

NEUTRON-RICH NUCLEI IN COSMIC RAYS AND
WOLF-RAYET STARS

N. Prantzos¹, M. Arnould², J. P. Arcoragi³ and M. Cassé¹

1. Service d'Astrophysique, Institut de Recherche Fondamentale, CEN Saclay, France.

2. Institut d'Astronomie et d'Astrophysique Université Libre de Bruxelles, Belgique.

3. Département de Physique, Université de Montréal, Canada.

1. Introduction Wolf-Rayet stars figure prominently in astrophysical research (see e.g. Humphreys and Davidson, 1984). As a bonus, they seem to offer, in the same way as supernovae and supernova remnants in the recent past, an interesting connection between classical astronomy and high energy astrophysics due to their unusual composition and their huge mechanical power (Cassé and Paul, 1981, 1982, Maeder, 1983, 1984, Prantzos and Arnould 1983, Prantzos 1984a, b, Arnould 1984, Audouze 1984, Meyer 1985, Prantzos et al 1985). The material flowing from WC stars (carbon-rich WR stars) contains gas which has been processed through core-helium burning, i.e. considerably enriched into ^{12}C , ^{16}O , ^{22}Ne , and $^{25,26}\text{Mg}$. This composition is reminiscent of the cosmic ray source anomalies (e.g. Simpson 1983, Meyer 1985b). Encouraging agreement is obtained with observation in the mass range $12 < A < 26$ assuming acceleration of wind particles at the shock that delineates the WR cavity (Cassé and Paul, 1980), and adequate dilution with "normal" cosmic rays, but silicon poses a problem (e.g. Prantzos, 1984 a, b and Prantzos et al, 1985). If massive stars contribute significantly to the $^{25,26}\text{Mg}$ excess at the CR sources, they should also enhance other neutron-rich isotopes since the production of ^{25}Mg releases a copious amount of neutrons. These neutrons, in turn react with preexisting nuclei, producing a host of neutron-rich isotopes, of which a few are of interest for CR physics (Prantzos, Arnould and Cassé 1983, Blake and Dearborn 1984, Prantzos et al 1985). Detailed models of WR stars have been developed (de Loore et al 1985, Prantzos et al 1985b) delivering physical conditions (initial composition, temperature and density versus space and time coordinates) relevant to a consistent s-process calculation.

2. Results The stellar model developed within the Brussels-Saclay collaboration, coupled to a full s-process network, allows to follow the abundance of all nuclear species of interest, both in the stellar core and at the stellar surface. 4 different cases (50, 60, 80 and 100 M_{\odot} on the zero age main sequence) have been studied (for details see Prantzos et al, 1985). In all the cases considered only n-rich isotopes in the range $20 < A < 90$ are substantially enhanced at the end of helium burning (with a few exceptions however), due to the rather low neutron fluence ($\sim 8 \cdot 10^{26} \text{ n cm}^{-2}$), in agreement with Lamb et al, 1977. The global enhancement of a given isotope in the wind of

WC stars (60 % of all WR stars) relative to its solar system abundance will be denoted, in the following by $E_i^{WC} = \langle X_i^{WC} \rangle / X_{i0}$, X_{i0} is its solar mass fraction and the bracketed symbol stands for the double average of this mass fraction of this isotope over the duration of the WC phase and over the mass spectrum of its stellar progenitors (IMF).

More specifically:

$$X_i^{WC}(M) = \int_{WC} X_i^{(s)}(t, M) \dot{M}_{WC} dt / \Delta M_{WC}$$

where $X_i^{(s)}$ is the instantaneous surface abundance of i , \dot{M}_{WC} , the mass loss rate ($3 \cdot 10^{-5} M_{\odot} \text{yr}^{-1}$)

and $\Delta M_{WC} = \int_{WC} \dot{M}_{WC} dt$ is the total mass ejected during the WC phase.

$$\langle X_i^{WC} \rangle = \int_{50}^{100} \varnothing(M) \Delta M_{WC}(M) X_i^{WC}(M) dM \Big/ \int_{50}^{100} \varnothing(M) \Delta M_{WC}(M) dM$$

where $\varnothing(M)dM$ is the initial mass function (IMF).

Now, the enhancement of species i at the sources is

$$E_i^{CRS} = [1 + (1/f) \langle E_i^{WR} \rangle] / [(1/f) + 1] \quad (\text{Maeder, 1983})$$

with $\langle E_i^{WR} \rangle = 0.4 \langle E_i^{WN} \rangle + 0.6 \langle E_i^{WC} \rangle$,

$1/f$ denotes the fraction of CR particles coming from WR stars. The dilution factor f is obtained by adjusting the calculated overabundance of ^{22}Ne relative to ^{20}Ne (about 100, irrespective of the WR mass) to that at the CR sources (about 4).

We get $f \sim 35$: 1 CR particle out of 35 should originate from WR stars.

We predict the following correlated CR excesses E_i^{CRS} (selecting those > 1.2):

$^{12}\text{C}(2.4)$, $^{16}\text{O}(1.6)$, $^{21}\text{Ne}(2.0)$, $^{22}\text{Ne}(4.1)$, $^{23}\text{Na}(1.4)$, $^{25}\text{Mg}(1.7)$,
 $^{26}\text{Mg}(1.7)$, $^{36}\text{S}(1.6)$, $^{37}\text{Cl}(1.4)$, $^{40}\text{K}(3.2)$, $^{58}\text{Fe}(1.8)$, $^{59}\text{Co}(1.4)$,
 $^{61}\text{Ni}(1.4)$, $^{63}\text{Cu}(1.4)$, $^{65}\text{Cu}(1.6)$, $^{67}\text{Zn}(1.2)$, $^{69}\text{Ga}(1.2)$, $^{71}\text{Ga}(1.2)$,
 $^{70}\text{Ge}(1.2)$, $^{80}\text{Kr}(1.4)$, $^{82}\text{Kr}(1.2)$, $^{86}\text{Sr}(1.2)$, $^{152}\text{Gd}(1.4)$ and
 $^{202}\text{Hg}(1.2)$.

