SOLAR OXYGEN ISOTOPES AFTER GENESIS: IS THE FINAL WORD OUT?

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Introduction: The Genesis mission has provided information on the isotopic composition of the solar wind of unprecedented quality. The most striking result is that the composition of oxygen is not on the terrestrial ("mass-dependent") fractionation line, but that planetary oxygen is enriched in the heavy isotopes relative to solar wind oxygen, which is found at $\Delta^{17}O \approx -28‰$ [1]. If solar wind faithfully reflected the isotopic composition of oxygen in the Sun, the third most abundant element, this observation would have far-reaching consequences for our understanding of the role of various mass reservoirs during the formation of the inner planets and the planetary system.

Isotopic fractionation in the solar wind and in the outer convective zone of the Sun: We consider two processes which could modify the isotopic composition of solar oxygen before being captured in the Genesis targets. The first process is acceleration of oxygen ions out of the solar gravity field by Coulomb friction with solar wind protons and alpha particles. Inefficient Coulomb friction seems to be at least partially responsible for the strong depletion of helium in the solar wind relative to its abundance in the solar atmosphere. There is evidence that also other heavy elements are depleted in low-speed solar wind relative to the solar source, and it is clear that this process will produce some isotopic fractionation in low-mass elements such as helium, oxygen, neon and magnesium of the order of a several percent to a few permil per mass unit. Estimates from theoretical models indicate that this fractionation should operate more or less parallel to the terrestrial fractionation line, i.e., ^{17}O being about half as much depleted as ^{18}O. Observational evidence for such a fractionation comes from the Genesis mission [2] and from the Apollo foil experiments [3,4].

Isotopic fractionation in the outer convective zone of the Sun: The second process considered has been operating at the interface between the radiative and the outer convective zone of the Sun. From helioseismological observations we know that heavy elements have been depleted over the main-sequence lifetime of the Sun by gravitational settling on the order of typically 10 percent relative to their initial abundances [5]. Concomitant with the elemental depletion, heavier isotopes tend to be more strongly depleted than light isotopes [6,7]. Radiative acceleration associated with the radiation flux from the solar interior driven by the temperature gradient somewhat reduces the effect of gravitational settling. It only involves the electron shells, and it is therefore independent of the mass of the affected particles. The combination of mass-dependent downward gravitational settling and upward, mass-independent radiative acceleration leads to isotopic fractionation, which does not strictly follow the "mass-dependent" terrestrial fractionation line.

Gravitational Settling in Solar Models: We computed the evolution of models of 1 $M_\odot$ with a solar chemical composition given by [8] and a Sun-calibrated value for the mixing-length parameter. The stellar evolution code used for these computations is the Geneva code that includes a detailed treatment of rotational effects [9]. The braking law of [10] is used in order to reproduce the magnetic braking undergone by rotating low-mass stars during their main sequence evolution; the braking constant is calibrated in such a manner that rotating models reproduce the solar surface rotational velocity after 4.57 Gyr. In addition to rotation, atomic diffusion due to concentration and thermal gradients, and gravitational settling is included and the diffusion coefficients are computed according to the prescription by [11]. For this study, we simply focus on the surface abundances of 1 $M_\odot$ models, which reproduce the observed solar luminosity and radius at the age of the Sun. As a first step, a model is computed without rotation. This model includes atomic diffusion due to concentration gradients, while radiative accelerations are neglected. As a result of atomic diffusion and gravitational settling, the surface abundances change during the main-sequence evolution. The variation in the oxygen isotopes obtained at the solar age for this model is shown in Fig.1. In order to investigate the impact of rotation on these abundances, two rotating models have been computed with initial equatorial velocities on the zero-age-main sequence of 8 and 50 km/s. These models share exactly the same initial parameters as the non-rotating one except for the inclusion of rotational effects.

Oxygen isotopic abundances corresponding to the rotating models are also shown as blue full circles in Fig. 1. We note that the differences in the oxygen isotopic abundances decrease when the initial rotational velocity increases. This is due to the enhanced efficiency of mixing with the initial rotational velocity. Rotational mixing is indeed found to counteract the effects of gravitational settling in the external layers of solar-type stars [12], which results in smaller changes in the oxygen isotopic surface abundances for rotating models compared to the non-rotating one.

