

Aluminum and Oxygen Isotopic Ratios in Meteorite Grains: a Puzzle Solved By Nuclear and Stellar Physics

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Abstract. Low mass stars contribute to the chemical evolution of the Galaxy as well as more massive supernova progenitors. Indeed the limited amount of processed matter released into the interstellar medium by small objects is compensated by the large number of them. At the late stages of their evolution, stars with mass smaller than $3M_{\odot}$ undergo the Asymptotic Giant Branch phase, which has been found to be a unique site for synthesis of some nuclei heavier than Fe through slow neutron capture reactions. AGB nucleosynthesis is also characterized by H-burning coupled with mixing phenomena, which has been proved to account for anomalies in light element isotopic abundances from Li to Al observed in stellar spectra and meteorites. We present here the case of a large number of meteorite grains, whose isotopic composition offers a puzzles that only Nuclear and Stellar Physics coupled together might solve.

1. Introduction

In February 1969, a rare type of meteorite (a Type III carbonaceous chondrite) broke up in the atmosphere producing the falling of thousands of stones over a nearly 500-square-kilometer area around the village of Pueblito de Allende, in the Northern Mexico. The Allende meteorite turned out to contain some of the solids formed in the Early Solar System as well as dust formed in previous generation of stars. In particular the meteorite is notable for possessing abundant, large calcium-aluminium-rich inclusions (CAIs), which are among the oldest objects formed in our planetary system and report an isotopic composition distinct from the one of the Earth. Beside CAIs, other micrometer to submicrometer inclusions in Allende, called "presolar grains", bring precious pieces of information about stellar nucleosynthesis. Indeed their "isotopic anomalies" contain evidence for processes that occurred in stars older than the Sun, and are of particular importance in helping us to constrain their nucleosynthesis.

A consistent part of presolar grains (commonly called oxide grains) is made up of Al_2O_3 grains, which are classified in four groups according to the Oxygen isotopic mix they show [1]. Grains belonging to group 1 and 2 are characterized by values of $^{17}\text{O}/^{16}\text{O}$ and $^{18}\text{O}/^{16}\text{O}$ inconsistent with explosive nucleosynthesis scenarios and are then believed to form in evolved low mass stars, during the Red Giant Branch (RGB) phase or Asymptotic Giant Branch (AGB) one [2]. However, the high dilution in ^{18}O and the large abundance of ^{26}Mg found in a large part of group 2 grains can not be accounted for by the nucleosynthesis of those stars, unless to invoke the



existence of non-convective transport mechanisms coupled with H-burning ([3] and references therein).

Firstly, [4] suggested that the oxygen isotopic abundances of Al_2O_3 grains could hint to their formation in low mass red giant stars ($M \leq 3M_\odot$) where a deep and not convective mixing mechanism was at play. These authors developed a streams "conveyor belt" model able to enrich the stellar surface with fresh products of the CNO cycle by transporting matter downward, from the inner border of the stellar envelope to the regions where H-burning occurs, and upward, in the opposite direction. The work by [4] and the subsequent update were partially successful in reproducing the ^{18}O dilution shown by presolar grains, but part of group 1 and 2 oxide particles lays in regions of the $^{17}\text{O}/^{16}\text{O}$ versus $^{18}\text{O}/^{16}\text{O}$ diagram that were inaccessible to nucleosynthesis models (even considering deep mixing phenomena).