Among these species only a few are of practical interest for present CR research (table 1), the others being so rare that they are overwhelmed by spallation of heavier nuclei en route (e.g. Adams et al, 1981).

Element	CRS/SEP ⁽¹⁾	CRS/LG ⁽¹⁾	E_i^{CRS}
C	~3		2.4
O	~1.5		1.6
Na		0.8(2.0)	1.4
Co		1.3(1.6)	1.4
Cu		1.1(1.6)	1.4
Ga		1.5(1.5)	1.2

Table 1. Predictions of WR models confronted to observations.

SEP=Solar energetic particles, LG=Local galactic abundances.
 (1) Meyer (1985a,b) except for Ga (Anders and Ebihara, 1982).
 CRS abundances are those derived from the HEAO 3 data (Koch-Miramond et al, 1983, Engelmann, 1984 and Lund, 1984).
 (x)=within a factor of x).

C and O, having a high first ionisation potential are affected by selective filtering in the cosmic ray reservoir, both in SEP and Galactic CR sources. The CRS/SEP ratio is therefore sensitive to any deviation of Galactic CR sources from the standard (LG), irrespective to atomic discrimination, (Meyer 1985b)

The other elements, due to their uniformly low FIP are not affected by discriminating atomic effects.

Predicted enhancements are all within experimental uncertainties.

As concerns isotopes, we predict a definite enhancement of ^{58}Fe (by a factor close to 2), which is not far of reach of the present technology. We thus confirm our previous estimate (Prantzos, Arnould and Cassé, 1983, Prantzos, 1984a, b, Prantzos et al, 1985) and agree with Blake and Dearborn, 1984, at least qualitatively.

3. Conclusion Enhancement factors of a series of neutron-rich isotopes in CR sources, due to WR contamination, have been estimated. The predicted overabundances are all within observational uncertainties.

There is at least no contradiction with present observations. The best prospect to test the WR scenario is to measure the

$^{58}\text{Fe}/^{56}\text{Fe}$ with an accuracy of about 20 %.

Acknowledgements: We thank all our colleagues of the Brussels-Saclay collaboration for constant help and support. We are indebted to C. Ryter and A. Raviart for generous allocation of computer time.

References:

- Anders, E. and Ebihara M., 1982, *Geochim. Cosmochim. Acta* 46, 2363.
- Arnould, M., 1984, *Adv. Space Res.*, 4, 45.
- Audouze, J., 1984, *Moriond Symposium: "High Energy Cosmic Rays"* p. 325.
- Blake, J. B. and Dearborn, D. S. P., 1984, *Adv. Space Res.*, 4, 89.
- Cassé, M.; and Paul, J. A., 1980, *Ap. J.*, 237, 236.
- Cassé, M. and Paul, J. A., 1981, 17th *Int. Cosmic Ray Conf.* 13, 111.
- Cassé, M. and Paul J. A., 1982, *Ap. J.*, 258, 860.
- de Loore, C., Prantzos, N., Arnould, M. and Doom, C., 1985, *Moriond Symposium: "Nucleosynthesis and its applications on nuclear and particle physics"*, in press.
- Engelmann, J., 1984, *European Cosmic Ray Symposium, Kosice*.
- Humphreys, R. M. and Davidson, K., 1984, *Science*, 223, 243.
- Lamb, S. A., Howard, W. M., Truran, J. W. and Iben, I. Jr, 1977, *Ap. J.*, 217, 213.
- Lund, N., 1984, *Adv. Space Res.*, 4, 5.
- Koch-Miramond, L., Engelmann, J., Goret, P., Juliusson, E., Masse, P., Soutoul, A., Perron, C., Lund, N. and Rasmussen, I. L., 1983, 9, 275. 18th *Int. Cosmic Ray Conf.*, 9, 275.
- Maeder, A., 1983, *Astron. Astrophys.*, 120, 130.
- Maeder, A., 1984, *Adv. Space Res.*, 4, 55.
- Meyer, J. P., 1985, *Ap. J. Suppl.*, 57, 151.
- Meyer, J. P., 1985, *Ap. J. Suppl.*, 57, 173.
- Prantzos, N., 1984a, *Adv. Space Res.*, 4, 109.
- Prantzos, N., 1984b, *Moriond Symposium: "High Energy Cosmic Rays"*, p. 341.
- Prantzos, N. and Arnould, M., 1983, in "Wolf-Rayet stars: Progenitors of Supernovae?", *Observatoire de Paris-Meudon*, pII. 33.
- Prantzos, N., Arnould, M. and Cassé M., 1983, 18th *Cosmic Ray Conf.*, 9, 155.
- Prantzos, N., Arcoragi, J. P. and Arnould, M., 1985, *Moriond Symposium "Nucleosynthesis and its applications on nuclear and particle physics"*, in press.
- Prantzos, N., de Loore, C., Doom, C. and Arnould, M., 1985, *Moriond Symposium*.