Stellar Rotation
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Rotation and Abundances in Red Giants

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Abstract. The abundances of red giants will be reviewed, in particular those of carbon, nitrogen, oxygen and ^{12}C:^{13}C. The observed abundances are compared to predictions based on recent models with stellar rotation. Three topics will be emphasized: abundances in very metal-poor stars related to a previous generation of supernova; ^{12}C:^{13}C in red giants and rotation induced extra mixing; CNO abundances in yellow supergiants and their connection with models computed with rotation.

1. Introduction

Three aspects regarding abundances in red giants, pointing to evidences on stellar rotation will be discussed. (a) The extremely low metallicity stars of the Galactic halo, of low masses around 0.7 to 0.8 $M_\odot$, show in their atmospheres the products of nucleosynthesis of the first generation of stars (population III). Their nucleosynthetic products are probably the result of only a few supernovae, perhaps in some cases just one supernova having exploded nearby (Audouze & Silk 1995). In particular, a large nitrogen excess found in some very metal-poor stars may be the result of rotation on the evolution of a massive star that later exploded as a supernova, before the formation of the most metal-poor extant halo stars. (b) Rotation induced extra-mixing required to explain low values of ^{12}C:^{13}C in red giants of all metallicities and in a large range of masses, from open clusters to globular clusters and field stars. (c) CNO abundances in yellow supergiants of different rotational velocities may reveal which of them have been through the red supergiant phase, and the effect of rotation on CNO abundances.

O-Na and Mg-Al anticorrelations will not be discussed here, given that there are evidences that this is not an effect occurring along the Red Giant Branch (RGB), but rather due to "primordial variations", coming from a previous generation of stars (Charbonnel, this meeting).

Comments about Li will appear along the text, but Li abundances will also not be discussed in detail given that it is too extensive a subject, and that the decrease of Li along the RGB occurs from a combination of mixing and temperature decrease at the surface layers (e.g. Castilho et al. 2000), and effects due to an extra mixing may be less clear cut than in the case of ^{12}C:^{13}C ratios.

2. Abundances in Low Metallicity Halo Stars

Reference nucleosynthesis calculations of supernovae below 40 $M_\odot$ are those by Woosley & Weaver (1995, hereafter WW95) and Thielemann et al. (1996). WW95 included metal-free stars and $Z = 10^{-4}$ in the mass range 11-40 $M_\odot$. Calculations of nucleosynthesis in zero-metal or very low metallicity very massive stars ($M > 100\ M_\odot$) were carried out by Heger & Woosley (2002), Heger et al. (2002). In these models no rotation and therefore no rotation-induced mixing of the helium convective shell with the hydrogen envelope are considered, such that no nitrogen is produced. In Heger & Langer (2000) and Heger et al. (2000) rotation was taken into account, and nitrogen production was obtained - the authors caution however about the sensitivity of nitrogen production to the uncertainty of parameters on the treatment of rotationally induced mixing. Meynet & Maeder (2002a, hereafter MM02) in paper VIII of their series on the rôle of rotation in stellar evolution, studied the effects of rotation on abundances. In particular regarding the CNO elements, Figs. 20 and 21 of MM02 show that C/O vs. O/H is more sensitive to mass range, whereas N/O vs. O/H is sensitive to rotation.

Two recently analysed very metal-poor stars were revealed to be interesting cases: CS 22949-37 (Depagne et al. 2002; Norris et al. 2002) and CS 29498-43 (Aoki et al. 2002a) - see Table 1. Aoki et al. even proposed to classify them into a new class of "metal-poor stars with excesses of Mg and Si", in fact we could go even farther and propose "with excesses of CNO(Na)MgSi" and with no excesses for elements heavier than $Z > 15$, being normal relative to all the heavier elements. In particular the absence of excesses of s-elements rules out the possibility of mass transfer from an AGB companion. It is important to note that these stars are exceptions with respect to the majority of metal-poor stars (Norris et al. 2001; Depagne et al. 2002; François et al. 2003).