As a second step, we estimate the impact of the radiative acceleration g_{rad} on surface abundances by simply assuming that g_{rad} is equal to 10% of the gravity. A non-rotating model is then computed with the same initial parameters as previous models, except for the inclusion of this crude assumption for the radiative acceleration. As illustrated in Fig. 1 with the red triangle, the differences in the oxygen isotopic abundances are smaller for this model than for the non-rotating model without radiative acceleration. We also note that this model does not yield noticeable deviations from the mass-dependent fractionation line. Enhancing the radiative acceleration to an unrealistically high value, $g_{rad}/g=0.4$, would lead, however, to a slight deviation from the short-dashed, black "mass-dependent" fractionation line. The long-dashed red line in Fig. 1 illustrates the expected track of models with extreme radiative acceleration.

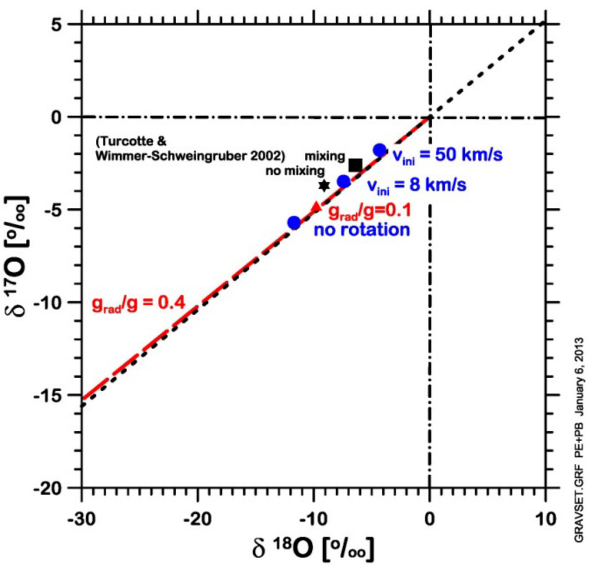

Fig. 1: Oxygen isotopic abundances for different solar models. Blue dots correspond to rotating and non-rotating models computed with atomic diffusion due to concentration and thermal gradients, and gravitational settling, but without radiative acceleration g_{rad}. Black symbols correspond to the models by [7] while the long-dashed red line indicates the change of the oxygen isotopic abundances as estimated with the approximation of [6] using an extreme value of g_{rad}.

The results shown in blue symbols in Fig. 1 are based on stellar models including a detailed treatment of rotational effects, but only a crude assumption for the radiative acceleration. It is then interesting to compare these results with the ones obtained by [7] (black symbols), which are based on models including a detailed treatment of radiative forces, but are computed without mixing (an ad-hoc correction for turbulent mixing has been introduced a posteriori). The difference in the oxygen isotopic abundances decreases when the correction due to mixing is applied, in good agreement with the results of our rotating models. We also see that the changes in the oxygen isotopic abundances are similar for our non-rotating model including g_{rad} and the model without mixing of [7]. Note that the results of the models of [7] slightly deviated from the mass-dependent fractionation line. We believe that this is due to the detailed inclusion of radiative forces in their models compared to the simple assumption used for g_{rad} in our models. We thus realize that solar models computed with different assumptions for the inclusion of rotational effects and radiative acceleration do not predict solar oxygen isotopic abundances *below* a universal mass-dependent fractionation line. We conclude that these effects cannot be responsible for the large observed deviations of solar wind oxygen from the terrestrial fractionation as observed by the Genesis mission.

Conclusions: Isotopic fractionation in the lower corona and in the source regions of the solar wind has been recognized as a relevant ingredient for the interpretation of Genesis results. An important observational constraint will be provided by the precise measurements of the magnesium isotopes with Genesis [13,14]. Earlier attempts to infer isotopic fractionation of Mg in the solar wind from in situ measurements were marginally conclusive. From our preliminary investigation it appears that the isotopic effects observed in various elements of Genesis targets support theoretical models; but these models so far also do not predict that isotopic fractionation due to inefficient Coulomb drag or gravitational settling is able to cause substantial deviations from the "mass-dependent" fractionation line. However, a comprehensive, multi-isotope analysis of all mechanisms involved is still missing.

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