The ^{26}Mg excess found in presolar grains hints to their formation in ^{26}Al rich environments, for this reason [5] indicated as their stellar progenitors late AGB stars where the H-burning takes place at temperatures higher than those typical of the previous RGB stage and where a contribution to ^{26}Al production comes also from slow neutron capture process. Nevertheless, the $^{26}\text{Al}/^{27}\text{Al}$ ratio shown by several grains is higher than the level predicted by the standard AGB models (not including deep mixing phenomena). Dealing with non convective mixing contribution to AGB nucleosynthesis, [6] clarified that because of the long life of ^{26}Al ($\sim 7.17 \cdot 10^5$ years) its abundance is strongly related with the depth of mixing penetration while it does not significantly depend on the mixing velocity nor on the mixing rate. Indeed the isotope is produced by the H-burning shell via the $^{25}\text{Mg}(p,\gamma)^{26}\text{Al}$ reaction, which efficiently burns just at relatively high temperature. However, reproducing values of $^{26}\text{Al}/^{27}\text{Al} \geq 0.01$ requires to push the mixing into layers of the H-burning shell so deep and hot that the process will affect the stellar energy balance with relevant luminosity feedback.

The parametric models of the quoted authors were essentially based on a fine tuning of two free parameters: the amount of material mixed into the stellar envelope and the maximum penetration of the mixing. The first one depends in its turn both on the velocities of the upward and downward streams of matters, and on the fraction of the area, at fixed radius, occupied by the "conveyor-belt". Understanding the physical causes of extra-mixing would be a big step forward in our knowledge of stellar physics and it would provide a model for deep mixing whose characteristics will be fixed by the physical conditions of the stellar environments and no longer set by the fine tuning of free parameters. In this paper we will present the case of a mixing mechanism induced by stellar magnetic fields.

2. Nuclear physics inputs and calculations

The puzzle of the oxygen isotopic mix of group 1 and 2 oxide grains was solved in the last years thanks to a series of nuclear physics measurements, which allowed (i) to state that these grains can not be formed in massive AGB stars [7] and (ii) to obtain a full match between the dust oxygen abundances and the predictions of deep mixing models for low mass red giants [8, 9](and references therein). In particular, RGB stars with mass from 1 to $2M_\odot$ and solar composition were proved to be progenitors of group 1 grains thanks to the $^{14}\text{N}(p,\gamma)^{15}\text{O}$ cross section measurements by [8] as well as AGB stars with mass smaller than $1.5M_\odot$, experienced an efficient mixing, were shown to account for the Oxygen isotopic ratios of group 2 grains because of the determination of the low energy cross sections of proton-induced reactions on $A = 17$ and $A = 18$ oxygen isotopes via the Trojan Horse Method (THM, [10, 11]).

The THM overcomes enhancement effects due to electron screening and allows to measure reaction cross section between charged particles in the energy range typical of H-burning in low mass red giants (a few tens of keV). For this reason it was employed to extract the strength of the 65 keV resonance in the $^{17}\text{O}(p,\alpha)^{14}\text{N}$ reaction [12], the strengths of the 20 keV one in the $^{18}\text{O}(p,\alpha)^{15}\text{N}$ reaction and the contribution to its rate of the tail of the 656 keV broad resonance

[13]. Moreover, the strength of the 65 keV resonance in the $^{17}\text{O}(p,\alpha)^{14}\text{N}$ reaction, measured by means of the THM, was used to renormalize the corresponding resonance strength in the $^{17}\text{O} + p$ radiative capture channel. As results, more accurate reaction rates for the $^{18}\text{O}(p,\alpha)^{15}\text{N}$, $^{17}\text{O}(p,\alpha)^{14}\text{N}$, and $^{17}\text{O}(p,\gamma)^{18}\text{F}$ processes were deduced [9, 14] and later introduced into the models for proton-capture nucleosynthesis coupled with mixing episodes presented by [15].

By employing those 3 reaction rates in an updated version of the "conveyor-belt" mixing model by [4] and [6], [9] succeed in reproducing the whole range of oxygen isotopic mix values measured in group 2 grains, indeed nucleosynthesis model curves reach the "forbidden" area of the $^{17}\text{O}/^{16}\text{O}$ vs $^{18}\text{O}/^{16}\text{O}$ diagram.