These stars fit well into the 35 $M_\odot$ supernova model of labeled Z35B of WW95, which due to insufficient explosion energy, would show a fallback of the inner shells, and the elements ejected are restricted to C, O, Ne, Na, Mg, Al and some Si. A complementary model is that by MM02, where rotation is included, inducing mixing of carbon with proton-rich material and thus producing large amounts of nitrogen - see also Meynet & Maeder (2002b). Siess et al. (2002) presented models of Z=0 stars of masses 0.8–20 $M_\odot$, with production of large amounts of C and N; in these models no rotation is considered.

Table 1. Abundances of CS 22949-37 and CS29498-43

star	[Fe/H]	[C/Fe]	[N/Fe]	[O/Fe]	[Mg/Fe]	[Si/Fe]	[Ba/Fe]
CS 22949-37	-4.0	+1.17	+2.57	+1.98	+1.58	+0.72	-2.42
CS 29498-43	-3.75	+1.9	+2.28	–	+1.81	+1.07	-0.45

2.1. Nitrogen in Metal-Poor Stars

Laird (1985) and Carbon et al. (1987) derived nitrogen abundances for metal-poor dwarfs from low resolution spectra. Tomkin & Lambert (1984) derived N abundances for dwarfs of $-2.3 < [Fe/H] < -0.3$ using the NH 3360 Å bands.

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These are essentially the last results on nitrogen abundances in a large sample of metal-poor stars.

In giants the C deficiencies and N overabundances due to convective mixing make it difficult to derive the "original" N from which the star was formed - for example, Fig. 5c by Boothroyd & Sackmann (1999) gives an illustrative picture of C deficiencies along the RGB. Therefore, in order to know the N abundance in very metal-poor stars, dwarfs are to be studied; however their hotter temperatures are such that molecular bands are faint — in very metal poor stars even the NH 3360 Å bands will be weak, unless if there is a strong excess of N. Therefore it is difficult, or essentially impossible to obtain the behaviour of [N/Fe] vs. [Fe/H] at very low metallicities below [Fe/H] $<$ -3.0. On the other hand, observations at moderate metallicities such as those of Carbon et al. should be remade by taking into account a more detailed determination of stellar parameters, and using high resolution spectra.

2.2. Carbon/Nitrogen-Rich Very Metal Poor Stars

According to Ryan (2003), 10% to 25% of metal-poor stars are C-rich; with part of them being C-rich and s-elements-rich, probably as a result of mass transfer from an AGB companion, and part are C-rich and s-normal. The different types of C/N vs. heavy element abundances in CH/CN rich, metal-poor stars, were extensively discussed by Hill et al. (2000) and Aoki et al. (2002b). In terms of this review, it is the latter class, of s-normal ones that are interesting from the point of view of nucleosynthesis having occurred in a first generation of stars.

It should appear that the first generation of stars has produced large amounts of C and N, and this might be related to rotation, and rotation is more important in metal-poor stars according to MM02.

3. Rotation and ^{12}C:^{13}C in Red Giants

The literature reporting ^{12}C:^{13}C ratios in red giants is extensive. Pilachowski et al. (1997) discussed the use of different carbon isotope ratios indicators (mainly CH, CN, CO) appropriate for different types of stars. Field giants were studied in the 70's and 80's in several papers (e.g. Lambert & Ries 1981; Sneden & Pilachowski 1984; Brown & Wallerstein 1989). The effect of ^{12}C:^{13}C decrease along the Red Giant Branch (RGB) is more clearly seen in studies of clusters: Gilroy (1989) presented ^{12}C:^{13}C ratios in stars of the RGB of 20 open clusters, and Gilroy & Brown (1991) determined the ratio in giants of M67. These authors concluded that in the lower GB ^{12}C:^{13}C is compatible with standard mixing predictions (Iben 1967; Sweigart et al. 1989), but towards the tip of the RGB and in the clump, ^{12}C:^{13}C is lower than predictions, requiring an extra-mixing mechanism. Another conclusion is that ^{12}C:^{13}C ratios decrease with decreasing mass, and levels off at a value ^{12}C:^{13}C $\approx$ 30 for clusters with turn-off mass of $\sim$2.2 $M_{\odot}$. Charbonnel et al. (1998) made observations of stars with well determined bolometric magnitudes, and found that ^{12}C:^{13}C ratios drop from $\sim$20 to $\sim$7 between $M_{bol} = +1.0$ to $+0.5$; in the same interval ^{12}C:^{14}N drops by 0.2-0.4 dex and Li disappears.

