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Thermohaline Mixing and the Variation of [C/Fe] with Magnitude in M3

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We use observations of M3 to constrain thermohaline mixing. This is done by matching [C/Fe] and [N/Fe] along the RGB of M3. We find our models can explain observations if it is assumed there is a spread of $\sim$ 0.3 - 0.4 dex in [C/Fe] in the stars in M3 from their birth. We reproduce the full spread in [C/Fe] at the tip of the RGB. Thermohaline mixing can produce a significant change in [N/Fe] as a function of absolute magnitude on the RGB for initially CN-weak stars, but not for initially CN-strong stars, which have so much nitrogen to begin with that any deep mixing does not significantly affect the surface nitrogen composition.

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1. Introduction

Standard stellar evolution theory predicts that first dredge-up (FDU) is the only mixing event during the red giant branch (RGB) ascent that will alter a star's surface composition. Observations on the other hand suggest some form of non-convective mixing must occur where the products of partial hydrogen burning are cycled into the envelope. The discrepancy between canonical theory and observations can be seen in Figure 1a. The observational results imply that standard models do not include essential physics that lead to 'deep mixing'. Although many candidate extra-mixing mechanisms exist we have chosen to investigate the role of thermohaline mixing: a doubly diffusive mixing that is driven by a molecular weight inversion (see [6, 3, 7]).

2. Method

[11] and [12] have compiled from various sources carbon and nitrogen observations along the giant branch of M3. This has provided us with a dataset to test our understanding of thermohaline mixing. M3 is a typical cluster with [Fe/H]$= -1.4$, it displays all of the classical globular cluster abundance inhomogeneity patterns but is not as extreme as M13 or M92 (see [1] for more on M92). Traditionally the $^{12}C/^{13}C$ ratio has been used as a tracer to probe the extent of extra mixing. However this ratio saturates at the equilibrium value rather quickly in low metallicity stars, and hence is of limited utility. We match carbon depletion as a function of (absolute) visual magnitude for M3 ([11]). We also include nitrogen as an extra tracer. The level of depletion of carbon will depend on the efficiency of the extra-mixing mechanism. We employ the 'Ulrich-Kippenhahn-Ruschenplatt-Thomas' prescription (see [14, 10, 3]) and vary the dimensionless free parameter C_t. This parameter is related to the aspect ratio α of the rising element (assumed cylindrically symmetric) via $C_t = (8/3)\pi^2\alpha^2$. [10] favour $C_t = 12$, corresponding to a slow, traditional "blob-like" kind of mixing. $C_t = 1000$ produces faster mixing favoured by [3] and corresponds to finger-like structures with $\alpha \sim 6$. Our set of reaction rates for hydrogen burning come primarily from [8] and [9]. For the $^{14}N(p,\gamma)^{15}O$ reaction an updated rate from [2] is used. This rate is a factor of two less than previously thought for main-sequence and RGB stars.

3. Results

The value of C_t governs the extent of mixing. In Figure 1a thermohaline mixing is excluded from the model. Canonical models produce very little change in the carbon abundance following FDU. It is almost not visible on this scale, contrary to the observations. Figures 1b, 1c and 1d include thermohaline mixing. In each panel we provide four models, these represent different values of C_t, and hence the aspect ratio. We include: $C_t = 12$ as per [10] (dashed lines), $C_t = 1000$ as per [3] (solid lines) and two intermediate values, $C_t = 120$ (dot-dashed lines) and $C_t = 600$ (comparable to [14], Ct=658, dotted lines). Figure 1b suggests that it is unlikely that M3 started off with a scaled solar CNO composition. In all globular clusters where the CN abundances have been investigated for stars at low luminosity, such as sub-giants, the CN bimodality has been present. This argues strongly for the spread being present in the stars at their birth. In Figure 1c we have altered the initial CNO abundance whilst keeping the metallicity constant so that the abundances

