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STARBURSTS AND THE PRODUCTION AND DISPERSAL OF HEAVY ELEMENTS

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RESUMEN

Aquí estudiamos otras propiedades de los llamados *starbursts*. En particular encontramos la cantidad de material que reinsertan en el medio interestelar como función del tiempo, a consecuencia de las explosiones de supernova de todas las estrellas masivas ($M_* \geq 8M_\odot$). Usando diferentes aproximaciones a la evolución estelar, también encontramos las tasas de producción de oxígeno y de hierro como función del tiempo y de la masa total del *starburst*. Los recién creados nuevos elementos claramente incrementan la metalicidad de las superburbujas resultantes, hecho que ha de tomarse en cuenta cuando se calcule el enfriamiento y la luminosidad en rayos X de las superburbujas. También hacemos notar que serán necesarios varios cientos de millones de años para cambiar la metalicidad del medio interestelar.

ABSTRACT

Here we derive some further properties of starbursts; namely the amount of matter returned to the interstellar medium by means of supernova explosions from massive stars ($M_* \geq 8M_\odot$), as a function of time. Following different approximations to stellar evolution we also derive the time dependent oxygen and iron production rates as a function of the starburst mass. The newly created heavy elements clearly enhance the metalicity of the resultant superbubbles, fact that should be taken into consideration when calculating the cooling and the X–ray luminosity of superbubbles. It however will take several times 10^8 yr for them to enhance the metalicity of the ISM.

Key Words: **HYDRODYNAMICS — ISM: METAL ABUNDANCES — ISM: — STARS: STARBURSTS — STARS: METAL PRODUCTION RATES**

1. THE METAL PRODUCTION RATES IN MASSIVE STARBURSTS

So far the consensus indicates that massive starbursts in a wide variety of galaxies all follow an initial mass function similar to that derived by Salpeter for the solar neighbourhood. Our approach then assumes an initial stellar mass distribution (IMF)

$$n(m) = f_0 m^{-\alpha}, \tag{1}$$

within a range of upper $M_{up} = 100\ M_\odot$ and lower $M_{low} = 1\ M_\odot$ cutoff masses and a slope of $\alpha = 2.35$. The normalization constant f_0 is determined by the total mass of the star cluster M_{SB},

$$f_0 = \frac{(\alpha - 2)M_{SB}}{M_{up}^{2-\alpha} - M_{low}^{2-\alpha}}. \tag{2}$$

Assuming for simplicity that massive stars lose *all their mass* as they explode as SNe (Pilyugin 1993; Pilyugin & Edmunds 1996), we find the total ejected mass as a function of the cluster age t,

$$M_{ej}(t) = f_0 \int_{M_\star(t)}^{M_{up}} m^{1-\alpha} \mathrm{d}m = M_{SB} \frac{M_\star(t)^{2-\alpha} - M_{up}^{2-\alpha}}{M_{low}^{2-\alpha} - M_{up}^{2-\alpha}}, \tag{3}$$

where the mass of the stars exploding after an evolutionary time t, ($M_\star(t)$), has been found using the approximations of Chiosi, Nasi & Sreenivasan (1978) and Stothers (1972) to the main sequence lifetime of massive stars:

$$M_\star(t) = \begin{cases} 10\,(9\times10^6/t)^2 M_\odot, & \text{for } \; 30\ M_\odot \le M_\star \le 100\ M_\odot \\ 10\,(3\times10^7/t)^{5/8} M_\odot, & \text{for } \; 7\ M_\odot \le M_\star \le 30\ M_\odot. \end{cases} \tag{4}$$

Heavy element yields from massive stars have been considered in a number of papers (e.g. Renzini et al. 1993). However, the exact values depend strongly on the adopted stellar evolution models. A recent attempt to incorporate the injection of heavy elements in the hydrodynamics of superbubbles, by D'Ercole & Brighenti (1999), has included only averaged values. We have decided to consider several possible scenarios. The oxygen yield as a function of the stellar mass ($M_\star$) can be approximated by two different tracks: one is the "no wind" (NW) Pilyugin & Edmunds (1996) analytic approximation to the models of Maeder (1992) and Thielemann et al. (1993),

$$Y_O(M) = 0.094\,(M-10.5)^{1.272}\,M_\odot, \tag{5}$$

which neglects the oxygen yield for stars with a mass smaller than 10.5 $M_\odot$. The second "with wind" (WW) approximation, follows from stellar evolution models accounting for stellar winds (Maeder 1992; Woosley, Langer & Weaver 1993). In this case eq. (5) can be used within the 10.5 $M_\odot \le M_\star \le 25\ M_\odot$ range, assuming a constant yield up to the upper mass limit $\mathrm{M}_{up} = 100\ \mathrm{M}_\odot$.

