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GAMMA RAYS FROM ACTIVE REGIONS IN THE GALAXY : THE POSSIBLE CONTRIBUTION OF STELLAR WINDS

CATHERINE J. CESARSKY AND THIERRY MONTMERLE

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

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ABSTRACT

Massive stars (> 20 $M_\odot$) release a considerable amount of mechanical energy in the form of strong stellar winds. A fraction of this energy may be transferred to relativistic cosmic rays by diffusive shock acceleration at the wind boundary, and/or in the expanding, turbulent wind itself. Massive stars are most frequently found in OB associations, surrounded by H II regions lying at the edge of dense molecular clouds. The interaction of the freshly accelerated particles with matter gives rise to γ-ray emission. In this paper, we first briefly review the current knowledge on the energetics of strong stellar winds from O and Wolf-Rayet stars, as well as from T Tauri stars. Taking into account the finite lifetime of these stars, we then proceed to show that stellar winds dominate the energetics of OB associations during the first 4 to 6 million years, after which supernovae take over. In the solar neighborhood, the star formation rate is constant, and a steady-state situation prevails, in which the supernova contribution is found to be dominant. A small, but meaningful fraction of the COS-B γ-ray sources may be fueled by WR and O stellar winds in OB associations, while the power released by T Tauri stars alone is perhaps insufficient to account for the γ-ray emission of nearby dark clouds. Finally, we discuss some controversial aspects of the physics of particle acceleration by stellar winds.

I. INTRODUCTION

Five years have elapsed since the publication of the first COS-B catalogue of γ-ray sources (Hermsen et al. 1977). One of the most important informations brought by this catalogue, and subsequently confirmed by a more homogeneous and complete list of sources (Swanenburg et al. 1981), is that these sources have a very narrow galactic latitude distribution, and therefore must be physically linked with the youngest objects in the Galaxy. This strongly suggests that some stellar associations, like OB associations or T associations, and/or their placental molecular clouds, may constitute a class of γ-ray sources. In this paper, we discuss this type of γ-ray source.

The following ingredients are required : a cosmic-ray "factory", a confinement mechanism efficient enough to keep the cosmic rays within the vicinity of the factory for some time, and a concentration of interstellar matter, with which cosmic-ray protons and electrons can collide to produce high-energy γ-rays ; alternatively, a strong radiation field leading to γ-ray emission via the inverse Compton mechanism.

Let us consider these ingredients in turn. Obvious concentrations of interstellar matter are molecular clouds, or cloud complexes ; a typical molecular cloud has a mass $\sim 10^5\ M_{\odot}$, and a linear size $\sim$ 10-100 pc. We attribute the confinement of cosmic rays close to the factory to resonant interactions of cosmic rays with Alfvén waves they have themselves generated, while streaming through the surrounding gas at a velocity greater that the local Alfvén velocity (see Wentzel 1974 and references therein). These waves are damped strongly in dense, neutral clouds, but only weakly in ionized media, such as HII regions surrounding early-type stars, or the low-intensity, million-degree "hot interstellar medium" (HIM). If a large flux of cosmic rays is released in a short time, the particles remain strongly confined within the vicinity of the acceleration region for a long time, even if neutral gas is present (see details in Kulsrud and Zweibel 1975). If the cosmic rays are released over a long time, the net flux is lower, and so is the growth rate of the waves. When the cosmic-ray factory is surrounded by an H II region, particles are still efficiently scattered in the vicinity of the acceleration region ; if it is embedded in a dense, neutral cloud, particles are nevertheless partially confined within the cloud, because of scattering in the surrounding HIM. Problems related to cosmic-ray confinement is dense clouds have been examined by Cesarsky and Völk (1978), and Zweibel and Shull (1982). Detailed self-consistent models of sources embedded in various media have been constructed by Montmerle and Cesarsky (1981, 1982).

•Supernovae (i.e., supernova shocks, or supernova remnants) are the most popular cosmic-ray factory. Indeed, it has been suggested (Montmerle 1979, Montmerle and Cesarsky 1980), that 1/3 to 1/2 of the COS-B sources can be identified with "SNOBs" (Supernova remnants physically linked with OB associations, or with giant HII regions, containing early-type stars). It is evident that electrons are accelerated and trapped in supernova remnants , in view of their radio emission by the synchrotron mechanism. Quantitatively, it has been found that, for 8 SNOBs for which all the relevant information was available, the inverse Compton contribution to γ-ray emission is small, while the bremsstrahlung contribution can reasonably account for the bulk of the γ-rays observed, provided the electron spectrum extends down the energies as low as 10 or 20 MeV. Of course, this leaves room for a possible contribution of cosmic-ray protons, via direct $\pi^\circ \rightarrow 2\gamma$ decay, resulting from their collisions with H atoms. In the solar neighborhood, electrons and protons contribute about equally to the γ-ray emissivity above 100 MeV (Cesarsky, Paul and Shukla 1978, Lebrun and Paul 1979), whereas, at 1 GeV, electrons are 100 times less numerous than protons . More recent work on the relation between supernovae exploding in or close to molecular clouds, and γ-ray sources, has been discussed by several people in this Symposium.

Our own task is to consider another potential cosmic-ray factory, the stellar winds (see Cassé and Paul 1980), and to assess their role in a possible connection between stellar associations and γ-ray sources. In section II, we summarize some of the relevant information available on stellar winds from massive OB stars, and from low-mass, T Tau stars. In section III, we compute the overall energetics of supernovae and stellar winds on various scales, with the conclusion that winds in general do not play a major role, but may be quite significant in some interesting cases. In section IV, we address some of the physics underlying the results of section III : diffusive shock acceleration at the wind boundary, possibility of injection of particles from the thermal pool or by stellar flares, etc... We conclude in section V by a brief outlook on some developments needed to firmly establish the links between stellar winds and γ-ray sources.

II. PROPERTIES OF MASS-LOSING STARS

A. MASSIVE STARS

Data gathered at various wavelengths (mainly in the UV and radio ranges) have shown that massive O and B stars ($M > 20\ M_\odot$) shed a considerable amount of mass in the form of stellar winds (e.g. de Loore 1980). The mass-loss from O stars is on the order of $10^{-7}\ M_\odot\,yr^{-1}$, Of stars reaching $10^{-6} M_\odot\ yr^{-1}$. The winds blow at highly supersonic velocities (2000 to 3500 $km.s^{-1}$). The corresponding kinetic "luminosities" are large, $\gtrsim 10^{36}$ to 10^{37} $erg.s^{-1}$. Integrated over the lifetime of these stars (typically a few million years), the energy released is therefore of the same order as that of a supernova explosion. This energy will be released in most cases *within* an OB association, since 70 % to 80 % of the known O stars belong to associations ; the remainder are runaway stars (Cruz-González et al. 1974).

The maximum rates of mass-loss presumed to last on a significant timescale are observed in Wolf-Rayet (WR) stars. These stars, of which about 200 are known, are related either to old Pop. II stars (cores of planetary nebulae ; about 60 are known) or to Pop. I stars (Van der Hucht et al. 1981). In that case, they are thought to be a late, but comparatively brief (a few 10^5 yrs, e.g. Maeder and Lequeux 1982) evolutionary stage of O stars, perhaps immediately preceded by an Of phase (Conti, Niemela and Walborn 1979) Several models exist for this transition (Maeder 1982, de Loore 1980), but is is thought that all O stars above $\sim 23\ M_\odot$ display the "WR phenomenon" before becoming SN II supernovae (Maeder and Lequeux 1982). However, the WR stars appear to be linked less frequently than O stars with OB associations (or giant H II regions as their tracers), since at least ~ 60 % are isolated objects (Van der Hucht et al. 1981). (In view of the links between WR and O stars, it is not clear why this is so.)