This sensitivity of the resulting oxygen isotopic mix to reaction rates adopted in calculations, and in particular of those of the $^{17}\text{O} + p$ process, is due to the fact that when an efficient deep mixing is at play the stellar envelope composition closely resemble the one of CNO equilibrium (at a temperature T , typical of the deepest layer reached by the streams of matter) which on its turn is determined by the equation

$$\frac{dY(^{17}\text{O})}{dt} = Y(^{16}\text{O})Y(H)R_{16\text{O}(p,\gamma)} - Y(^{17}\text{O})Y(H)(R_{17\text{O}(p,\alpha)} + R_{17\text{O}(p,\gamma)}) \quad (1)$$

where $Y(i)$ means the abundance in number of the i th isotope and any reaction rate R is temperature and density dependent. From the previous equation, the equilibrium value of the $^{17}\text{O}/^{16}\text{O}$ ratio turns out to be

$$\frac{Y(^{17}\text{O})}{Y(^{16}\text{O})} = \frac{R_{16\text{O}(p,\gamma)}}{R_{17\text{O}(p,\alpha)} + R_{17\text{O}(p,\gamma)}} \quad (2)$$

One can notice that equilibrium values of the $^{17}\text{O}/^{16}\text{O}$ isotopic ratio do not depend on the initial isotopic abundances but are instead determined by the values of the reaction rates. As a consequence, in [9]'s calculations the $^{17}\text{O}/^{16}\text{O}$ ratio result larger because of THM cross sections of the $^{17}\text{O} + p$ reactions are smaller (see Figure 3, 4 and 5 in [9]) than those reported in [8].

Despite the nice agreement between the theoretical predictions and the dust contents in ^{17}O and ^{18}O and the success of the parametric extra-mixing model by [15, 9] in explaining the isotopic ratios of CNO elements, as observed in stellar photospheres [16], a big challenge about the ^{26}Mg excess found in presolar grains (hinting to their formation in a ^{26}Al -rich environments) remains. Especially after that a possible solution coming from nuclear physics was excluded by the measurement of the $^{25}\text{Mg}(p,\gamma)^{26}\text{Al}$ cross section published in [17] and by the recent one of the $^{26}\text{Al}(p,\gamma)^{27}\text{Mg}$ by [18].

3. Novelties from stellar physic

In the last years [19] demonstrated that the full MHD¹ equations can be solved analytically in an exact way when applied to the radiative layers of low mass evolved stars. This fact allows to build a mixing model where the mass transport is driven by the buoyancy of magnetized structures. Such an idea derives from an application to a later evolutionary phase of the dynamo model developed by Parker for the Sun [20]. Recently, [21] have verified that the physical conditions of the H-shell of RGB and AGB stars, with mass smaller than $2.5M_{\odot}$, allow for the solution of MHD equations and have presented a non-parametric model for a mass circulation mechanism by applying the analytical solutions found by [19] to the stellar region of interest. In this framework, the mixing velocity is the radial component of the one by which magnetized structures (or flux tubes) expand and has the form:

$$v_r = v_0 \left(\frac{r}{r_0} \right)^{-(k+1)} \quad (3)$$

¹ magnetohydrodynamic

where r is the position along the stellar radius, while k is a number smaller than -1 dealing with the form of the plasma density distribution, which has to have the simple form $\rho \propto r^k$. In this approach the mixing depth is determined by k . Indeed the rising of magnetized structures starts from the deepest stellar layers whose physical conditions admit an analytical solution of MHD equations. [21] have shown that in low mass AGB stars those layers have the values of k ranging from -3.5 to -3.1 (the smaller is k the deeper is the mixing).

