NUCLEOSYNTHESIS OF $^{26}\text{Al}$ IN ROTATING WOLF-RAYET STARS

A. Palacios$^1$, G. Meynet$^2$, and C. Vuissoz$^3$

$^1$Institut d’Astronomie et d’Astrophysique - U.L.B. - CP-226, Bd du Triomphe, B-1050 Brussels (Belgium), palacios@astro.ulb.ac.be
$^2$Observatoire de Genève, CH-1290 Sauverny (Switzerland), Georges.Meynet@obs.unige.ch
$^3$Laboratoire d’Astrophysique de l’EPFL - Observatoire - CH-1290 Chavannes-des-Bois (Switzerland), Christel.Vuissoz@obs.unige.ch

ABSTRACT

The $^{26}\text{Al}$ radionuclide can be detected through its decay emission line at 1.809 MeV, as was first observed by Mahoney et al. (1982). Since then, COMPTEL on board of the CGRO satellite, performed a sky survey in this energy range, and provided maps of the $^{26}\text{Al}$ distribution in the Galaxy. These results revealed that the main contributors to the synthesis of $^{26}\text{Al}$ are most likely the massive stars, which contribute through their winds (Wolf-Rayet stars) and through their supernova explosion. Comparison between these observations (in particular observations in localized regions such as the Vela region and the Cygnus region) and the models available at that moment, showed however the need for improvements from both theoretical and observational points of view, in order to improve our understanding of the $^{26}\text{Al}$ galactic distribution as well as that of its synthesis. With the launch of the INTEGRAL satellite in October 2002, the observational part will hopefully be improved, and the construction of better resolution maps at 1.809 MeV is one of the main aims of the mission. From a theoretical point of view, we need the most up-to-date predictions in order to be able to interpret the forthcoming data.

In this paper, we address this latter part, and present new results for $^{26}\text{Al}$ production by rotating Wolf-Rayet stars and their contribution to the total amount observed in the Galaxy.

Key words: nucleosynthesis; rotation; stellar evolution.

1. $^{26}\text{Al}$ SOURCES

$^{26}\text{Al}$ is a radioactive nuclide that can be produced by hydrostatic nucleosynthesis in H burning regions, by explosive nucleosynthesis and by spallation. Its half-life time in its ground state is of $7.2 \times 10^5$ yr, and it is thus a good tracer of recent nucleosynthetic events in the Galaxy. The maps obtained with COMPTEL (Diehl et al. 1995, Knödlseder et al. 1999, Plüschke et al. 2001) allowed to pin down the main contributors to the diffuse emission observed mainly in the galactic plane: massive stars (Prantzos & Diehl 1996, Knödlseder 1999). These objects end their lives with a supernova explosion, during which $^{26}\text{Al}$ can be synthesized and will eventually be expelled (Heger et al. 2003). The more massive (and shorter lived) ones will also contribute during quiescent evolutionary phases through their winds.

2. WOLF-RAYET STARS

Wolf-Rayet (hereafter WR) stars are the bare cores of massive O–type stars that lost their hydrogen rich envelope due to very strong stellar winds or by mass transfer in a close binary system. They exhibit at their surface the products of the internal nucleosynthesis accompanying first the central H–burning (WN phase) and then central He–burning phase (WC and WO phases). At solar metallicity, all stars more massive than about 30 $M_{\odot}$ go through a WR phase, which typically lasts for a few $10^5$ years in the case of non-rotating objects (Meynet & Maeder 2003; 2004), and massively contribute to the chemical enrichment of the interstellar medium (hereafter ISM).

$^{26}\text{Al}$ is synthesized during the central H–burning phase in these stars, and is eventually ejected into the ISM as the star is peeled off by strong winds during the WR phase. The amount of $^{26}\text{Al}$ ejected in the ISM through winds is very sensitive to mass loss rates, metallicity, rotation and initial mass. Meynet et al. (1997) presented a first study of the effects of initial mass and metallicity, as well as the effects of different possible prescriptions for convection. At that time, they could already show that the amount of $^{26}\text{Al}$ ejected increases with metallicity and initial mass. In the grid of models used by Meynet et al. (1997), artificially twice enhanced mass loss rates were used, which appeared at that time to better fit...
the observed properties of the WR stars in a series of environments (Maeder & Meynet 1994).