Furthermore, the OB associations in which there are WR stars are quite rare (see Humphreys 1978) : they have therefore specific kinetic properties, in much the same way SNOBs do (see discussion in section III).

A feature worth mentioning is that the galactic distribution of WR stars displays a steep galactocentric gradient near the solar radius : compared with the blue supergiants, they are 3 times more frequent between 7 and 9 kpc than between 9 and 11 kpc, and 10 times more than between 11 and 13 kpc (Maeder, Lequeux and Azzopardi 1980). This will have consequences for the contribution of the winds to the overall energetics on a galactic scale (section III).

Another property of massive stars in OB assocations, which is particularly helpful for cosmic-ray confinement, is their ability to produce extended H II regions around them. However, the number of ionizing Lyman continuum photons is a strong function of the spectral type : for instance, it is 10^{50} s^{-1} for O4 stars like in the Carina Nebula, and only 10^{49} s^{-1} for O6 stars, the earliest type found in the Orion Nebula (M 42), and as low as 10^{45} s^{-1} for B 2 stars (see Panagia 1973). As a result, the sizes of the H II regions are strongly dependent on the stellar content of the OB associations : 50 pc in radius for Carina (this figure includes the contribution of the associated WR stars), down to $\sim$ 2.5 for Orion, or less for associations having later-type stars.

B. LOW-MASS STARS

Recent progress has also been made as regards another class of mass-losing stars : the T Tauri stars. These are low-mass stars ($M \lesssim 2\ M_\odot$), which usually cluster in associations (T associations), and are linked to small molecular clouds ($\sim 10^3 - 10^4\ M_\odot$), usually called "dark clouds". Many observational methods are used to derive the mass-loss characteristics of T Tauri stars : radio emission, Hα emission line width measurements, etc...

As discussed by De Campli (1981), the mass-loss rates derived are affected by large uncertainties (up to 3 orders of magnitude in some cases), but rates on the order of up to a few 10^{-8} $M_{\odot}$ yr^{-1} are consistent with the observational data and, perhaps, explainable by theory. On the other hand, the terminal velocities are moderate, though still supersonic, $\sim$ 250 $km.s^{-1}$. As a result, the energy release per star is not enormous ($\sim 10^{32}$ $erg.s^{-1}$), but the T Tau 's are numerous (up to several tens in the ρ Oph dark cloud for instance) and, at least in their earliest stages, concentrated and buried within their parent cloud.

While T Tau stars have spectral types (K5 to M5) corresponding to cool photospheres ($\sim$ 3500 °K), recent UV observations have shown that a significant part of their surface is covered by hot emission regions analogous to, but much more extended than, solar plages (Giampapa et al. 1982). They are not likely, however, to drive extended H II regions - a significant difference, in our context, with hot stars.

III. STELLAR WINDS : CONTENDERS OF SUPERNOVAE AS GENERATORS OF COSMIC RAYS AND GAMMA RAYS ?

A. MECHANICAL ENERGY RELEASED BY MASSIVE STARS

The lifetime of an OB association is typically 2×10^7 years, after which the association is dispersed because of random star motions (e.g., Blaauw 1964, Reeves 1978). The stars end their lives in the form of supernovae (SN II).

The formation timescale for stars in associations (i.e., on a small scale) is much smaller than the stellar lifetimes, hence we can approximate the birth of an association by a localized *burst*. In the solar neighborhood (i.e., on a larger scale), births and deaths of massive stars average out, resulting in a *steady state*. On this scale, the star formation rate must have been constant formore than 3×10^9 yrs, at least for stars below 10 $M_\odot$ (Grosbøl 1978).

Lequeux (1979) has derived the Initial Mass Function (IMF), using the stellar population of the solar neighborhood ($\lesssim$ 2.5 kpc), for masses 2.5 to 100 $M_\odot$. He included a correction for old-population runaway stars. Claudius and Grosbøl (1980) derived the IMF of individual young OB associations : their results, at least in the range 2.5 - 10 $M_\odot$, are compatible with those of Lequeux. We emphasize that the situation for higher masses is much less clear. Consequently, we first use Lequeux's IMF (which is comparatively poor in stars with masses above 20 $M_\odot$), and then investigate the consequences of using another, more recent IMF, which is richer in high-mass stars (Garmany, Conti,and Chiosi 1982).

We adopt, for the rate of star formation $\dot{N}$, and for the number of stars formed simultaneously, N, per unit area (with masses in $M_\odot$), the following expressions :

Steady state :

$$\frac{dN}{d\ell nM} = \zeta' M^{\alpha} \quad \begin{cases} \zeta' = 1.3 \times 10^{-3}\ yr^{-1} kpc^{-2} \\ \alpha = -2.0 \end{cases} \qquad (3.1)$$

Burst :

$$\frac{dN}{d\ell nM} = \zeta M^{\alpha} \qquad \alpha = -2.0 \qquad (3.2)$$

ζ being a normalisation factor, which may vary from one association to the next ; it is related to the "strength" of the burst. In both cases, the IMF extends up to M_{max}.

The lower limit M_p to the mass of the progenitors of type II supernovae is still under debate, and we take $M_p = 4\ M_\odot$ or $M_p = 8\ M_\odot$. The progenitors of type I supernovae are not well understood ; they are presumably low-mass stars in binary systems. It is therefore impossible to derive a SN I rate using IMF considerations, but observations of supernova explosions in external galaxies of type similar to the Milky Way suggest that the rates of SN I and SN II explosions are about equal (Tammann 1981). We assume that the same is true in the solar neighborhood. The kinetic energy released by each supernova explosion is taken to be $\overline{E}_s = 10^{51}$ ergs for both types.

As for stellar winds, the rate of mass-loss $\dot{M}$ is observed to depend mainly on the bolometric magnitude M_{bol} of the star. The influence of other parameters, such as gravity, temperature, etc... cannot be clearly disentangled, given the observational uncertainties (e.g., de Loore 1980). Using a theoretical HR diagram, it is possible to derive an empirical relation between $\dot{M}$ and the luminosity L (Lamers 1981), and, going one step further, an $\dot{M}$ - M relation (since for high masses, the luminosity remains constant throughout the evolution), in the form :

$$\dot{M} = \lambda M^{\mu} \qquad \left.\begin{array}{l} \lambda = 10^{-\varepsilon}\ M_{\odot} yr^{-1} \\ \mu = 1.6 \end{array}\right\} M > M_{min} = 20\ M_{\odot} \qquad (3.3)$$

$$\lambda = 0 \qquad M < 20\ M_{\odot}$$

The wind terminal velocity is, on average :

$$<w> = 2500\ km.s^{-1}$$

The theoretical lifetime $\tau(M)$ of stars is :

$$\tau(M) = \theta_1 M^{\gamma_1} \qquad M > 15\ M_{\odot} \qquad (3.4)$$

with $\theta_1 = 5.7 \times 10^7$ yrs, $\gamma_1 = -0.7$ (from de Loore 1980), and

$$\tau(M) = \theta_2 M^{\gamma_2} \qquad 4M_{\odot} < M < 15\ M_{\odot} \qquad (3.5)$$

with $\theta_2 = 9.4 \times 10^7$ yrs, $\gamma_2 = -1.73$ (from Miller and Scalo 1979).

