of a proton of energy E and velocity v on either side of the shock. In that case,

$$\ell_{u,d}(cm) \sim 10^{13} (E/mc^2)(B_{u,d}/10^{-5} G)^{-1} (w_s/3000 \text{ km s}^{-1})^{-1}$$

which, for E < 10^6 GeV, is certainly always much smaller than R_s and $(R_w - R_s)$. Thus, in the following, we consider acceleration by a plane wave ; also, all the acceleration takes place in the <u>low density regions</u> (wind and shocked gas in the bubble) on both sides of the shock, so that energy losses due to Coulomb and inelastic interactions do not inhibit the acceleration (for a discussion of these effects, see Völk 1980 ; ref.8). We assume that the shock is adiabatic, so that the fast particle energy spectrum (in the relativistic region) is proportional to E^{-2}.

Direct injection of stellar flare particles into the shock region is probably prohibited by adiabatic losses in the expanding wind (ref.8). In the solar cavity, however, interplanetary acceleration processes have been observed to be still very efficient at distances as large as ~ 20 A.U. from the Sun (Mc Donald et al. 1981 ; ref.9) ; thus, it is plausible to assume that injection of low-energy (MeV) particles into the shock region is the consequence of analogous stellar "interplanetary" processes.

2. AN IDEALIZED MODEL OF A COMPLEX ASSOCIATED WITH OB STARS

Astronomical observations tell us that, in general, associations of bright, young "OB" stars are located on one side of a molecular cloud (detected via transitions of the CO molecule, taken as a tracer of molecular

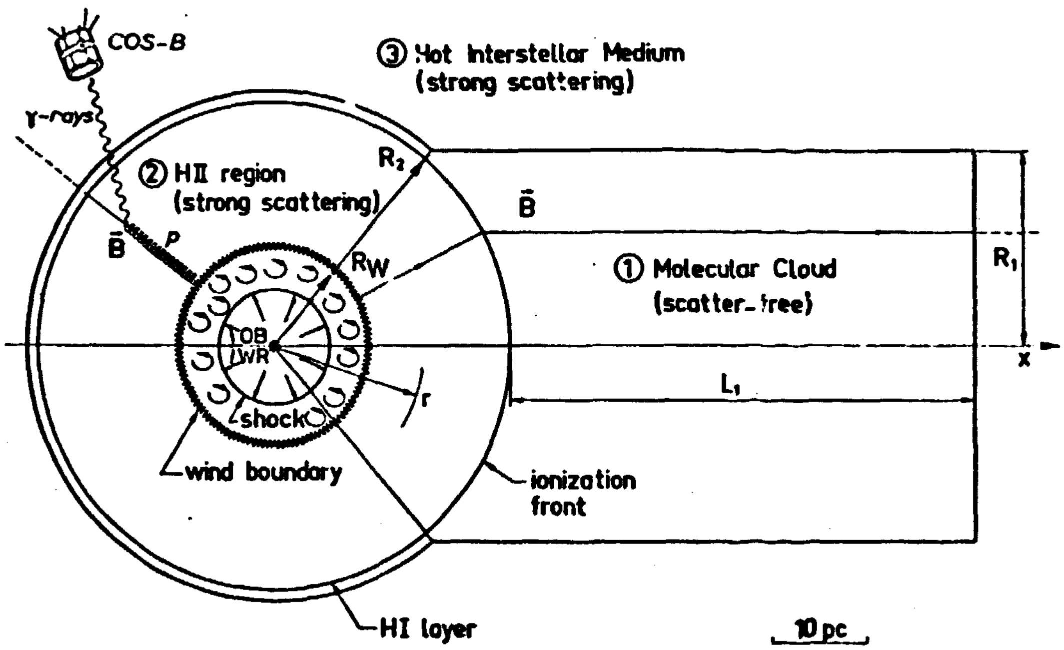

Fig. 1 Idealized model of a complex associated with young, hot, "OB" stars. We explain the γ-ray emission possibly observed in terms of wind-acceleration of protons, partial confinement, and collisions with the surrounding matter, followed by π^{o} decay. (The scale here corresponds to the Carina complex.)

hydrogen, which makes up the bulk of the mass of the interstellar clouds). Because of their high surface temperature ($T_e \sim 20\,000 - 40\,000$ K), these stars ionize a large HII region ~ 1 pc or more in diameter ; the most massive ones ($\gtrsim 20\ M_\odot$), in addition, shed large amounts of matter in the form of stellar winds (at rates ~ 10^{-7} to $10^{-5}\ M_\odot .\ yr^{-1}$). Altogether, stars, HII region(s) and molecular clouds associated together form a "complex".