The long term iron contamination comes mainly from the SNIa, which produce 0.5–0.7 $M_\odot$ of iron after the ^{56}Ni decay. However, we are interested here in the earlier stages of the starburst evolution and thus the iron yield from the SNIa has not been taken into account. The iron production from type II SN is highly uncertain (see Renzini et al. 1993) and, therefore, we have considered two extreme models: that of Arnett (1991) and that of Thieleman et al. (1992). In the Arnett (1991) model, the iron yield increases with the mass of the star, and can be approximated by a linear function for stars between 10 $M_\odot \le M_\star \le 40\ M_\odot$.

$$Y_{Fe}(M_\star) = 0.02 + 0.006\,(M_\star - 10)\,M_\odot, \tag{6}$$

For other stellar masses we have assumed constant values of Y_{Fe}. $Y_{Fe} = 0.02\ M_\odot$, for $M_\star \le 10\ M_\odot$, and $Y_{Fe} = 0.2\ M_\odot$ for $M_\star > 40\ M_\odot$. In the model of Thielemann et al. (1992), the iron yield is approximated by the exponential function

$$Y_{Fe}(M_\star) = \frac{0.423}{\exp\left[0.31(M_\star - 10.5)\right]} + 0.045\,M_\odot, \tag{7}$$

within the 13 $M_\odot$ – 25 $M_\odot$ range, and assumed to be constant outside this range and equal to $Y_{Fe}(M_\star) = 0.24\ M_\odot$ for low mass stars, and $Y_{Fe}(M_\star) = 0.05\ M_\odot$ for stars with an initial mass larger than 25 $M_\odot$. We shall refer to the above approaches for deriving the iron production rates as A (for Arnett 1991), and T (for Thielemann et al. 1992), respectively.

Figure 1 shows the time dependent total amount of matter injected into the superbubble interior (M_{ejecta}) as a consequence of type II supernova for the NW and A approximations and the WW and T assumptions (panels **a** and **b**, respectively). This is to be compared with the total amount of oxygen (M_O) and iron (M_{Fe}) produced by the star cluster during the first 40 Myr of evolution. Note that at this time the amount of iron has not yet reached its final value, as an important contribution is expected from stars with a mass smaller than 10 $M_\odot$.

As shown by Silich et al. 2000, if one takes into consideration the time dependent injection of heavy elements into the growing superbubble, one would find important changes in metalicity. Silich et al. considered a variety of cases in which the ejecta mixes with the matter thermally evaporated from the outer shell of swept up matter, and have shown how the metalicity that one may infer is strongly dependent of the tracer (O, or Fe) used to compare with solar values. The resultant metal content has also an important effect on the radiative cooling and on the X–ray luminosity of superbubbles.

We have also assumed that the stellar matter ejected before the first SN explosion ($\sim$ 3 Myr) has the same metallicity as the ISM. Note that the expressions used for the yields are for solar metallicity stars (which are the ones available) while the stars in the models have metallicities of 0.1 $\mathrm{Z}_\odot$.