To compute the total power released by WR stars, it is best to use directly the statistical data, since their relation to other stars is not fully understood. The surface density σ of WR stars in the solar neighborhood is $\sigma \sim 1.8\ kpc^{-2}$ (Hidayat, Supelli and Van der Hucht 1981). Also, we take $\dot{M} = 3 \times 10^{-5}\ M_{\odot} yr^{-1}$ and $w = 2500\ km.s^{-1}$ for all WR stars.

(i) steady state

In the *steady state* case, the average mechanical powers released by supernovae and stellar winds per unit area are :

$$\left.\begin{array}{l} \overline{P}_s(I) = \overline{P}_s(II) \\ \overline{P}_s(II) = \overline{E}_s \int_{M_p}^{M_{max}} \frac{d\dot{N}}{dM}\, dM \end{array}\right) \qquad (3.6)$$

$$\left.\begin{array}{l}\overline{P}_w(OB) = \displaystyle\int_{M_{min}}^{M_{max}} \frac{1}{2}\, \dot{M}\langle w\rangle^2 \,\frac{d\dot{N}}{dM}\, \tau(M)\, dM \\ \overline{P}_w(WR) = \frac{1}{2}\, (\sigma \dot{M} w^2)_{WR}\end{array}\right)$$

With the IMF of Lequeux and $M_{max} = 120\ M_\odot$, one has, altogether :

$$\begin{array}{l}\left\{\begin{array}{l}\overline{P}_s = 2 \times 10^{52}\ \text{erg.kpc}^{-2}\ (10^6\ \text{yr})^{-1}\ \text{if}\ M_p = 8\ M_\odot, \\ \overline{P}_s = 8 \times 10^{52}\ \text{erg.kpc}^{-2}\ (10^6\ \text{yr})^{-1}\ \text{if}\ M_p = 4\ M_\odot\ ;\end{array}\right. \\ \overline{P}_w(OB) = 1.3 \times 10^{51}\ \text{erg.kpc}^{-2}\ (10^6\ \text{yr})^{-1}, \\ \overline{P}_w(WR) = 3.5 \times 10^{51}\ \text{erg.kpc}^{-2}\ (10^6\ \text{yr})^{-1}.\end{array} \qquad (3.7)$$

Therefore, WR stars dominate the energetics of stellar winds, not only individually, but also collectively. Still, the total mechanical power released by supernovae exceeds that of stellar winds by a fairly large factor :

$$\left.\begin{array}{l}\overline{P}_s/\overline{P}_w = 5\ \ \text{if}\ M_p = 8\ M_\odot \\ \overline{P}_s/\overline{P}_w = 20\ \ \text{if}\ M_p = 4\ M_\odot\end{array}\right\} \qquad (3.8)$$

These results depend only weakly on M_{max}, provided, of course, that $M_{max} >> 20\ M_\odot$. For instance, if $M_{max} = 60\ M_\odot$ instead of 120 $M_\odot$, $\overline{P}_w$ is lower by 20 %, $\overline{P}_w(WR)$ by 10 %, $\overline{P}_s$ is practically unchanged. The results are not very sensitive either to the slope of the IMF, if different at high masses from that at low masses. For instance, if $dN/dM \propto M^{-2.6}$ above 20 $M_\odot$, as proposed by Garmany, Conti and Chiosi (1982), the ratio $\overline{P}_s/\overline{P}_w$ of eq. (3.8) is decreased by 20 %.

However, the results of eqs. (3.8) are perhaps not valid beyond the solar neighborhood. Given the magnitude of the observed WR/OB gradient (section II) as a function of galactocentric distance (a factor of 10 increase from 13 to 7 kpc) we cannot rule out the intriguing possibility that winds from WR stars shed more mechanical energy than supernovae in the inner galaxy.

(ii) Burst

Let us turn now to the energetics of a region where a *burst* of star formation has just taken place. During the lifetime of an OB association, some field stars may explode as SN I ; they are so rare that we disregard their contribution. The mechanical energies released are given by :

$$\left.\begin{aligned} & E_s(II) = p_s \bar{E}_s \int_{M(t)}^{M_{max}} \frac{dN}{dM}\, dM \quad \begin{cases} p_s = 0 \text{ if } t < \tau(M_{max}) \\ p_s = 1 \text{ if } t \geq \tau(M_{max}) \end{cases} \\ & E_s(I) << E_s(II) \end{aligned}\right\} \quad (3.9)$$

$$\left.\begin{aligned} & E_w(OB) = p_w \int_o^t dt \int_{M_{min}}^{M^*} \frac{1}{2} \dot{M} <w>^2 \frac{dN}{dM}\, dM \\ & \begin{cases} p_w = 1,\ M^* = M_{max} & \text{if } t < \tau(M_{max}) \\ p_w^p = 1,\ M^* = M(E) & \text{if } \tau(M_{max}) \leq t \leq \tau(M_{min}) \\ p_w = 0, & \text{if } t > \tau(M_{min}) \end{cases} \end{aligned}\right\} \quad (3.10)$$

For WR stars, it is not possible to make a similar evaluation without some additional assumptions about their genesis. We then assume that all stars having more than 23 $M_\odot$ become WR stars near the end of their evolution, and that this stage lasts $\sim 4 \times 10^5$ yrs (Maeder and Lequeux 1982). The total energy supplied by a WR star is then $\bar{E}_{WR} \simeq 7 \times 10^{50}$ ergs, comparable to that of a SN explosion. Since this energy is released on a comparatively short timescale, the contribution of WR stars can be calculated like that of SN (eq. 3.9), with $p_{WR} = 1$ for $\tau(M_{max}) \leq t \leq \tau(23\ M_\odot)$, and $p_{WR} = 0$ elsewhere.

To calculate the normalization factor ζ appearing in eq. (3.2), we will consider that OB associations having very early-type stars (O4, O3) i.e. $M_{max} \simeq 120\ M_\odot$, contain roughly 40 stars with masses above 15 $M_\odot$ (O stars and supergiants ; see Humphreys 1978). Then $\zeta = 2 \times 10^4$.

The corresponding (absolute) powers $\overline{P} = \dot{E}$ are represented as a function of time on Fig. 1 for OB and WR winds and for SN II explosions. With $M_{max} = 120\ M_{\odot}$, the total power turns out to be approximately constant in the wind-dominated phase of the OB association, $1-2 \times 10^{38}$ erg.s^{-1} Winds dominate during the first ∿ 5 million years, SN II thereafter. Such a configuration could be representative of the Carina Nebula, which contains 3 WR stars and several O3 stars (and probably no supernova , see discussion in Montmerle, Cassé and Paul 1982), or of the Cygnus X complex, featuring 7 WR stars and several O3-C4 stars in its two youngest associations. The mechanical energy determined from the actually measured mass-loss from the early-type and WR stars present in the Carina Nebula is ∿ 3×10^{38} erg.s^{-1} (Montmerle 1981), which compares favourably with the results shown on Fig. 1.