Moreover, in agreement with [21, 22] the mixing rate forced by magnetic buoyancy is given by

$$\dot{M} = 4\pi\rho_e r_e^2 v_e f_1 f_2 \quad (4)$$

where r_e is the stellar radius at the interphase between the radiative region and the convective envelope and v_e is the speed by which r_e is reached by rising materials. f_1 is the fractional area the flux tubes occupy when the stellar radius is r_e and f_2 is their filling factor. Extrapolating solar conditions to an evolved star, a field of a few 10^5 Gauss may be involved in magnetized structure occupying a fraction of 1 – 2% of the whole area at the base of convective envelope ([19], and references therein), while f_2 is of about 1/100 of the section of the magnetized structures (which are actually almost empty, with electrically-charged materials concentrated in thin current sheets, see e.g. [23]). Since v_e has to be smaller than the convective velocity in the bottom envelope layers (v_{conv}) to allow the macroturbulence to destroy magnetized structure and release the trapped mass into the surface, we adopted a value of $v_e \leq v_{conv}$, which for AGB stars with $1.2 - 1.5M_\odot$ is of the order of 100 m/s. In the light of the above estimate for f_1 , f_2 and v_e , the $\dot{M}$ values obtained range between a 0.3 and $1.3 \cdot 10^{-6} M_\odot/\text{yr}$, which are in the range found previously by [15] (with their parametric model of mixing) to account for the oxygen isotopic composition of group 2 oxide grains and the $^{12}\text{C}/^{13}\text{C}$ isotopic ratio observed in the spectra of MS and S stars [24].

4. Results

We applied a model of mass circulation induced by stellar magnetic fields [19] to study the isotopic composition of oxide presolar grains. In particular we aimed to reproduce the smaller values of ^{18}O as long with the higher one of ^{26}Mg (from the decay of ^{26}Al) measured in dust of RGB and AGB origin.

We performed our calculations employing the THM estimates of the $^{17}\text{O}(\text{p},\alpha)^{14}\text{N}$, $^{17}\text{O}(\text{p},\gamma)^{18}\text{F}$ and $^{18}\text{O}(\text{p},\alpha)^{15}\text{N}$ low-energy reaction rates and assuming flux tubes rising from layers where $k = -3.5, -3.4, -3.3, -3.2$ and -3.1 , as suggested by [21]. Computation results are shown in figure 1 for a $1.2M_\odot$ evolved star with solar composition. In panel A the grey squares along the dashed line report the oxygen isotopic abundances in the envelope of stars approaching the RGB phase with different mass (from 1 to $1.7M_\odot$ as indicated by the labels). Such values, which result to be sensitive to $^{14}\text{N}(\text{p}, \gamma)^{15}\text{O}$ but not affected by the $^{17}\text{O} + \text{p}$ reaction rates employed in stellar model calculation, remain almost unchanged for the rest of stellar evolution if no mixing phenomenon occurs. Since a dilution of the $^{18}\text{O}/^{16}\text{O}$ abundance in the stellar envelope is needed to reproduce the values measured in group 2 grains (solid points in figure 1A), our MHD mixing model has been introduced in nucleosynthesis calculations for both the RGB and AGB phase and the effects on the temporal evolution of chemical abundances are shown by the downward red curves (the darker is the color, the smaller is the value of k , the deeper is the mixing).

The sequence of curves cover the whole area where group 2 oxide grains lie. By using the same set for the nuclear physics input, we get therefore a confirmation of what was found by [9]: the dust in exam can be explained by most efficient mixing cases applied to a $1-1.5M_\odot$ stars; but these conclusions are now based on a deep-mixing mechanism rooted in a more physical approach, and based on necessary processes of plasma physics.

