JOURNAL OF THE KOREAN ASTRONOMICAL SOCIETY
40: 107 ~ 111, 2007

THE ORIGINAL ENVIRONMENT OF THE SOLAR SYSTEM INFERRED FROM THE OXYGEN ISOTOPE ANOMALIES

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(Received November 30, 2007; Accepted December 12, 2007)

ABSTRACT

The original environment of the solar system can be inferred by studying the oxygen isotope ratios in the Sun as well as in primitive meteorites and comets. The oxygen isotopic fractionation measured in primitive meteorites is mass-independent, which can be explained by the isotopic-selective photodissociation of CO. The isotopic-selective photodissociation model in a collapsing cloud by Lee et al. (2007) imply the birth of the Sun in a stellar cluster with an enhanced radiation field, which is consistent with the inferred presence of ^{60}Fe.

Key words : ISM:astrochemistry — stars:formation— solar system:formation

I. INTRODUCTION

Most stars form in clusters (Lada & Lada 2003) even though the detail process of star formation has been studied the most in isolated low mass star forming cores. Our star, the Sun, seems alone at present with the closest stellar neighbor at 1.3 pc. However, it is not certain whether the Sun formed in a cluster or in isolation. Some memory of the environment where the Sun formed might exist within the remnants of the formation of the Solar System. In this regard, primitive meteorites, interplanetary dust particles, and comets have been considered as the best sources to search for memory of conditions prior to and during formation, since they escaped from significant physical and chemical processing and therefore may preserve some relic of interstellar material. For instance, the inferred presence of short-lived radionuclides, especially ^{60}Fe, in meteorites (Wadhwa et al. 2007) suggests that the Sun formed near a massive star, which went through the core collapse of a supernova and provided the radionuclide to the solar nebula (Ouellette et al. 2005) or to the proto-solar molecular cloud (Gounelle 2006).

The radiation environment where the Sun formed must have also left some evidences in chemistry affected by photolysis. If the Sun formed in a cluster, the ultraviolet radiation field around the proto-Sun would have been enhanced by 4 to 5 orders of magnitude compared to the standard local interstellar radiation field. Clayton et al. (1973) discovered that oxygen isotopes in calcium aluminum rich inclusions (CAIs) embedded in primitive meteorites had different ratios from those seen in terrestrial rocks, where the oxygen isotopic fractionation depends on mass. Recent theories suggest this mass-independent fractionation recorded in meteorites can be understood as a result from the isotopic-selective photodissociation of CO, either in the Solar Nebula (Clayton 2002, Lyons & Young 2005) or parent cloud (Yurimoto & Kuramoto 2004). The photodissociation of CO is strongly coupled with the strength of the far-ultraviolet (FUV) radiation field as well as the CO column density. The studying of oxygen isotope ratios in the Solar system, therefore, will place strong constraints on its formation environment.

The oxygen isotope composition of the Sun is central to understanding the oxygen isotope evolution of the Solar System as recorded in meteorites. However, recent Solar wind oxygen isotope measurements in lunar metal grains have yielded dramatically different results. Defined as the isotopic delta value, $\delta^{17,18}\mathrm{O}_{\mathrm{SMOW}} = 1000 \times [\frac{[^{17,18}\mathrm{O}/^{16}\mathrm{O}]_{\mathrm{Sun}}}{[^{17,18}\mathrm{O}/^{16}\mathrm{O}]_{\mathrm{SMOW}}} - 1]$, where SMOW is the standard mean ocean water, the measured Solar values were -50 permil in one case (Hahizume et al. 2005) and $+50$ permil in the other (Ireland et al. 2006). $\delta^{17,18}\mathrm{O}_{\mathrm{SMOW}} = -50$ permil indicates that the Sun is enriched in ^{16}O, but $\delta^{17,18}\mathrm{O}_{\mathrm{SMOW}} = +50$ permil means that the Sun is enhanced in heavier oxygen isotopes. Clayton (2002) predicted that the Sun would have $\delta \sim -50$ permil based on the isotopically-lightest CAIs, which were assumed to have oxygen isotope ratios similar to the bulk parent cloud. However, based on the CO self-shielding model in a collapsing low mass star forming cloud, Lee et al. (2007) have showed that the Solar oxygen isotopic anomalies could vary depending on the strength of the surrounding radiation field

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(G_0) when the Sun formed. Therefore, the direct and accurate measurement of the Solar oxygen isotopic ratio (potential results from Genesis) will constrain the radiation environment of the proto-Sun. However, Lee et al. (2007) have suggested that the oxygen isotope anomalies measured in meteorites and comets can place constraints on the original radiation environment and provide predictions on the oxygen isotope anomalies of the Sun.