In reality, M_{max} is probably different from one association to the next. For instance, the Orion OBId association (Trapezium cluster, ionizing M42), contains no star above ∿ 30 $M_{\odot}$ (earliest type O6), but is however known to be much younger than the lifetime of a 30 $M_{\odot}$ star (less than 5×10^5 yrs [e.g. Reeves 1978], as compared to 4×10^6 yrs). The stellar content is therefore very different from that of the "Carina-like" associations mentioned earlier.

Taking now $M_{max} = 30\ M_{\odot}$ as representative of Orion-like associations, we obtain Fig. 2. Orion is in the pre-WR stage, and Fig. 2 gives $P_w = 4.5 \times 10^{37}$ erg.s^{-1}, as compared with 5×10^{37} erg.s^{-1} obtained by summing the actual contribution of stars with known mass-loss (Montmerle 1981). Once the WR stage is reached, it lasts only ∿ 1/10 of the total association lifetime. This explains - qualitatively - why there are relatively few associations with WR stars in them. Note also that SNRs dominate the energetics as soon as the first mass-losing stars die : this may also explain why there are more SNOBs than WR-dominated associations.

Another interesting case is the Gould Belt (Stothers and Frogel 1974), an expanding ring of gas clouds and young stars, lying ∿ 150-500 kpc around the sun and thought to be about 30 million years old (see Olano 1982). It probably originated in a huge burst of star formation, followed by other, smaller events. Its estimated age indicates that, as a whole, this part of the solar neighborhood has been in the SN-dominated phase for the last several million years (*).

(*) A very different scenario for the origin of the Gould Belt has been presented by Strauss, Poeppel and Vieira (1979). These authors consider that the Belt is a self-gravitating system, born as a result of the collapse of a massive clump of gas ($\sim 10^7\ M_\odot$), about 50 million years ago. The gas would have been almost entirely turned into stars, and the expansion of the Gould Belt in the galactic plane would simply be the dynamical consequence of the vertical collapse of the clump on the plane. In this model, the energy released by stellar winds in the solar neighborhood must have been considerable (see, e.g., Cassé and Paul 1980). However, if the IMF of Lequeux (1979) holds, the model also predicts a density of 1 to 5 $M_\odot$ stars - no higher-mass star is still alive after 5×10^7 yrs - about 150 times higher than observed. Models of the Gould Belt such as recently proposed by Olano (1982), in which the expansion is driven by stellar winds and SN explosions, are much more satisfactory in this respect.

B. STELLAR WINDS, γ-RAYS, AND COSMIC RAYS

The power required to maintain the observed cosmic ray pool in the solar neighborhood is $\sim 2.3 \times 10^{51}$ erg.kpc^{-2} $(10^6\ \mathrm{yr})^{-1}$, (e.g., Blandford and Ostriker 1980). If supernovae are the factories of galactic cosmic rays, the efficiency of conversion of mechanical energy into cosmic-ray energy must be :

$$\eta_s = 10\ \% \text{ if } M_p = 8\ M_\odot,\ \eta_s = 2.5\ \% \text{ if } M_p = 4\ M_\odot.$$

Local stellar winds can fulfill the energy requirement only if $\eta_w \simeq 1$. On this basis, local supernovae are still the prime candidates for the acceleration of local galactic cosmic rays. It is interesting to note that, if $\eta_w \simeq \eta_s$, stellar winds contribute a fraction $f_w \simeq 1/5$ to $1/20$ of the particles (see below). In the framework of the self-consistent model of the γ-ray source 2CG288-0 associated with the Carina Nebula, Montmerle and Cesarsky (1981) have found that the efficiency η_w required is indeed of a few percent.

More generally, considering the evolution of OB associations as a function of time leads to other consequences as regards γ-ray sources and peculiarities in the cosmic rays.

In addition to the Carina Nebula, several other galactic regions are known to contain WR and/or Of stars, most notably the Cygnus region, which includes two associations (Cyg OB 1 and OB 2), apparently Carina-like, in the WR-wind dominated phase (Fig. 1). The regions expected to have the most powerful winds are known to be associated with γ-ray emission : the γ-ray flux of 2CG288-0 measured by COS-B is 1.6×10^{-6} photons (> 100 MeV).$cm^{-2}.s^{-1}$ (Swanenburg et al. 1981) whereas the Carina Nebula lies at ∿ 2.5 kpc from the Sun. The Cygnus complex, ∿ 1.8 kpc away, is also a strong γ-ray emitter, but with a structure more complex than a simple source.

Using the catalogue of Humphreys (1978), and assuming that the acceleration and confinement properties are as in the case of the Carina Nebula, it is possible to predict which of the known associations should be visible in γ-rays. The result is that only some of the associations featuring WR stars lie above the visibility threshold of COS-B (1.0×10^{-6} ph.$cm^{-2}.s^{-1}$ for a source) : Cyg OB 2, which is part of a bright γ-ray complex, Sco OB 1, ∿ 2 kpc away, unfortunately near the galactic center direction, hence buried in a strong galactic γ-ray background, and the Carina associations. Six other associations featuring WR and/or Of stars, are either not powerful enough or too distant to be visible (Cassé , Montmerle and Paul 1981).

What about Orion-like associations in the wind-dominated phase ? If, again, efficiencies of acceleration and confinement are the same than in the Carina Nebula, we would clearly expect them to be below the visibility threshold of COS-B, if at a typical COS-B source distance, $\sim$ 2 kpc. This is also confirmed by Cassé , Montmerle and Paul (1980).

But Orion itself should emit a flux of $\sim 10^{-5}$ ph.cm^{-2}.s^{-1}, whereas no γ-ray source is found in this region. We attribute this lack of observed γ-ray emission to a much lower confinement efficiency, considering that M42 is a much smaller H II region than the Carina Nebula (Cesarsky and Montmerle 1982).

In the supernova-dominated phase, Orion-like associations release much more energy, and thus are in a much better position to power a γ-ray source; hence the possible identification of SNOBs with a significant fraction of the γ-ray sources (Montmerle 1979).

In short, OB associations may be "typical" COS-B sources only if they are powered by WR winds or supernovae. (This is not inconsistent with the assertion of Wolfendale [1982], that most molecular clouds - hence, OB associations - are "inert" γ-ray emitters, i.e., dominated by ambient galactic cosmic rays.)

If true, the very fact that an association is a γ-ray source indicates that the cosmic rays must have traversed a grammage X not small with respect to the proton interaction length, $\sim$ 70 g.cm^{-2}. This is most easily done while associations are still young and embedded in a dense gaseous medium. In the case of the Carina Nebula, taking confinement by ionized regions into account, we find X $\simeq$ 40 g.cm^{-2} (Montmerle and Cesarsky 1981). Most nuclei will then be broken up by spallation reactions, while antiprotons (in addition to γ-rays) will be copiously produced as secondaries resulting from inelastic collisions of protons with the cloud particles. This type of "dense source" may explain the high $\bar{p}/p$ ratio observed at a few GeV by Golden et al. (1979), and Bogomolov et al. (1979), but not the $\bar{p}$ flux detected around 300 MeV by Buffington et al. (1981), see Cesarsky (1982). The number of such $\bar{p}$ sources required is consistent with the number of γ-ray sources and peaks of γ-ray emission in the galactic plane observed by COS-B (Cesarsky and Montmerle 1981 ; Cowsik and Gaisser 1981). Given the values of f_w = 1/5 to 1/20 found above, it may well be that a sizeable fraction of the (γ-ray + $\bar{p}$) sources are related to stellar winds embedded in dense, ionized regions.