Let us therefore consider an idealized model of a complex, in which a spherical HII region (associated with OB stars) of radius R_2 sits on the side of a cylindrical molecular cloud of length L_1, radius R_1. The stellar wind boundary, of radius R_w, separates the shocked region from the denser part of the HII region, of density n_2 and temperature T_2. The molecular cloud, of density n_1, and temperature T_1, is very weakly ionized. The particles accelerated in the shock region will experience resonant Alfvén-wave scattering, in the HII region, owing to self-generated waves. We minimize the possible resulting confining properties by assuming that the magnetic field $\underline{B}$ is radial in the HII region, longitudinal in the molecular cloud ("minimal confinement hypothesis") (see fig.1). The "Hot Interstellar Medium" (HIM, McKee and Ostriker 1977 ; ref.10) surrounds the molecular cloud and the HII region. Völk and Forman (1981 ; ref.11) have studied a problem somewhat similar to ours, but assuming a complete spherical symmetry for both the ionized and neutral regions, and focussing on acceleration.

Taking the recent γ-ray observations by the European satellite COS-B as a constraint on possible acceleration of cosmic-ray nuclei in HII regions (giving γ-rays by collisions on the surrounding medium via π^{o} decay), we will consider here the case of the Carina complex, which is on the line-of-sight to the error box of the γ-ray source 2CG288-00 (Swanenburg et al. 1981.; ref.12).

If the Carina complex is indeed identified with 2CG288-00, the γ-ray luminosity is $L_\gamma = 5 \times 10^{35}\ erg.s^{-1}$ at 2.7 kpc. This luminosity cannot be accounted for by the interaction of average-density cosmic rays permeating a molecular cloud of mass ~ several $10^5 M_\odot$; a mass of at least ~ $5 \times 10^6\ M_\odot$ would be required, and seems quite extreme (although not ruled out) at the present time. The kinetic power from the OB and Wolf-Rayet stars present in the Carina Nebula amounts to $P_w = 5 \times 10^{38}\ erg.s^{-1}$ (see discussion in Montmerle 1981 ; ref. 13, and Montmerle et al. 1981 ; ref.14.)

Representative values of the physical parameters involved are :

n_2	$= 100 \sim 250\ cm^{-3}$	n_1	$= 100\ cm^{-3}$
T_2	$= 10^4$ K	T_1	$= 100$ K
B_2	$= 10\ \mu G$	B_1	$= 10\ \mu G$
R_2	$= 25$ pc	L_1	$= 50$ pc
R_w	$= 10$ pc	R_1	$= 20$ pc

3 PARTICLE TRANSPORT IN THE HII REGION

Following the considerations made in sect. 1, protons are accelerated at R_w, the wind boundary. The proton distribution $f(p,r)$ at R_w is :

$$f(p,R_w)\,dp \propto p^{-\Gamma}\ dp \qquad (1)$$

with $\Gamma \geq 4$, corresponding to an energy distribution $E_p^{-\Gamma'}$, with $\Gamma' \geq 2$.
In the HII region surrounding the wind boundary and extending from R_w to R_2 (see fig.1), the post-shock turbulence has essentially died out, but diffusion of the protons by resonant Alfvén-wave scattering can still occur owing to the proton gradient associated with the spherical geometry and inelastic losses.
As a result, the protons will stream along the (radial) field lines with a streaming velocity v_s. This velocity can be found when the protons are self-confined, by equating the growth and damping rates of the waves :

$$\Omega f_p (1 - v_s/v_A)/n^* = \Gamma_d(J) \qquad (2)$$

In eq.(2), Ω is the proton Larmor frequency, n^* the density of the ionized gas, Γ_d (J) is the damping rate corresponding to the appropriate damping mechanism : if $v_A > v_{sound}$, the damping may take place via wave-wave interactions and decay into sound waves (Wentzel 1974 ; ref.15) ; if $v_A < v_{sound}$, this is no longer possible, and one invokes saturated nonlinear Landau damping (Cesarsky and Kulsrud 1981 ; ref.16). $J(r_L) = (\Delta B/B)^2$ is the ratio of the magnetic energy densities in the waves and in the ambient medium. Also, in eq.(2),

$$f_p = f(r_L > r_L(p)) \qquad (3)$$

i.e., f_p is the integral number of protons of momentum p having a Larmor radius larger than r_L.
It will turn out that $v_s > 50$ km.s^{-1} (see below sect.4). This means that the streaming velocity may be considered as large with respect to the velocities characterizing the waves and the medium, i.e., respectively, the Alfvén velocity $v_A \sim 2$ km.s^{-1}, and the (observed) expansion velocity of the HII region $v_{exp} \sim 15$ km.s^{-1}.
As a result, in the general particle transport equation valid for resonant scattering (e.g. Cesarsky 1980 ; ref.17), one can neglect convection since $v_s \gg v_A$ and v_{exp}, as well as adiabatic losses since $v_s \gg v_{exp}$.
The transport equation then reduces to a simple diffusion equation, including inelastic losses :

$$\nabla.(K \, \nabla f) + f/\tau = 0 \qquad (4)$$

where K, the diffusion coefficient, is assumed to be constant in each region depicted in fig.1. This assumption is equivalent to taking an average value over each region. The validity of this approximation may be checked a posteriori (see sect. 4).