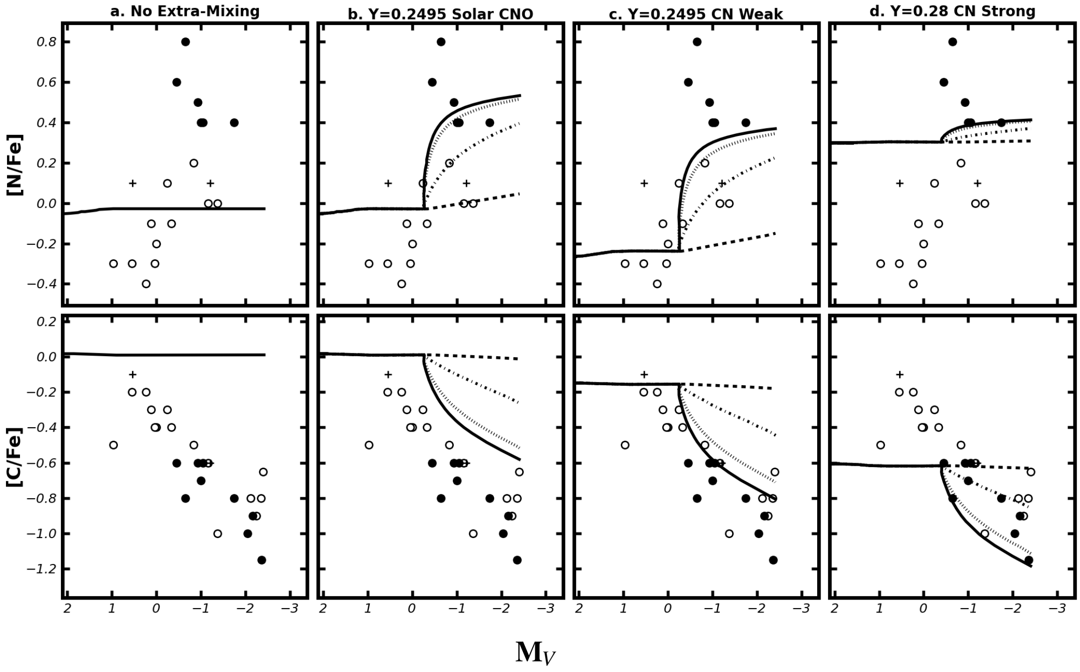

Figure 1: Here we compare our models to [11, 12] compilation of M3 observations. Open circles denote CN-weak stars, filled circles CN-strong stars, whilst the crosses represent stars of intermediate CN strength. Where extra mixing is included in our models C_t= 12 (dashed lines), C_t= 120 (dot-dashed lines), C_t= 600 (dotted lines), C_t= 1000 (solid lines). In Figure 1c, the CN weak models have X(C)= 5.45×10^{-5}, X(N)= 1.5×10^{-5} and X(O)= 2.86×10^{-4}. In Figure 1d the CN strong models have X(C)= 1.90×10^{-5}, X(N)= 5.5×10^{-5} and X(O)= 2.60×10^{-4}.

match the CN weak stars just before FDU. We set X(C)= 5.45×10^{-5}, X(N)= 1.5×10^{-5} and X(O)= 2.86×10^{-4}. Here both the faster mixing cases are a good fit to the data. The CN strong stars show the result of hot H burning, including CN and ON cycling. We have therefore changed the initial helium abundance as well as the CNO ratios such that X(C)= 1.90×10^{-5}, X(N)= 5.5×10^{-5},X(O)= 2.60×10^{-4} and Y= 0.28. Generally speaking increasing the helium abundance will delay the onset of the extra mixing. Here a slower mixing is a good fit for the carbon abundance, whilst the faster mixing is able to account for the more extreme carbon values. These models are unable to match the more extreme nitrogen enhancements in the CN strong stars. The most N enhanced stars show evidence for ON cycling and their initial N abundance is due to this rather than the mixing we investigate here.

4. The Efficiency of Thermohaline Mixing

In this study we have empirically determined a value of C_t= 1000 is required to match the observations of carbon and nitrogen in low mass, globular cluster giants. The same value found by [3] and has been applied to stars of various mass and metallicity . Models have successfully accounted for the behavior of carbon and nitrogen as well as ^{3}He. The amount of ^{3}He depleted and returned to the interstellar medium using C_t= 1000 is consistent with measurements of HII regions. The details of the mixing inside stellar interiors remains contentious. Although laboratory experiments and fits to observations suggest finger-like structures, recent hydrodynamical models by [13], [4] and [5] favor the blob-like geometry preferred by [10]. If this is true then low mass stars will only destroy $\sim$ 20% of the ^{3}He required. Unless hydrodynamical models can reproduce the geometry suggested by the observations then there is still a significant gap in our understanding of RGB mixing.

5. Conclusion

1. There is a spread of $\sim$ 0.3 - 0.4 dex in [C/Fe] in the stars in M3 from their birth.
2. Deep mixing works in both CN-weak and CN-strong giants, in fact when combined with fact (1) it can explain the full spread in [C/Fe] at the tip of the RGB, i.e., $M_V \sim -2$ or brighter.
3. Deep mixing can produce a significant change in [N/Fe] as a function of M_V on the RGB for initially CN-weak stars, but not for initially CN-strong stars, which have so much N to begin with that any deep mixing does not significantly affect the surface.

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