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Communication présentée à : 2. IAP Meeting on nuclear astrophysics
Paris (France)
7-11 Jul 1986

2nd IAP Rencontre: Nuclear Astrophysics
July 7-11, 1986

MASSIVE STARS, "X-RAY RIDGE", AND GALACTIC ^{26}Al GAMMA-RAY LINE EMISSION

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Abstract. Massive stars interact with their parent molecular cloud by means of their ionizing flux and strong winds, thereby creating giant, hollow HII regions. To account for the observed structure of these HII regions, it appears necessary that all the wind energy be dissipated. Dorland and Montmerle have recently proposed a new dissipation mechanism; in the process, diffuse hard X-rays are emitted. If the observed galactic X-ray "ridge" results from this process on a galactic scale, it can be accounted for by the interaction of ~3000 WR stars (mostly within a ~6.5 kpc ring) with their surrounding interstellar gas. This result is essentially consistent with the suggestion by Prantzos and Cassé that the galactic ^{26}Al γ-ray line emission originates in WR stars.

I - INTERACTION OF MASSIVE STARS WITH THE INTERSTELLAR MEDIUM

Massive stars ($\gtrsim 20\ M_\odot$) are generally found in OB associations, located in the outer layers of giant molecular clouds. The stars interact with the dense cloud material through their ionizing Lyman continuum radiation, and through their strong winds, especially if Wolf-Rayet (WR) stars are part of the OB associations, being the latest stages of the most massive O stars (e.g., Prantzos et al.[1]). The resulting giant HII regions are characterized by large cavities surrounded by thick shells, often tens of pc in diameter.

However, the classical "hot interstellar bubble" models (e.g., Weaver et al.[2]) do not reproduce the thick shell structure, nor the expansion velocities, and this has led several people (e.g., Chu[3]) to suggest that the bubble evolution is momentum-conserving (i.e. involves a strong dissipation of the wind energy) rather than energy-conserving, as in the classical models (see however Van Buren[4]).

Indeed, assuming that the dissipation of the wind energy takes place in a thin layer downstream of the wind shock, and also taking into account the evolution of massive stars in selected real OB associations, Dorland et al.[5] have shown that the thick-shell/hollow structure of giant HII regions could be well reproduced. Figs.1 and 2 show, respectively, the time evolution of the mass loss rate and of the Lyman continuum flux for the OB association exciting the Carina nebula. This OB association contains several O3 and WR stars; its evolution has been computed with stellar evolution models featuring mass-loss and overshooting in the convective core (Doom[1], Prantzos et al.[6]). Fig.3 shows the structure of HII regions with wind energy dissipation, and Fig.4 shows the resulting evolution of the inner and outer radii of the thick ionized shell, which matches well the present values.

II - WIND ENERGY DISSIPATION AND DIFFUSE X-RAY EMISSION

Examining the question of wind energy dissipation, Dorland and Montmerle[7] noticed that one reason why the classical bubble models fail is that steep temperature gradients exist near the wind shock. In this case, the usual laws of heat conduction (which is the main

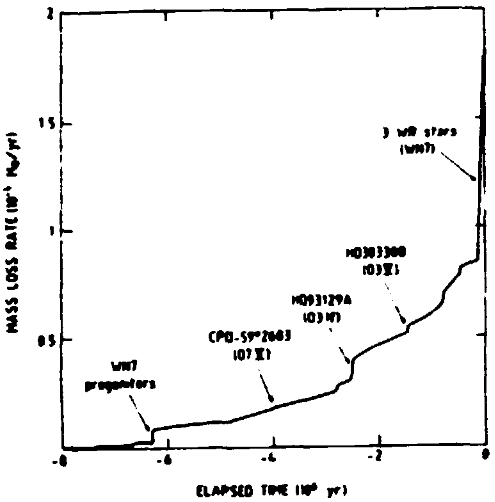

Fig.1

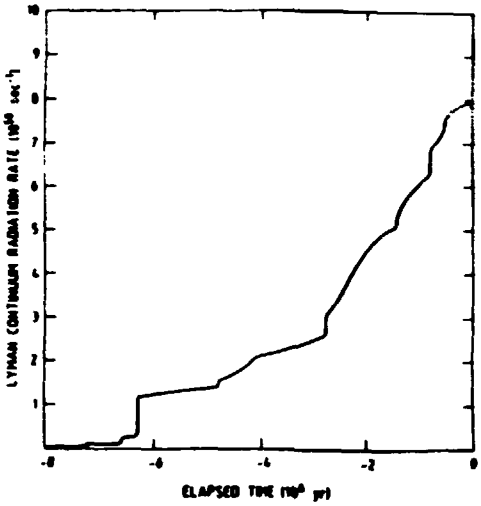

Fig.2

Fig.1 - Time evolution of the total mass-loss rate of the stars exciting the Carina nebula. The birth of a few of the earliest-type stars is indicated.