II. ISOTOPIC-SELECTIVE PHOTODISSOCIATION OF CO AND MATERIAL FRACTIONATION BETWEEN GAS AND ICE

There are two separate processes related to the enrichment of heavier oxygen isotopes in our Solar system. First there must be an enhancement of heavier oxygen isotopes in ice and their deficiency in gas. Second, the segregation between ice and gas components (i.e. material fractionation) must occur to lead to anomalies in the forming bodies in the inner Solar system.

The first process can operate by the isotopic-selective photodissociation of CO. $C^{16}O$ and its isotopologues ($C^{18}O$ and $C^{17}O$) have dissociation initiated by the line absorption (pre-dissociation) at wavelengths of 91 to 110 nm, and hence the strength of photodissociation depends on line opacity (i.e. column density). (The photodissociation rate also depends on continuous opacity since dust grains absorb the FUV radiation.) This process is called self-shielding. Owing to its higher abundance, $C^{16}O$ self-shields more effectively than its isotopologues and appears in abundance closer to the source radiation. Thus, due to this isotopic-selective photodissociation, there will exist a layer of atomic ^{18}O (and ^{17}O) when all ^{16}O is locked in $C^{16}O$. This ^{18}O (and ^{17}O) can freeze onto grains and react with hydrogen to make isotopically enriched water ice. The water ice stays frozen because grains are colder than its sublimation point; thus there will exist a water ice layer where ^{18}O is enriched relative to ^{16}O (above the value of 1/500 estimated for the ISM).

Once the water ice has the enrichment of heavier oxygen isotopes, ice must be separated from the CO gas, which is deficient in heavier oxygen isotopes, to produce the oxygen isotopic anomalies in the forming bodies in the inner Solar nebula. Cuzzi & Zahnle (2004) and Ciesla & Cuzzi (2006) have suggested that this material fractionation is possible in the inner Solar nebula by showing that the ice coated grains accreted to the outer disk at the early stages settle in the midplane of the disk, grow in size, and move inward to small radii due to gas drag. In contrast, the gas can be removed from the disk midplane through advection, diffusion, or dispersal (Yurimoto et al. 2007). As described above, dust grains coated with icy mantles contain the enhancement in heavier oxygen isotopes owing to the formation of water ice on grain surfaces by the frozen atomic oxygens resulted from the isotopic-selective dissociation of CO. Therefore, when the drifting grains cross the water evaporation front (snow line), the water ice evaporates to enhance the inner nebula in $H_2^{17}O$ and $H_2^{18}O$ vapors (Cuzzi & Zahnle 2004), which cool down, condense again, and finally constitute planets and meteorites in later evolutionary stages. We know that disks exist from early stages in the star formation process and accretion is mediate by the disk (Terebey et al. 1984; Hartmann 1998). In addition, the grain growth and settling have been detected in disks (Kessler-Silacci et al. 2006; Furlan et al. 2006). Therefore, the second process, material fractionation is potentially operative during evolutionary stages prior to the proto-Sun achieving its final mass.

III. MODEL CALCULATIONS OF OXYGEN ISOTOPE ANOMALIES IN THE OUTER DISK AND THE PROTO-SUN

As described in the previous section, the irradiation of the surfaces of protoplanetary by both stellar and interstellar radiation can produce strong isotopic enhancements that can enrich the midplane (Lyons & Young 2005). Therefore, the oxygen isotope anomalies detected in CAIs can be explained by these irradiated disk models. However, the irradiated disks likely do not provide enough mass to alter bulk Solar oxygen isotope ratios, except possibly by a large addition of water-rich material to the Solar convective zone. For a convective zone mass of 0.03 $M_\odot$, and assuming cometary material with water with $\delta^{17}O = 200$ permil, about 50 Earth masses of comets (a mass comparable to the Oort cloud) are needed to increase $\delta^{17}O$ of the convection zone by $\sim$ 50 permil. Such large input of planetary material to stellar convective zone does not appear to be supported by recent observations of extra-Solar planetary systems (Ecuvillon et al. 2006).

The surface of the cloud is also irradiated and isotopic enrichments will be carried by water-ice coated grains via collapse to the forming disk (Yurimoto & Kuramoto 2004). However, Yurimoto & Kuramoto (2004) did not present a detailed model of this process, but Lee et al. (2007) have investigated this question in the context of the chemo-dynamical model of cloud collapse developed by Lee et al. (2004). This model approximates the pre-collapse evolution as a sequence of Bonnor-Ebert (BE) spheres (Boonor 1956; Ebert 1955) with increasing central densities. BE spheres are believed to best describe the density structure of condensing cores prior to collapse (Evans et al. 2001; Bergin & Tafalla 2006). After 5×10^5 years condensation, collapse ensues in an inside-out fashion according to the Shu (1977) solution. Throughout the computation the gas and dust energetics and chemical evolution are calculated self-consistently.