In the following, we present the results obtained for a new grid of models including rotation and updated mass loss prescriptions for the different evolutionary phases that massive stars are likely to go through. Part of these results were discussed in Vuissoz et al. (2004).

3. ROTATION INDUCED MIXING

Massive stars are known to have high equatorial velocities ($<v> = 200 – 250 \text{ km.s}^{-1}$) while on main sequence. Such a rotation affects the evolution of stars in several ways. It first has a direct incidence on its structure through the centrifugal acceleration. It also affects the mass loss in terms of geometry and quantity. Finally it triggers instabilities in the radiative interior of the star, which allow transport of angular momentum and chemical species.

Transport of angular momentum and chemical species is ensured by the meridional circulation, which settles in to balance the thermal disequilibrium induced by the departure from spherical symmetry in rotating objects, and by the shear instability associated with the turbulent layers in regions with high angular velocity gradients (Zahn 1992; Maeder & Zahn 1998).

We chose an initial velocity $v = 300 \text{ km.s}^{-1}$ for all masses and metallicities, taking into account that this value is compatible with the mean averaged observed velocity of O-type stars at solar metallicity. Considering this, the rotating models used here well reproduce a series of observed features for O-type and WR stars, that non–rotating models fail to fit (Meynet & Maeder 2004).

4. RESULTS FOR $^{26}\text{Al}$

The effects of rotation on $^{26}\text{Al}$ production in WR stars are consequences of both the effects on the mass loss and of the rotation induced mixing. The main results for what concerns $^{26}\text{Al}$ are the following:

- At given metallicity, rotation allows stars with lower initial masses to enter the WR phase. When we take stellar rotation into account (which is an observational fact), the number of stars contributing to the $^{26}\text{Al}$ enrichment of the ISM through stellar winds is thus increased. The total contribution of WR stars to the galactic content of $^{26}\text{Al}$ is larger when using rotating models than when using non–rotating ones, as can be seen in Fig. 3, and as will be discussed in the next section.

- At given mass and metallicity, rotation results in an entrance into the WR phase at an earlier age.
evolutionary stage (not necessarily at an earlier time). For instance the solar metallicity 60 M_☉ star model enters the WR phase during the core He-burning phase when it is non-rotating and during the end of the core H-burning phase when it is rotating. In this last case the duration of the WR phase is longer so that the cumulative time interval during which 26Al is expelled is larger for rotating stars. This leads to an enhancement of the 26Al yields. This is well illus-
trated in Figs. 1 and 2 where the evolution of the cumulated mass of 26Al is shown as a function of time for both rotating and non-rotating models.

- The higher the metallicity, the larger the ejected mass of 26Al (see Fig. 1 and Fig. 2).

This is due to the metallicity dependence of mass loss rates and to the higher 25Mg mass fraction available for 26Al synthesis at higher metallicity.

- Rotation allows surface enrichment of 26Al prior to the WR phase. This is a direct consequence of the combined effects of meridional circulation and turbulence which allow 26Al to diffuse outwards from the convective core, where it is produced by proton capture on 25Mg, up to the radiative envelope, and to appear earlier at the surface of the star.

5. CONTRIBUTION OF WR STARS TO THE 26Al GALACTIC CONTENT

One can evaluate the contribution of WR stars to the total galactic mass of 26Al in the following way:

\[ M_{26}^{gal} = \tau_{26} M_{26}^{gal} = M_{26}^{gal} \]

\[ = \int_{0}^{R} 2\pi r d\rho(r) \int M_{LWR}(r, \rho, Z) dM \]

\[ \Phi(M) Y_{26}(M, r, Z) dM \]

\[ \text{if } \tau_{26} = 1.44 \text{ Myr} \approx 1 \text{ Myr}, \]

(1)

R is the galactic radius taken equal to 15 kpc. \( \sigma(r) \) is the surface density distribution of atomic and molecular hydrogen according to Scoville & Sanders (1987). This quantity is used to mimic the present star formation rate in the Galaxy, provided that the molecular clouds distribution is considered a good tracer of the star forming regions. \( M_{LWR} \) is the minimum mass for a star to enter the WR phase at a given metallicity. Its dependence on initial velocity and initial metallicity is explicitly taken into account.