Still, mass-losing stars are not found exclusively in associations, or in large cloud complexes : for instance, we have seen that many WR stars or runaway O stars do not belong to associations. In this context, it is interesting to note that Cassé and Paul (1982) have proposed that, to account for the observed overabundance of ^{22}Ne in cosmic rays, about 1/60 of the galactic cosmic ray flux should originate in WR stars and traverse no more than the usual ∿ 7 $g.cm^{-2}$.

C. GAMMA RAYS ASSOCIATED WITH LOW-MASS STARS ?

Compared with the energy output of winds from massive stars and SN, the mechanical energies associated with T Tau stars seem minute , about 3 × 10^{32} $erg.s^{-1}$ at most per star.

However, molecular clouds contain a large number of these stars (T Tau or related pre-main-sequence objects), lying often within the boundaries of the cloud. A powerful tool to detect them is through their highly variable X-ray emission : about 60 such stars were found in a recent *Einstein* survey of the ρ Oph cloud (Montmerle et al. 1982), associated with the γ-ray source 2CG353+16, i.e., more than twice the previously known number of such objects. The total mechanical energy released $P_{w,tot}$ is therefore on the order of

$$P_{w,tot} \simeq 2 \times 10^{34} \text{ erg.s}^{-1}$$

Assume further that the rate of conversion of gas into stars is ∿ 10 % (which is reasonable for ρ Oph if the PMS stars have ∿ 3 $M_\odot$ on average, with a cloud mass of ∿ 2000 $M_\odot$, see discussion in Montmerle et al. 1982). For clouds having M ∿ 10^5 $M_\odot$, we get about 3000 stars, i.e., a total power ∿ 5 × 10^{35} erg.s^{-1}. This remains small with respect to the contribution of massive stars.

Now, if we assume that the confinement properties of the Carina Nebula and of the ρ Oph cloud are identical, scaling for the wind powers, "ρ Oph -like" clouds should not be visible at the level of 10^{-6} ph.cm^{-2}.s^{-1} further away than 32 pc. This indicates that either the confinement is even more efficient, or that an energy source other than the PMS star winds is present. For the specific case of ρ Oph, there may be up to 9 massive B2 stars present (see discussion in Montmerle et al. 1982), boosting the wind power to 4 × 10^{35} erg.s^{-1}. The "visibility range" then becomes ∿ 140 pc, in satisfactory agreement with the distance of the cloud.

An alternative proposal has been made by Morfill et al. (1980), in terms of a chance collision between the ρ Oph cloud and a fraction of an old supernova remnant believed to be associated with the North Polar Spur, and visible in soft X-rays. If true, the source 2CG353+16 would then fall into the SNOB class, even though the original supernova is not genetically linked with the cloud.

IV. MAKING A GAMMA-RAY SOURCE OUT OF STELLAR WINDS

A. A HANDY MECHANISM : DIFFUSIVE SHOCK ACCELERATION

During the past years, the theory of particle acceleration by shock waves in a diffusive medium has developed rapidly (see recent reviews by Axford 1981, Drury 1982). This mechanisme relies on the fact that fast particles of velocity v increase their momentum by a relative amount $\sim w/v$ every time they cross a shock of velocity w. If particles are scattered efficiently on both sides of the shock, they remain trapped for some time in the shock vicinity, and, on average, cross the shock v/w times. But a few particles remain around for a longer time, as in any Fermi-type mechanism, so that a power-law spectrum of cosmic rays develops. The most attractive feature of such a mechanism is that, in the case of a plane shock, and in the time-independent limit, the spectral index depends only on the compression ratio of the shock, $\rho(\text{downstream})/\rho(\text{upstream})$ (Bobalsky 1977 a,b, 1978a,b), as long as the angle φ between the magnetic field direction and the shock normal is not too close to 90° ($\sec\varphi \ll v/w$). In the context of galactic cosmic-ray acceleration, it has been applied to supernova shocks, and to stellar wind terminal shocks, which separate the wind from the external medium. Stellar wind terminal shocks are like inverted supernova shocks, the shocked gas lying outside of the shock (Weaver et al. 1977).

Depending on the value of the diffusion coefficient K in the vicinity of the shock, different results are obtained. If $K(R) \gtrsim wR$ (when R is the shock radius), the adiabatic losses suffered by the particles while they are diffusing in the stellar wind (in the absence of local acceleration, see next section), hinder seriously the efficiency of the acceleration mechanism. In that case, even in the time-independent, linear limit (i.e., neglecting the back-reaction of cosmic rays on the shock), the problem is extremely cumbersome. Webb, Axford and Forman (1981) were able to solve the problem analytically when the diffusion coefficient K is assumed to be independent of momentum, and proportional to the distance to the star, while Drury (1982) gives a solution valid when K/(wR) is small, but not negligible. For a given rate of particle injection, the maximum yield in cosmic rays is obtained when K/(wR) is very small, in which case the shock can be considered as planar, allowing to recover the simple power-law spectrum predicted by the elementary theory.

The limit $K \ll wR$, which is thus the most favourable for stellar wind acceleration of cosmic rays, has been adopted in recent discussions of this problem by Montmerle and Cesarsky (1981), Völk and Forman (1981) and Cesarsky and Montmerle (1982). In the remainder of this paper, we will discuss the most controversial issues regarding this type of model.

B. CURRENT OBJECTIONS TO THE PLAUSIBILITY OF STELLAR WIND ACCELERATION, AND POSSIBLE WAYS OUT

The initial framework for SW acceleration (Cassé and Paul 1980) involved the possibility of injecting MeV particles by stellar-flare-like events, to fulfill a possible requirement of pre-existing non thermal particles injected into the diffusive shock mechanism.

Two major objections were put forward against this approach :

1) Adiabatic losses suffered by flare particles, during their transport out to the border of the wind cavity, typically a few million times the stellar radius, must be enormous, thus bringing efficiently the initially non -thermal particles back into the thermal pool (Völk 1981, Völk and Forman 1982).

2) The magnetic field lines, anchored to a mass-losing star, are in the form of Archemadean spirals if the star is rotating (Parker 1958). As a result, far from the star, the magnetic field is azimuthal, and diffusive shock acceleration does not work any more.

Possible ways out of these difficulties exist. Montmerle and Cesarsky (1981) point out that stellar flares particles can be re-accelerated by encounters with shocks while they traverse the stellar wind cavity ; indeed, recent observations have shown that interplanetary acceleration does occur in the solar wind, and, apparently the farther from the Sun, the more efficiently (McDonald 1981). Völk and Forman (1982) consider, following Eichler (1979), Krymsky (1980) and Ellison, Jones and Eichler (1981), that the particles participating in the acceleration process are ions picked out of the tail of the thermal plasma, instead of being injected at $\sim$ MeV energies separately. Rather than elaborating a self-consistent scheme of shock-regulated injection, they assume, in analogy with the Earth's bow shock, that $\sim$ 1 % of the stellar wind ions are injected into the process. They argue that the acceleration can only be intermittent, occuring along small parts of the shock where the magnetic field lines are at a finite angle to the shock, for a time on the order of a stellar rotation period at most, $\sim 10^5$-10^6 sec. In such short times, the ions can reach only a few MeV. As a result, according to these authors, stellar winds could at best be associated with sources of nuclear γ-rays, but not of γ-rays in the COS-B range, which require protons above $\sim$ 1 GeV.