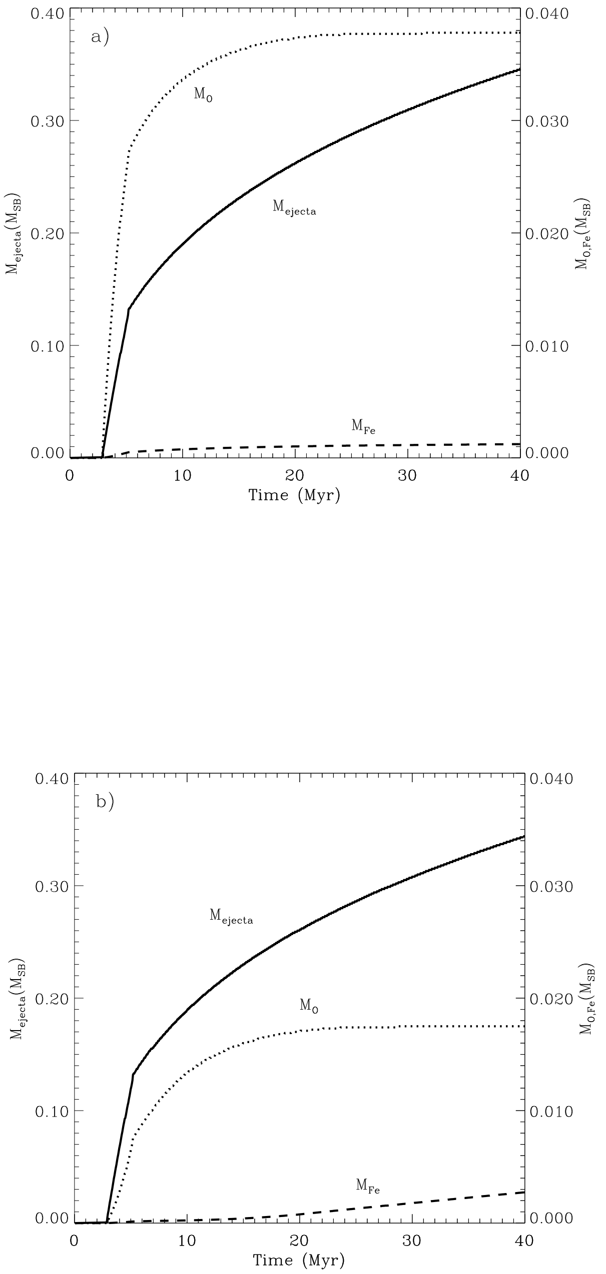

Fig. 1. Time–dependent metal production from starbursts. The panels display the cumulative amount of matter (in units of the starburst mass M_{SB}) ejected by SNe as a coeval starburst evolves in time (solid line). Also shown are the amounts corresponding to oxygen (dotted lines) and to iron (dashed lines). **(a)** The oxygen production values were derived under the NW assumption and those for iron following the A approximation. **(b)** The corresponding values resulting from the WW and the T approximations for oxygen and iron, respectively.

The metallicities of the hot bubble interior relative to solar are given by

$$Z_{hot,O} = \frac{M_{ej,O}/Z_O + Z_{ISM} M_{ev}}{M_{ev} + M_{ej}}, \tag{8}$$

$$Z_{hot,Fe} = \frac{M_{ej,Fe}/Z_{Fe} + Z_{ISM} M_{ev}}{M_{ev} + M_{ej}}, \tag{9}$$

where M_{ev} is the mass added to the shocked wind region due to the cold outer shell evaporation.

The superbubble interior is to remain hot throughout the starburst supernova phase (50 Myr), and then after the last supernova explosion, radiative cooling will begin to bring its temperature down. The decrease in temperature will cause pressure gradients, particularly if there are large and strong density fluctuations in which cooling may proceed more rapidly (see Tenorio–Tagle 1996). The fluctuations are expected from the thermal evaporation from the outer shell of swept up matter and from the condensations immersed in the hot superbubble interior. To readjust and re–establish pressure balance strong shock waves will be driven into the cooling condensations, causing them to become more compact, denser and thus even faster radiators, as they fall towards the disk of the host galaxy. During the fall, Rayleigh–Taylor instabilities would favor the fragmentation of the compressed condensations causing the rain of heavy element droplets into a large section of the host galaxy disk. It is in this way that the newly created heavy elements, generated in a region of less than 100 pc (the starburst volume) are dispersed over several kpc (the dimensions of the superbubbles). Cooling takes about ($t_\Lambda = 3\mathrm{kT}/(\mathrm{n}\Lambda)$) 2×10^8 yr and during this time the organized (rotation) and chaotic motions in the galaxy will help to further disperse the new heavy elements. Diffusion of the heavy element droplets will then cause the enhanced abundances of the interstellar medium. Thus, the element abundances that we measure must have been caused by former generations of stars. The new elements violently released by the present bursts of star formation necessarily have to confront strong reverse shocks that would heat them up to the large temperatures detected in superbubbles. The large temperatures will inhibit their recombination, and thus their detection at optical frequencies, and it will delay their mixing with the ISM. It will take in fact about 2–4 $\times$ 10^8 years for them to begin to enhance the abundances of the ISM.

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