A reference study in metal-poor stars of -2. $<$ [Fe/H] $<$ -1. was carried out by Gratton et al. (2000): Li, C, N, O and ^{12}C:^{13}C were determined for

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62 stars. Their conclusion is that Li, ^{12}C, ^{13}C and ^{14}N change abruptly at a luminosity near the RGB bump, after the molecular weight barrier is canceled; and that mixing seems to be a function of metallicity, reaching a maximum value at [Fe/H] $\sim$ -1.5. A recent work on metal-poor field giants of -2.4 $<$ [Fe/H] $<$ -1.0 by Keller et al. (2001), using CO vibration-rotation bands, shows that, definitely, ^{12}C:^{13}C values on the upper RGB are much lower in metal-poor stars than in metal-rich ones. They also sugest that an extra-mixing proceeds at lower evolutionary stages on the RGB, in the lower metallicity giants. Keller et al. find that in low metallicity stars the ^{12}C:^{13}C ratio drops from the 1st dredge-up value around ^{12}C:^{13}C $\approx$ 25 to ^{12}C:^{13}C $<$ 10 at magnitudes 0.5 $< M_V <$ 1.0, again confirming the need for an extra-mixing process, occurring at a luminosity corresponding to the RGB bump. Similar results were obtained by Charbonnel et al. (1998). In a work on ^{12}C:^{13}C in globular clusters, in particular ω Centauri, Smith et al. (2002) have found that ^{12}C:^{13}C ratio in 11 stars of this cluster are close to the equilibrium value of 3.5, therefore requiring an extra-mixing, more efficient than invoked in previous papers for metal-poor giants.

Finally, note that a value ^{12}C:^{13}C = 4, close to the equilibrium value is also found for the very metal-poor giant CS 22949-37 (Depagne et al. 2002).

A complete theoretical model of mixing was presented by Charbonnel (1994, 1995), where meridional circulation is coupled to turbulence induced by stellar rotation. Besides a detailed treatment of the transport of chemicals and angular momentum are taken into account. This model does explain lower ^{12}C:^{13}C and Li relative to standard models, and these abundances depend on the extent reached by the convective envelope, which in turn is a function of mass and metallicity. Rotation was also taken into account by Denissenkov & Tout (2000).

Other groups developed different successful mechanisms to explain the extra mixing in the red giant branch, such as the Cold Bottom Processing (CBP) by Boothroyd & Sackmann (1999), the partial mixing by Goriely & Mowlawi (2000), Siess et al. (2002), where however the models are parameterized and rotation is not explicitly included as the driving mechanism causing the mixing. See more details in Pinsonneault (this meeting), Charbonnel (this meeting).

4. CNO in Yellow Supergiants

Yellow supergiants may have evolved directly from the main sequence or may have gone through an incursion to the red supergiant phase, where CN-cycle material is brought to the surface in the 1st dredge-up process. CNO abundances in A-supergiants may give therefore important information on massive (5-20 $M_\odot$) stars. One expects as well that rotation may be related to CNO abundance changes. Venn (1995) analysed 22 Galactic A-supergiants, having found enhanced [N/C] values, as expected from the 1st dredge-up, but corresponding to a partial mixing, such that it was concluded that the mixing is probably rather due to a process occurring during the main sequence evolution. Venn (1999) analysed 10 A-supergiants of the Small Magellanic Cloud, where the main result is that these stars show a variety of N excesses, suggesting that there is also some mixing in addition to the 1st dredge-up. A star-to-star variation would suggest a possible relation with stellar rotation and consequent different degrees of mixing. Barbuy et al. (1996) started a program on CNO abundance

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determination in a sample of 60 F9Ib supergiants of different rotations. One expects the high rotation stars to present more mixing of CNO elements, and that part of the stars evolve directly from the main sequence, and others should have gone through an incursion to the red supergiant phase. The whole sample has now been observed using the Feros spectrograph at ESO, and the analysis is under way. The 9 stars analysed in 1996 showed small enhancements of N; we believe that this was due to a selection of the lowest rotation stars, such that low N was in fact expected.

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