Fig.2 - Corresponding time evolution of the total Lyman continuum radiation.

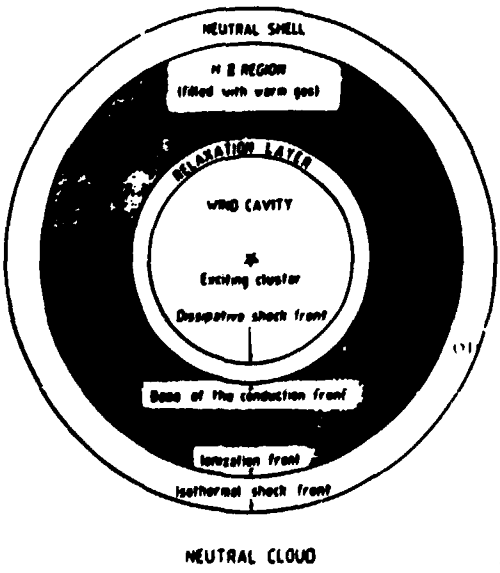

Fig.3

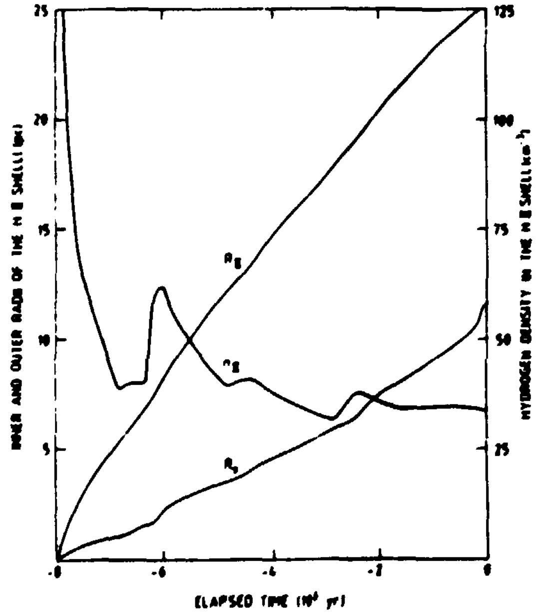

Fig.4

Fig.3 - Structure of a giant, hollow HII region with complete energy dissipation in a thin layer downstream of the wind shock.

Fig.4 - Time evolution of the Carina nebula, corresponding to the stellar evolution depicted in Figs.1 and 2. R_I is the inner radius of the thick HII shell (Fig.3), R_{II} is the corresponding outer radius, and n_{II} is the average shell density. (The model assumes an initial molecular cloud density of 500 cm^{-3}). (Figs.1-4 are based on ref.5).

energy transport agent in classical bubble models) are not applicable. More precisely, the ratio L_T/λ of the temperature gradient scalelength to the mean free path of the electrons downstream of the shock is smaller than the critical value $(L_T/\lambda)_c \simeq 500$ (Gray and Kilkenny[8)]). The (non-linear) problem has been studied in the framework of laser-heated fusion plasmas, and new laws been found by Luciani et al.[9)], and applied by Dorland and Montmerle[7)] (hereafter DM) to the problem of wind energy dissipation in hollow HII regions, as now summarized.

In brief, the consequences of non-linear heat conduction are twofold:

(i) The electron distribution function is strongly non-Maxwellian: it features essentially a "hot" electron tail, coupled with a "warm" nearly Maxwellian electron population. The hot tail can be characterized by an equivalent temperature T_h; the warm electrons have a temperature corresponding to the maximum of the isobaric cooling function, and it can be shown that all the wind energy is efficiently radiated in a thin "conductive-radiative" dissipation ("CRD") layer downstream of the wind shock.

(ii) The actual conductive flux q can be related to the conventional "free-streaming" value $q_{FS} = n_e m_e (kT/m_e)^{3/2}$ by $q = \zeta q_{FS}$, where ζ is called the "flux-limit factor". In plasmas, depending on the physical conditions, the theory predicts $0.16 < \zeta_{th} < 3.2$, whereas laboratory values are $0.03 < \zeta_{lab} < 0.10$. The agreement is therefore not yet satisfactory, and we have left ζ as a free parameter - the only one of our model.