In fact, the objections above, and the arguments of Völk and Forman (1982), rest almost entirely on the assumption that the solar wind is "typical" of stellar winds, and that some parameters, like the diffusion mean free path, have values similar to those measured in the interplanetary space at $\sim$ 1 A.U.

However, the winds from the kind of stars which are of interest here, i.e. mainly massive O and WR stars, and T Tauri stars, are *very different* from the solar wind. The basic reason for this different behavior, is that their mass-loss rates (10^{-8} $M_{\odot}yr^{-1}$ to 10^{-5} $M_{\odot}yr^{-1}$) are enormously higher than the Sun's (10^{-14} $M_{\odot}yr^{-1}$), which, in turn, implies widely different driving mechanisms.

For massive O stars, the mass-loss is probably driven by the enormous radiation output ($L_{bol} = 10^{39}$ erg.s^{-1}), as discussed recently by Lucy (1982a), although extreme cases (like some WR stars) remain to be fully explained. On the other hand, it has been known for some time that such a mechanism leads to Rayleigh-Taylor-type instabilities in the flow (Nelson and Hearn 1978) ; the basic physical ideas are as follows. The momentum is imparted to the gas by interactions with the stellar radiation at frequencies corresponding to the resonance lines of the ions, mainly in the UV range. If a part of the gas ("blob") has a slightly higher density than its surroundings, the resonant radiation is more efficiently trapped there, thus increasing the net radiative force ; at the same time, the regions just in front of the blob are partially shielded. As a result, the blob becomes accelerated with respect to the surrounding gas, until the combined "shadows" of similar blobs closer to the star attenuate the radiative force on the blob considered.

Calculations (Lucy 1982b) show that the velocities reached by the blobs are largely supersonic, reaching a few hundreds of km.s^{-1} with respect to the expanding flow. Assuming, for simplicity, that all blobs are equidistant, a few tens of such blobs may coexist along a given radius of an O star wind cavity. This view, although rather crude at present, is consistent with the observations : the blobs are made of gas at $\sim$ a few 10^4 K, emitting the UV lines which display strong P Cygni profiles, and the surrounding expanding gas is heated at X-ray temperatures by the supersonic blob motions, resulting in a two-phase fluid, as observed. As for WR stars, simple radiative transfer in a monotonic wind cannot explain the highest mass losses observed, but including backscattering of the stellar UV photons on the blobs appears a promising way to solve this problem (see discussion in Lucy 1982b).

This framework enhances the possibility of shock acceleration *within* the expanding flow. The acceleration of particles by a collection of randomly oriented shocks has been studied by Bykov and Toptyghin (1982). They consider in particular the specific problem of particle acceleration in an expanding wind, and show that, for the case of interest here, the ratio of the adiabatic loss time to the acceleration time is $\beta \simeq wL/(v\Lambda)$, when L is the mean distance between the shocks, v the velocity of the particles and Λ their diffusion mean free path. (It is worth noting that the shocks must not be too highly packed, otherwise the time spent by the particles in the vicinity of a given shock is too short to lead to an appreciable gain in energy.)

Typical values of the parameters for O stars are : $w = 2500\ km.s^{-1}$, $L \approx 1/20\ R_w$ where R_w is the radius of a wind cavity, i.e. $L \simeq 0.1$ pc (see Lucy 1982b). We are interested in the fate of $\sim$ MeV particles, for which $v \simeq 1.5 \times 10^4\ km.s^{-1}$. The value of the magnetic field strength B in the cavity is difficult to guess. In a Parker-type wind, $B \sim 3 \times 10^{-6}$ G at the terminal shock, provided its value at the stellar surface is ~ 100 G. Such a value of the surface field may be implied by the recent observations of soft X-ray emission from O stars, if interpreted in the framework of the "confined corona model" (Vaiana 1981). In the disordered wind considered here, we can expect some turbulent dynamo effect, hence expect B to be somewhat stronger, perhaps on the order of 10^{-5} G. We take the particle diffusion mean free path as $\Lambda \approx r_g/a$, when r_g is the gyroradius, and $a < 1$ is a parameter which, in the framework of the quasilinear theory, is roughly equal to the ratio of the energy density in waves resonating with the cosmic rays to the energy density of the magnetic field. Therefore :

$$\Lambda(\text{cm}) = (1.5 \times 10^{10}/a)\ (10^{-5}\ \text{G}/B)$$
$$\beta = 4 \times 10^{6}\ a \times (B/10^{-5}\ \text{G})$$

In the stormy medium we are considering, it seems reasonable to expect $a \gg 10^{-6}$, hence $\beta \gg 1$: particles accelerated by flares at the surface of the star may very well get a boost in energy while coasting out to the terminal shock, in other words, be *continuously* accelerated along the flow. Then, these particles still have appreciable energies when they reach the shock.

Given the effects of differential rotation, we can expect that the magnetic field, even if partially regenerated by a turbulent dynamo in the wind, tends to be aligned parallel to the shock. However, in view of the fact that the blobs have radial surpersonic velocities with respect to the mean flow, the field must have also a significant component perpendicular to the shock, so that the angle φ is close, but not quite equal, to 90°. Acceleration can then occur only for particles which can overcome the injection theshold $v > w \sec \varphi$, i.e., mainly particles from stellar flares (as opposed to the wind particles themselves). The number of such particles available is probably not high enough to affect the shock structure so that the linear theory of shock acceleration is valid.

Provided the acceleration is not intermittent, the highest energies that cosmic rays of charge Z can attain at stellar wind terminal shocks may be as high as :

$$E_{max} = 4 \times 10^{6}\ Z(B/10^{-5}\ \text{G})\ (w/2.5 \times 10^{8}\ \text{cm.s}^{-1})^{2}\ \text{GeV}$$

whereas for supernova shocks :

$$E_{max} < 10^{5}\ Z(B/10^{-6}\ \text{G})\ \text{GeV}$$

(Cesarsky and Lagage 1981, Lagage and Cesarsky 1982). Stellar winds are better than supernovae to reach very high energies for two reasons : stellar wind shocks are bounded on both sides by a highly turbulent medium (and therefore short acceleration times are expected), and the shock velocity remains high significantly longer than for supernova shocks.

D. WINDS FROM T TAU STARS

As compared with O stars, the wind driving mechanisms for T Tau stars seem to be much less well understood. Of course, radiation is by far insufficient, in energy and in wavelength. What is sure, however, is that the winds from T Tau stars are very different from the acoustic wave-driven solar wind. In particular, if it were not so, the X-ray luminosity that one would expect from T Tau stars should be several orders of magnitude higher than observed (De Campli 1981 ; Montmerle et al. 1982).

A class of current models is based on Alfvén waves, assumed to originate in the "shaking" of the surface magnetic field by the convective zone which exists just below. The matter is driven by hydromagnetic pressure, and mass losses up to $\sim 10^{-8}\ M_{\odot} yr^{-1}$ may be explained in this way. (De Campli [1981] estimates that higher mass-loss rates cannot be explained and that the observational uncertainties are compatible with the conclusion that they do not exist.) As such, this mechanism does not generate shocks, and therefore does not appear to be able to lead to particle acceleration within the wind, as in the case of massive stars. But the stability of such a flow has not been studied, and it is known observationnally that, at least in some cases (YY Ori stars), there is evidence for a competition between mass outflow and accretion (see Appenzeller 1982), leading to Rayleigh-Taylor instabilities at the interface between the wind and the surrounding dense medium. Cases of non-spherical mass loss are also known in Herbig-Haro objects, related to T Tau stars (see Mundt and Hartmann 1982).