The boundary conditions are :
- at the wind boundary, the energy flux of the accelerated particles is a fraction η_a (acceleration efficiency) of the available wind power P_w (given) :

$$\eta_a P_w = 4\pi R_w^2 \int K \, \nabla f \; E dE \qquad (5)$$

- far from the acceleration region (that is, far from the Carina complex) at a distance X = scale height for cosmic rays along a magnetic flux tube in the Galaxy :

$$f(X,p) = 0 \qquad X \geq 1 \text{ kpc} \qquad (6)$$

At this point, we have enough information to determine the functional dependence of f on space, the diffusion coefficients being as yet unspecified. To normalize f, we make use of the fact that the γ-ray luminosity produced as a result of the irradiation of the HII region and the molecular cloud by the wind-accelerated protons must be equal to the γ-ray luminosity derived from the COS-B observations :

$$L_\gamma = \lambda_w \int Q_\gamma n_H \, dV \qquad (7)$$

In eq.(7) Q_γ is a factor which includes the γ-ray emissivity (proportional to the proton intensity) in the solar neighborhood and other numerical constants (for details, see Montmerle and Cesarsky 1981a ; ref.18). In this way

$$\lambda_w \approx f(R_w, p)/ f_\odot(p) \qquad (8)$$

$f_\odot(p)$ being the proton distribution function in the solar neighborhood. (The relation is approximate because it depends, strictly speaking, on the spectral shape of f(p) vs $f_\odot(p)$; here, the exponents are not too different.)
We still have to derive self-consistently the value of the diffusion coefficients K. For this purpose, we use equation (2), noting that the relation between the streaming velocity and the diffusion coefficient is simply :

$$K.\nabla f = v_s f \qquad (9)$$

and that, in the framework of the quasilinear theory,

$$K = 1/3 \, \lambda c = 1/3 \, r_L c/J \qquad (10)$$

Altogether, one then has 6 equations (eqs 2 ; 4, including conditions 5 and 6 ; 7 and 8 ; 9 and 10), to be solved for 4 unknown functions : f(p,r) to within a multiplicative constant, the diffusion coefficients K, the streaming velocity v_s, the magnetic inhomogeneity spectrum J ;

and 2 unknown constants, λ_w, the approximate ratio between the proton intensity at R_w and in the solar neighborhood, and η_a, the acceleration efficiency.

In our astrophysical context, we are interested mainly in finding the constants λ_w and η_a, in order to see quantitatively to what extent the proposed acceleration + confinement scenario is plausible.

Detailed solutions will be given elsewhere (Cesarsky and Montmerle 1981, in preparation). We will give in what follows a few numerical results (see ref.18 for additional details), relevant to the confinement problem in the HII region, and based on the values of the idealized model given in sect. 2.

In order to check the approximation made, we define a scale height δ by

$$<\nabla f> \sim f/\delta \qquad (11)$$

We find:

$\delta = 12 \sim 20$ pc

$v_s = 40 \sim 70\ km.s^{-1}$ in the HII region,

depending on the density n_H. Since $R_2 - R_w = 15$ pc, one has $\delta \simeq R_2 - R_w$, and $f(R_w)/f(R_2) \simeq 3$. Therefore, averaging over the HII region is not too bad an approximation.

Also:

$\lambda_w \simeq 170$, $\eta_a \simeq 2\%$ (E_p = 1-10 GeV).

About 50% of the wind-accelerated protons remain trapped in the HII region and produce γ-rays. In the molecular cloud, which is essentailly scatter-free, the confinement is realized by the outside HIM.

4. CONCLUDING REMARKS

The γ-ray source 2CG288-00, observed by COS-B in the direction of the Carina Nebula, can be plausibly interpreted in the framework of our idealized model, in which the cosmic rays are accelerated at the shock boundary of the stellar winds, and are partially confined in the HII region and in the molecular cloud. (This is part of a more general framework which tends to link a class of γ-ray sources and molecular complexes, see ref.13.)

The cosmic-ray density near the acceleration region is high; however, the associated pressure remains low with respect to the gas pressure (this does not hold for very high-energy particles, > 100 GeV) and its effect on the shock structure is negligible.

On the other hand, the required efficiency is low, in fact lower than the average efficiency of acceleration by supernova shocks taking into account SN statistics (up to ~ 8-12%, see e.g. Montmerle and Cesarsky 1981b; ref.19). If the particles accelerated by this mechanism are extracted from the wind, the implied injection rate is very low (~ 10^{-11}).

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