\( \Phi(M) \propto m^{-1(1+x)} \) is the Initial Mass Function, \( x \) defining the slope of the IMF. Here, two different prescriptions were used, in order to show the impact of this physical ingredient on the global production of 26Al by WR stars.

\( Y_{26}^{W} (M_i, r, Z) \) is the yield of 26Al (excluding the supernova contribution) for a given mass \( M_i \) at a given metallicity \( Z \).

The expression in Eqn. 1 is normalized so as to account for a rate of 3 SNae per century in the Galaxy (e.g. Capellaro et al. 1999).

Furthermore, we considered a metallicity gradient along the galactic radius such as \( Z = 0.04 \) for \( r \leq 4 \text{ kpc} \) and \( d \log(Z)/dr = -0.07 \text{ dex.kpc}^{-1} \) beyond, with the condition that \( Z = 0.02 \) at \( r = 8.5 \text{ kpc} \) (solar neighbourhood).

In Fig. 3, we can see that the radial surface density profile of 26Al has a similar shape whether we use rotating or non-rotating models. In particular, in both cases there is a peak between 4 kpc and 6 kpc associated with the existence of the molecular clouds ring at 5 kpc, which is accounted for in the expression of the surface density distribution \( \sigma(r) \).

- The rotating models lead to a larger contribution of WR stars to the 26Al surface density profile in the inner 8 kpc ring. There, \( Z > Z_\odot \), and as seen in Fig. 1 and Fig. 2, the combined effects of metallicity and rotation lead to a substantial enhancement of the yields.

- The total mass of 26Al originating from WR stars is increased by a factor 2.5 to 2.9 when rotation is taken into account. The values obtained are also quite sensitive to the IMF slope, the Salpeter IMF \((x = 1.35)\) favouring a larger contribution, even though the Scalo IMF \((x = 1.7)\) is considered better suited for massive stars.

- For an IMF slope of 1.7, we obtain a total ejected mass of 26Al by WR stars of 1.27 M_☉ in case of rotating models, which represents 42% to 63% of the total observed mass, that is estimated to range between 2 and 3 M_☉.

According to the recent observations by RHESSI (a γ-ray observatory for the Sun which was able to measure the diffuse emission of both 26Al and 60Fe), the new estimate derived for the line ratio 60Fe/26Al ∼ 0.1 (see Smith’s contribution in these proceedings) is consistent with the value predicted by Tummes et al. (1995), from computations including the sole contribution of type II supernovae (SNII). This would designate SNII as the dominant contributors to the 26Al galactic content. However, the most recent computations of nucleosynthesis from SNII indicate that the line ratio 60Fe/26Al should be larger than about 0.4. If this is the case, as pointed out by Prantzos (2004; see also his contribution in these proceedings), 26Al should, at least up to a 50 % level, originate from sources that produce 26Al but do not produce 60Fe, as is the case for the WR stars. Our results show that rotating stellar models of WR stars could actually be responsible for such an amount of 26Al. Let us stress however, that this result has to be taken with caution, considering the 2.6 sigma level of the RHESSI detection of 60Fe and the large uncertainties existing on the physical parameters entering the derivation of such a quantity (see also Palacios et al., 2004).
6. CONCLUSIONS

We have presented new results concerning $^{26}$Al production by WR stars from a new grid of models including rotation and updated physics, in particular the most recent prescriptions for mass loss rates. Taking rotation into account globally leads to an enhancement of wind ejected mass of $^{26}$Al by very massive stars. Convolved with appropriate IMF and star formation rate indicator, these yields lead to a total mass of about 1.3 M$_\odot$ of $^{26}$Al originating from WR stellar winds. This value is in agreement with the conclusions drawn by Prantzos (2004) from recent measurements of the line flux ratio $^{60}$Fe/$^{26}$Al.

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