A good deal more work seems necessary at present to fully understand T Tau star winds, and therefore the situation as to the adiabatic losses of particles injected by the giant flares known to be present (Montmerle et al. 1982), or as to the magnetic field configuration, must still be considered as open.

V. CONCLUSIONS

Stellar winds can play a significant role in various areas of galactic astrophysics. This role is in general short-lived, since massive O stars (> 20 $M_\odot$) live only a few million years, WR stars a few 10^5 years, and T Tau stars also a few 10^5 years. Stellar winds probably dominate the energetics of the earliest stages of evolution of OB associations, giving rise to γ-ray sources observed by COS-B only if WR stars are present. They are also perhaps an original clue to some intriguing problems in galactic cosmic ray astrophysics, such as the origin of the ^{22}Ne excess, the high $\bar{p}/p$ ratio, or the origin of some very high energy cosmic rays.

On the other hand, time is working for supernovae. Indeed, since all stars with masses above 4 or 8 $M_\odot$ end up as supernovae, they largely outnumber the stars able to have strong stellar winds. In the long run, then, the victory of supernovae over stellar winds seems unavoidable... The situation, for various galactic environments, is summed up in Table 1.

Of course, the possible relatively small, albeit physically meaningful, role of stellar winds relies entirely on their assumed ability to accelerate particles to relativistic energies. On theoretical grounds, this has not been clearly demonstrated yet. But the prospects of such a demonstration look undoubtedly promising for O and WR stars. The situation, unfortunately, is much less clear for low-mass pre-main sequence stars, for which the very phenomenon of mass loss is still poorly understood.

Can we expect some advances on the observational side ? Obviously, one of the best ways is to look at OB associations in γ-rays, but a great leap forward is required from the experiments, both in angular resolution and sensitivity. The angular resolution must first help in assessing the identification of OB associations with a class of γ-ray sources, and must be such that it becomes possible to separate out possible γ-ray "hot spots" linked with OB associations in a molecular complex. For Orion as well as for Carina , at least a few arc minutes must be reached, a factor of 10 better than COS-B. The gain required in sensitivity should be large enough to allow observations of as many associations as possible in detail, in particular to check the links between confinement efficiency and extent of the ionized regions. A gain in sensitivity of a factor of 10 would allow to observe Orion-like associations out to $\sim$ 1.5 kpc, while an improved angular resolution would help in increasing the contrast with a possible galactic diffuse γ-ray emission on the same line of sight.

Even then, it should be stressed that the observational answer to the problem of CR acceleration by stellar winds may not be clearcut , as it is very difficult to be sure that, in an association or in a molecular cloud, no SN lies hidden somewhere. For instance, at face value, the diffuse X-ray flux from the Carina Nebula region could be explained in terms of a SNR a few 10^5 yrs old (Seward and Chlebowski 1982) ; we have seen that a SNR, associated with the North Polar Spur, may be at work to explain the γ-ray source in the direction of the ρ Oph dark cloud.

Perhaps another distinct possibility is to look for non-thermal radio emission from T Tau stars. One should however choose T Tau stars with weak mass loss, otherwise the free-free emission associated with the stellar wind (e.g., Berthout and Thum 1982) might bury the possible non-thermal emission. But only (comparatively) strong fluxes, on the order of a few mJy , could be detected with the best instrument to date, namely the Very Large Array.

It thus seems that, for some time, we will have to rely mostly on theory to decide whether or not stellar winds are able to accelerate particles. "The answer, my friend, is blowing in the wind", but we do not know yet how to listen to it...

Ackowledgment. We thank Michel Cassé for useful discussions.

TABLE 1

CONTRIBUTION OF STELLAR WINDS AND SUPERNOVAE TO COSMIC RAYS AND GAMMA RAYS IN THE GALAXY

Scale	Medium (distance)	Stellar winds important for :	Supernovae important for :	Remarks
Very small ($\lesssim$1 pc)	Dark clouds ($\lesssim$200 pc)	*T associations,* *if CR confinement* *strong enough :* γ-ray sources ?	*if chance* *collision with* *field SNRs :* γ-ray sources	ρ Oph cloud only known possible example
Small (∼10-100 pc)	Molecular clouds ($\lesssim$3 kpc)	*OB associations,* *if WR present* *(Carina, Cygnus):* { γ-ray sources $\overline{p}$ very high-energy CR ?	*OB associations,* *if SN present* *(SNOBs) :* { γ-ray sources $\overline{p}$	Average OB associations ("Orion-like") invisible as γ-ray sources
Medium ($\lesssim$1-2 kpc)	Solar neighborhood ($\lesssim$2.5 kpc) Gould Belt ($\lesssim$500pc)	^{22}*Ne excess in CR* *from isolated WR ;* *diffuse γ-ray features*	*Local CR ;* *diffuse γ-ray* *features*	$\overline{P}_s/\overline{P}_w$ = 5 or 20 (depending on SN progenitors)
Large	Galaxy	*dominant contribution* *to GCR from WR* *in the inner galaxy ?* *part of diffuse γ-ray emission*	*probable major* *contribution* *to GCR ;* *part of diffuse γ-ray emission*	gives SN acceleration efficiency : η_s = 2.5 to 10 %

FIGURE CAPTIONS

Fig. 1 : The energetics of a "Carina-like" OB association as a function of time. Such associations are characterized by a high mass cut-off in the IMF (slope $\alpha = -2.0$, after Lequeux 1979) at $M_{max} = 120\ M_{\odot}$. Wolf-Rayet stars (WR) are here supposed to be a late evolutionary stage of all stars more massive than $23\ M_{\odot}$, immediately preceding their explosion in the form of type II supernovae. The minimum mass for a star to have a strong stellar wind is taken as $20\ M_{\odot}$. (The average power is normalized so that the association comprises about 40 stars between $15\ M_{\odot}$ and $120\ M_{\odot}$, and matches the actual mechanical power released by the OB and WR stars in the Carina Nebula).

Fig. 2 : Same as Fig. 1, for "Orion-like" associations, characterized by $M_{max} = 30\ M_{\odot}$.