Here, we are interested in the hot electron component. DM derive the temperature T_h as a function of the average wind velocity V_w and of ζ : Fig.5 shows that, for typical values of V_w relevant to massive stars ($\sim$2-4000 km.s^{-1}), T_h is in the keV range. The ratio $[L_x/L_w]$ (V_w, ζ) of the corresponding X-ray luminosity of the CRD layer, normalized to the wind energy input rate, or "luminosity", $1/2\ \dot{M} V_w^2$ is shown on Fig.6. The results can be applied to various nebulae observed in X-rays; from the best studied one, the Carina nebula (see, e.g. Chlebowski et al.[10)]) , DM find that $\zeta = 0.085 \pm 0.005$ gives a good fit to both T_h and L_x/L_w. (Note that this value is also in the range

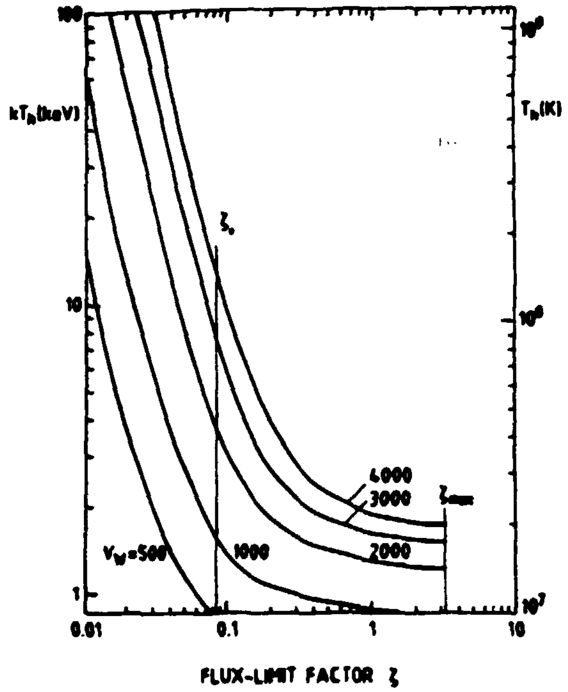

Fig.5

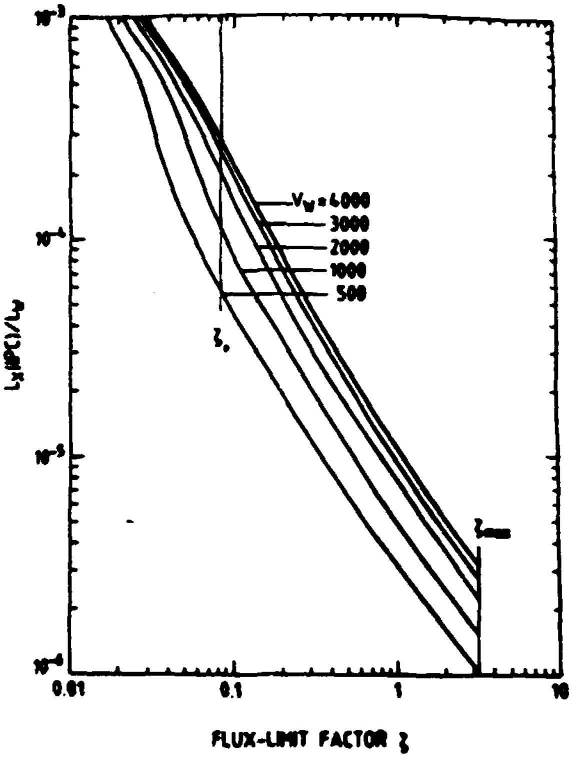

Fig.6

Fig.5 - The flux-limit factor $\zeta = q/q_{FS}$ gives a measure of the non-linearity of heat conduction. ζ_o is the "astrophysical" value, ζ_{max} the theoretical maximum value in plasma physics. T_h is the temperature of the "hot" electron component present in the "conductive-radiative" dissipation layer: for $\zeta = \zeta_o$, T_h is in the keV range for typical values of stellar wind velocities V_w.

Fig.6 - Same as Fig.5, for the corresponding diffuse X-ray luminosity of the CRD layer L_x (here taken in the range of the *Einstein* IPC instrument), normalized to the stellar wind "luminosity" L_w. A typical value of L_x (IPC)/L_w is seen to be $\sim 2 \times 10^{-4}$ (Figs.5 and 6 are based on ref.7).

of laboratory values). Using this value, one finds that, typically, $L_x/L_w \sim 2 \times 10^{-4}$, and $4 < T_h < 12$ keV for $2000 < V_w < 4000$ km.s^{-1}. These values are quite general, and depend only very weakly on properties of hollow HII regions (density, size, etc..).

