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On a Physical Mechanism for Extra-Mixing in Globular Cluster Red Giants

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Abstract. For the first time we propose a real physical mechanism for extra-mixing in red giants which can *quantitatively* interpret all the known star-to-star abundance variations in globular clusters. This is Zahn's mechanism (Zahn 1992; Maeder & Zahn 1998). It considers extra-mixing in a radiative zone of a rotating star as a result of joint operation of meridional circulation and turbulent diffusion.

1. Introduction

There is observational evidence of "extra-mixing" (EM) in the massive MS stars (Lyubimkov 1996), in the MS dwarfs (Talon & Charbonnel 1999), in the field and globular cluster RGB stars (Gratton et al. 2000; Kraft 1994). In particular, red giants (RGs) in many globular clusters populate the so-called "global anticorrelation" of [O/Fe] versus [Na/Fe] (Kraft 1994; Fig. 1, symbols). One of the possible explanations of its origin is the following. An RGB star consists of an electron-degenerated helium core, a hydrogen burning shell (HBS) and an extended convective envelope (in the direction of increasing radius). The HBS and the base of the convective envelope (BCE) are separated by a thin radiative zone. At the top of the HBS the temperature is high enough for the reaction ^{22}Ne(p,γ)^{23}Na to proceed even faster than O is depleted in the CNO-cycle. If EM could connect the BCE with the layers where O begins to decrease then it (in a collaboration with the envelope convection) would bring the Na-rich and O-poor material to the stellar surface.

2. The proposed mechanism for EM

Usually, EM in RGs has been modeled with a diffusion or other simple algorithm without specifying physical nature of that mixing (Denissenkov & Weiss 1996; Sackmann & Boothroyd 1999). Such models have free parameters to be adjusted to fit the observations. Particularly, the diffusion model of Denissenkov & Weiss (1996) has two parameters: the relative depth $\delta m_{\rm mix}$ ($\delta m = 0$ at the bottom of the HBS, where hydrogen content $X = 10^{-4}$, and $\delta m = 1$ at the BCE), and the rate $D_{\rm mix}$ of EM. The global anticorrelation has been reproduced quite

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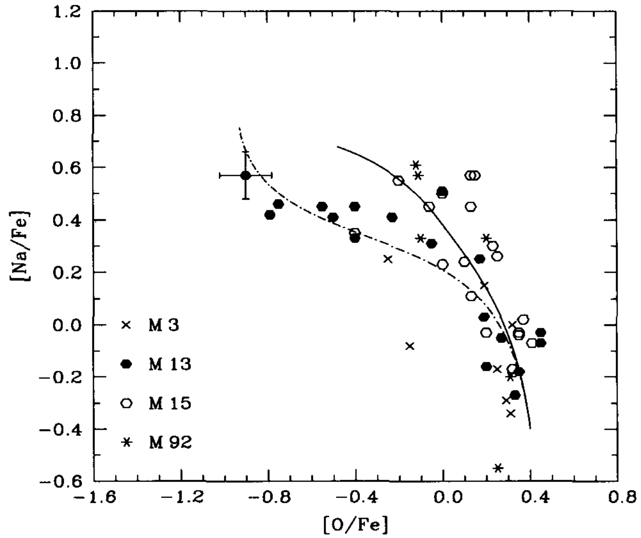

Figure 1. The global anticorrelation of [O/Fe] vs. [Na/Fe] and its theoretical reproductions by the diffusion (dot-dashed curve: mixing depth $\delta m_{\rm mix} = 0.06$ and rate $D_{\rm mix} = 2.5 \cdot 10^9$ cm^2 s^{-1}) and Zahn's (solid curve) model. For more details see Denissenkov & Tout (2000).

satisfactorily by this model with the mixing parameters $\delta m_{\rm mix} = 0.06-0.07$, $D_{\rm mix} = 1-5{\cdot}10^9$ cm^2 s^{-1} (Fig. 1, dot-dashed curve).

Quite recently a first real physical mechanism of EM in the globular cluster RGs has been proposed by Denissenkov & Tout (2000). This is Zahn's mechanism (Zahn 1992; Maeder & Zahn 1998). It considers EM in a radiative zone of a star as a result of joint operation of rotation-driven meridional circulation and turbulent diffusion[1].

3. Basic results

The basic results obtained in Denissenkov & Tout (2000) can be summarized as follows:

- It was pointed out that in the radiative zone between the HBS and BCE in a RG there is a stationary flow of the H-rich material directed inwards (it feeds the HBS) and that the rotation-driven EM has practically no influence on this flow. The angular momentum conservation law then requires a rather steep profile of the angular velocity ($\Omega \propto r^{-2}$). Hence, this radiative zone may be in a state of strongly differential rotation and, as a consequence, Zahn's mechanism can work here very efficiently.

[1]Charbonnel (1995) was the first to advocate the operation of Zahn's mechanism in RGs but she did not apply the full set of equations self-consistently.

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- Exactly the same value of the mixing depth $\delta m_{\rm mix} = 0.06 - 0.07$ like that estimated with the semi-empirical diffusion model of Denissenkov & Weiss (1996) was independently obtained with Zahn's mechanism in which $\delta m_{\rm mix}$ is no longer a free parameter. The rate of EM still left a free parameter but it could be *in principle* constrained by observations because $D_{\rm mix}$ was found to be proportional to the squared angular velocity at the BCE, $\Omega_{\rm BCE}$. However, for this we have to know a relation between $\Omega_{\rm BCE}$ and the surface rotational velocity.

- The solid curve in Fig. 1 was calculated with Zahn's mechanism and $\Omega_{\rm BCE}$ decreasing from $8 \cdot 10^{-6}$ to $2.7 \cdot 10^{-6}$ rad s^{-1} ($r^2_{\rm BCE}\Omega_{\rm BCE} = \rm const$ was assumed). It reproduces the global anticorrelation for most globular clusters except the unique cluster M13. RGs in M13 require about twice the rotation rate on average. Note that when transformed into the surface rotational velocity (under the assumption of the constant specific angular momentum distribution in the convective envelope; solid body rotation of the convective envelope would result in the surface centrifugal force exceeding gravity as the star evolves along the RGB!), the chosen values of $\Omega_{\rm BCE}$ turned out to give surface rotational velocities realistic for globular cluster RGs (less than 1 km s^{-1}). An alternative to the made assumption might be a decoupling between a slowly rotating envelope and a rapidly rotating core. The hypothesis of a rotation-driven EM in globular cluster RGs is supported by observations of Peterson, Rood & Crocker (1995) who found that the horizontal branch stars in M13 rotated about twice as fast as stars in M3, M15 and M92.

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