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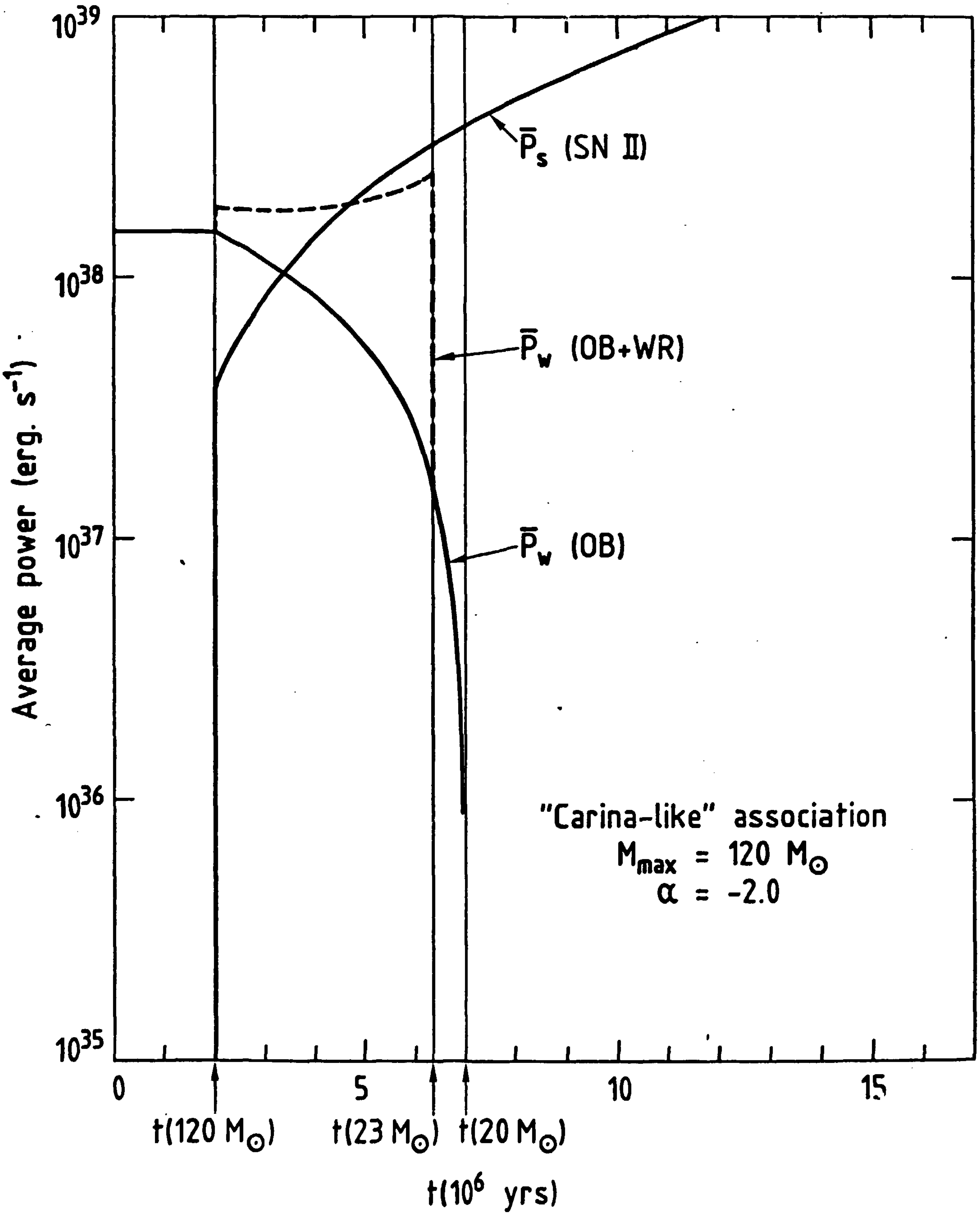
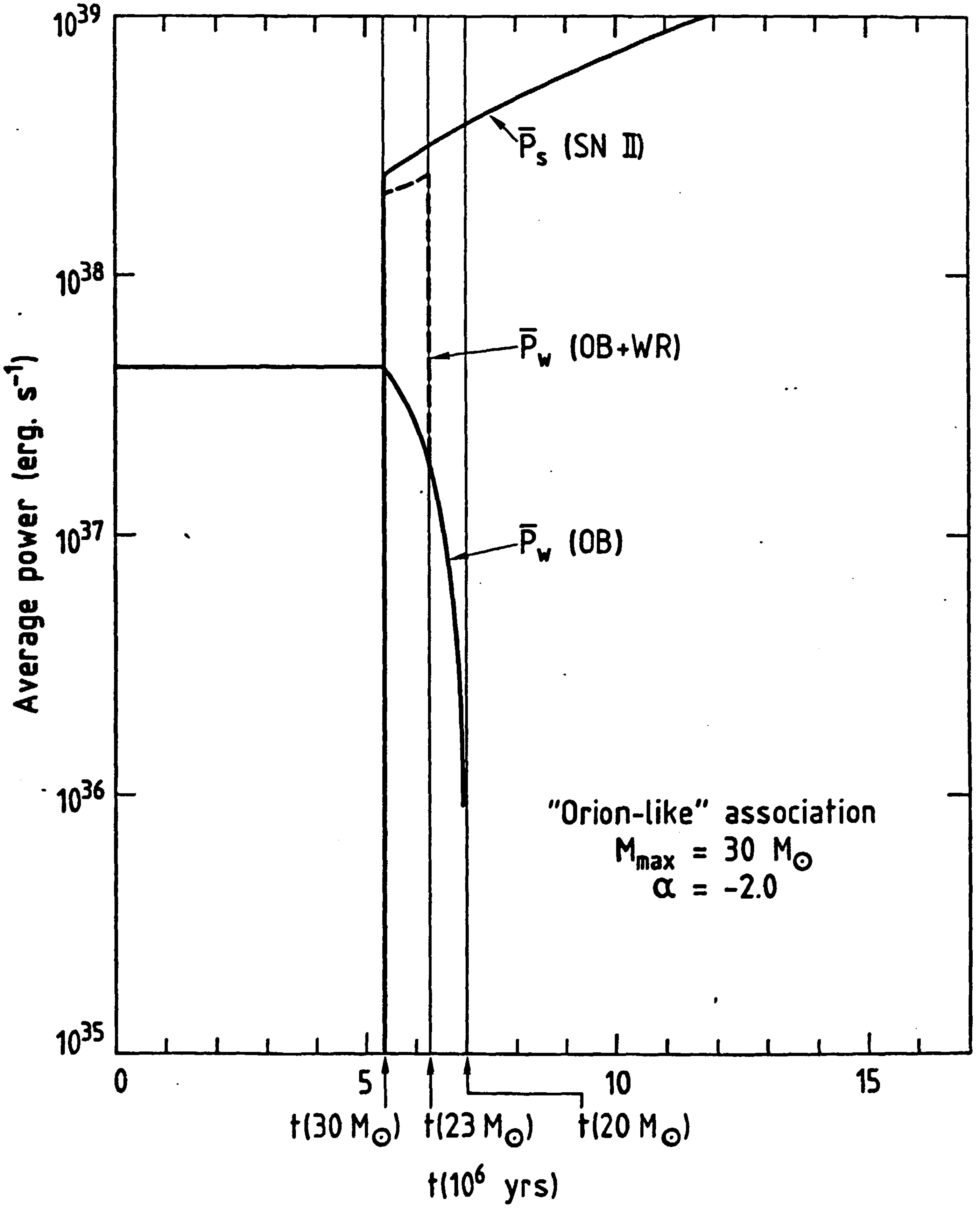

10^39
10^38
10^37
10^36
10^35
Average power (erg. s^-1)
P̄s (SN II)
P̄w (OB+WR)
P̄w (OB)
"Carina-like" association
Mmax = 120 M⊙
α = -2.0
0
5
10
15
t(120 M⊙)
t(23 M⊙)
t(20 M⊙)
t(10^6 yrs)

Fig. 1



Average power (erg. s^{-1})
10^{39}
10^{38}
10^{37}
10^{36}
10^{35}
$\bar{P}_s$ (SN II)
$\bar{P}_w$ (OB+WR)
$\bar{P}_w$ (OB)
"Orion-like" association
M_{max} = 30 $M_\odot$
α = -2.0
0
5
10
15
t(30 $M_\odot$)
t(23 $M_\odot$)
t(20 $M_\odot$)
t(10^6 yrs)

Fig. 2