III - THE "X-RAY RIDGE" AND MASSIVE STARS IN THE GALAXY

Recent X-ray observations by the EXOSAT and *Tenma* satellites suggest that the proposed dissipation mechanism may be taking place on a galactic scale. EXOSAT (Warwick et al.[11]), with relatively good large-scale imaging capabilities but poor energy resolution of its ME detector, found evidence for a diffuse galactic "ridge" of temperature 6 (+14, - 2) keV, of total luminosity $L_{x,gal} \simeq 1.5 \times 10^{38}$ erg.s^{-1}. On the other hand, Tenma (Koyama[12], Koyama et al.[13]) with good energy resolution but poor angular capabilities, found evidence for hard X-ray emission throughout the galactic plane, at temperatures 2 to 16 keV depending on the line-of-sight, with excesses in the directions of several well-known massive star-formation regions (Cygnus, Perseus, etc..). The derived total X-ray luminosity is $L_{x,gal} \simeq 10^{38}$ erg.s^{-1}. The thermal bremsstrahlung nature of the X-rays detected by Tenma is certified by the ubiquitous presence of Fe line emission. Several arguments tend to rule out the explanation of the X-ray "ridge" in terms of supernovae (Koyama et al.[13]), and we point out that the range of temperatures observed by Tenma is very similar to that deduced from the dissipation mechanism proposed by DM, suggesting that the X-ray "ridge" may in fact be the result of the interaction of winds from massive stars with their surrounding dense interstellar medium, throughout the galactic plane.

If we adopt this point of view, we can immediately derive the total galactic stellar wind "luminosity" $L_{w,gal}$:

$$L_{w,gal} \simeq 1.5 \times 10^{-4} \quad L_{x,gal}$$

(taking into account a suitable X-ray detector bandwidth correction). Introducing a correction factor δ for the "official" IAU distance to the galactic center ($\delta = 0.85$ for the formerly used 10 kpc), we find:

$$L_{w,gal} \simeq 6.5 \times 10^{41} \quad \delta^2 \quad \text{erg.s}^{-1}$$

(Incidentally, we note that $L_{w,gal}$ is then of the same order as the total galactic supernova energy rate).

Now WR stars are the most "mechanically luminous" stars, with mass-loss rates $\langle \dot{M} \rangle \sim 3 \times 10^{-5} a \; M_{\odot} \; yr^{-1}$ ($a \simeq 1$) and wind velocities $\langle V_w \rangle \gtrsim 3500$ km.s^{-1}. (It has been recently suggested that $\langle \dot{M} \rangle$ should rather be $4 \times 10^{-5} \; M_{\odot} \; yr^{-1}$ [14], in which case $a = 4/3$). Then, neglecting a possible 20% additional wind contribution of O stars, we find the total number N_{WR}^{X} of WR stars necessary to account for $L_{w,gal}$ from X-ray observations:

$$N^X_{WR} \sim 5500 \quad \delta^2/\alpha$$

i.e. $N^X_{WR} \sim 3000$ WR stars using the latest data.

Using further the EXOSAT results, which show that the ridge emission is mainly concentrated between longitudes ± 50°, we deduce that WR stars must be concentrated essentially within a 7.5δ kpc ring. We finally note that the ridge scaleheight, ~ 100 pc, is compatible with the O star scaleheight, hence presumably with the (poorly known) WR star scaleheight.

IV - LINK WITH THE GALACTIC ^{26}Al LINE EMISSION

Prantzos and Cassé[15)], and Prantzos[16)] have recently suggested that the 1.8 MeV ^{26}Al γ-ray line emission detected in several satellite and balloon observations could be accounted for by a total of $N^\gamma_{WR} \sim 8000$ WR stars in the galaxy, i.e.

$$N^\gamma_{WR} \sim 8000 \quad \alpha' \, \delta^2$$

if corrected by δ and α', which is the correction to the 1.8 MeV line yield when $\dot{M}$ becomes $\alpha \dot{M}$. According to Prantzos and Cassé[15)], most of the ^{26}Al is ejected during the pre-WR (Of) phase, so that the yield is not very sensitive to $\dot{M}$: α' should be ~ 1.

N^X_{WR}, as well as N^γ_{WR} are probably not known to better than a factor of 2, owing to various uncertainties, and therefore can be taken as mutually consistent. If one, however, takes these numbers at face value, the ratio $N^X_{WR}/N^\gamma_{WR} = 0.7/\alpha \simeq 0.5$ may be taken as expressing the ratio of WR stars inside dense, hollow HII regions, to their total number. This last figure is itself compatible with what is known about the presence of WR stars in OB associations (Lundström and Stenholm[17)]).

We therefore conclude:

i) The interpretation of the X-ray "ridge" emission of the galactic plane as resulting from stellar wind energy dissipation by the mechanism proposed by DM independently supports - and is supported by - the interpretation of the ^{26}Al γ-ray line emission in terms of synthesis by WR stars.

ii) To further observationally check these interpretations, one should look for detailed Fe X-ray line/Al γ-ray line correlations, especially in regions of massive star formation.

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