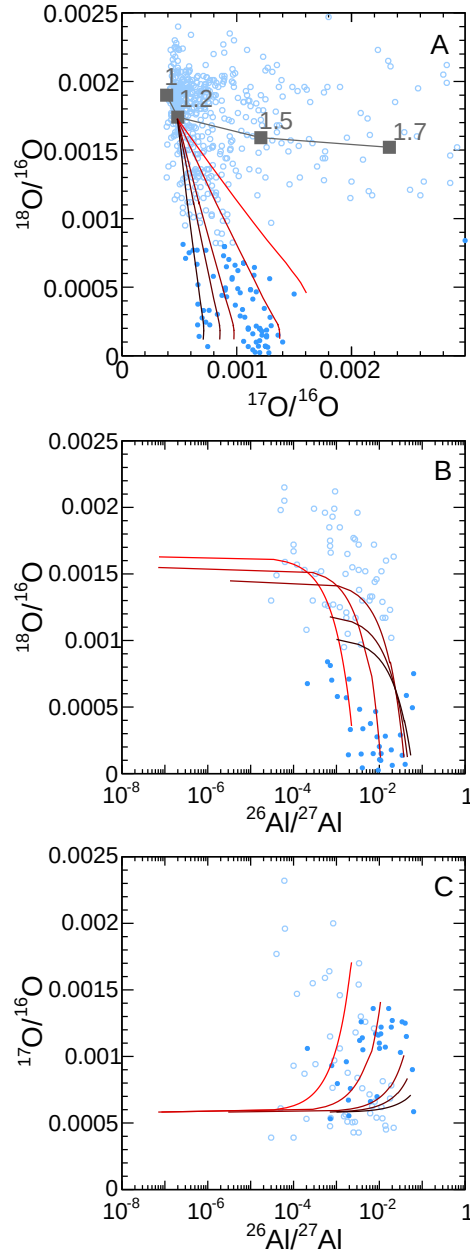


Figure 1. Panel A. Oxygen isotopic mix in the envelope of solar-metallicity stars approaching (dashed grey line). Full squares indicate the composition of stars with mass from 1 to 1.7 $M_{\odot}$, as indicated by the labels. Data points refer to measurements in presolar grains from [25]. We plot those of group 1 (open circles) and those of group 2 (filled circles). We do not report error bars in the figures, because they would confuse the plot, due to the large number of grains. In any case uncertainties are typically lower than 5-6% for all the grains of groups 1 and 2. The descending continuous lines refer to model results for deep mixing driven by magnetic buoyancy in a 1.2 $M_{\odot}$ star for different values of k , during the RGB and the AGB phase. The smaller the value of k , the darker the curve ($k = -3.5, -3.4, -3.3, -3.2, -3.1$). Panel B and C. The evolution of the oxygen isotopic ratios $^{17}\text{O}/^{16}\text{O}$ and $^{18}\text{O}/^{16}\text{O}$, respectively, as functions of $^{26}\text{Al}/^{27}\text{Al}$ for the same models and grains reported in panel A,

In panels B and C, the evolution of the oxygen isotopic ratios is shown as a function of the $^{26}\text{Al}/^{27}\text{Al}$ ratio for the same models and grains discussed so far. The curves deal with the same magnetic mixing cases shown in panel A. We notice that the success of magnetically-induced mixing lays in accounting for the range of values of $^{26}\text{Al}/^{27}\text{Al}$ up to 0.1, even adopting the already-quoted rate by [17] for ^{26}Al production and the one by [18] for its destruction. We recall that previous parametric models could not, instead, explain the whole range of ^{26}Al , as measured in presolar grains, see e.g. [15] and in particular their Figure 11.

The success of the MHD induce mixing in reproducing the whole isotopic composition of group 2 grains is due to the fact that in this model hot magnetized materials are pushed up into the envelope from below (driven by magnetic buoyancy) and the down-flow occurs as a consequence of mass conservations at the envelope border. In the parametric mixing described by [4], and later by [6], upflowing streams of materials are triggered (because of the mass conservation law) by the penetration of matters from the bottom of the stellar envelope.

In conclusion, the whole areas that group 2 oxide presolar grain occupy in the $^{17}\text{O}/^{16}\text{O}$ vs $^{18}\text{O}/^{16}\text{O}$ diagram, in the $^{17}\text{O}/^{16}\text{O}$ vs $^{26}\text{Al}/^{27}\text{Al}$ one and in the $^{18}\text{O}/^{16}\text{O}$ vs $^{26}\text{Al}/^{27}\text{Al}$ one are covered by curves of a physically-based model, for mixing in low mass evolved stars, employing a set of nuclear physics input measured ad-hoc by the THM in the energy range typical of AGB star nucleosynthesis.

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5. References

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