Fig. 1 presents a sample of results of Lee et al. (2007), where $\delta^{18}O$ calculated from the water ice is shown as a function of time and radius during collapse for a given strength of the external radiation field.

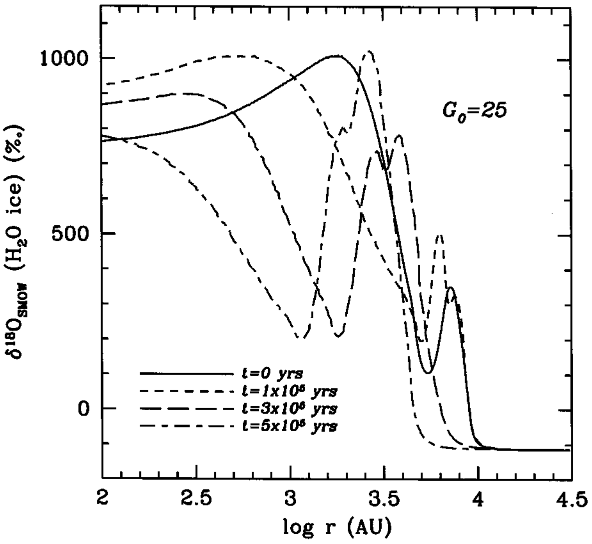

Fig. 1.— Sample of results from Lee et al. (2007) showing the spatial and temporal evolution of the oxygen isotopic enhancement carried by water-ice coated grains. In this model $t = 0$ refers to the stage just before collapse after 5×10^5 years of condensation in a cold starless phase. All other times listed are during the collapse phase and illustrate how the enrichment is carried inwards by infalling material. In addition, enrichments are seen deep in the cloud owing to the fact that the pre-collapse evolution starts with lower volume and column density, thereby allowing more gas to be affected by irradiation and isotopic-selective photodissociation.

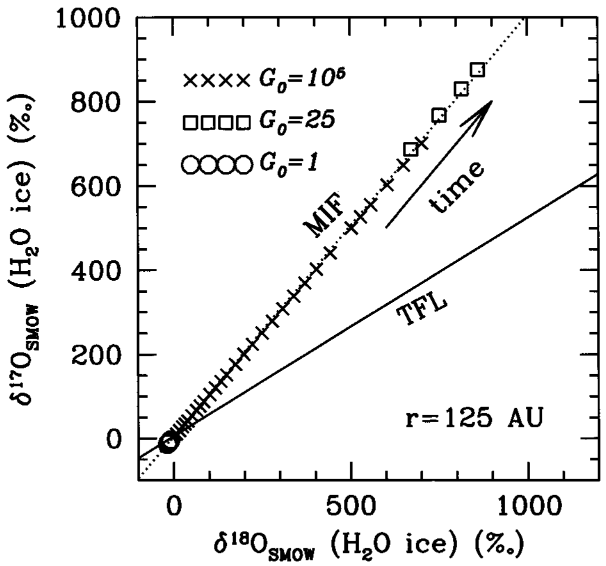

Fig. 2.— Sample of results from Lee et al. (2007) showing the evolution of isotope anomalies calculated from water ices at the outer boundary of the Solar Nebula (r=125 AU) in the models of G_0 = 1 (circles), 25 (squares), and 10^5 (x symbols). In the model of $G_0 = 10^5$, time steps for symbols start at the time step when the proto-Sun achieved its final mass and increase in the step of 5,000 years. In the models of G_0 = 1 and 25, however, the time step for the plot is 50,000 years to avoid confusion. The isotope anomalies in these two models do not vary much with time. Anomalies calculated from water ices plot along the line with a slope of 1, the mass-independent fractionation (MIF, dotted line) rather than the terrestrial fractionation line (TFL, solid line), as seen in meteorites.

They found that the inner radius of their model (~ 100 AU, assumed to be the outer edge of the disk) has a high degree of isotopic enrichment that is continually provided by collapse. The level of this enrichment depends on the strength of the external radiation field. Therefore, the combined process of the enrichment with the material fractionation operating in the inner disk, described by Cuzzi & Zahnle (2004) and Ciesla & Cuzzi (2006), can produce the oxygen isotope anomalies observed in meteorites. Lee et al. (2007) have also calculated the oxygen isotope anomaly in the Sun by assuming that the enrichment at the disk edge is preserved in the disk midplane, and the material fractionation occurs only during the final accretion phase. According to their results, the Sun can be either enriched or depleted in heavier oxygen isotopes depending on the strength of the external radiation field and on the time that it takes grains to evolve to a certain size (~ 1 m) subject to the material fractionation.

IV. THE ORIGINAL ENVIRONMENT OF THE SOLAR SYSTEM

Table 1 lists $\delta^{18}O$ calculated from all material accreted to the proto-Sun in the case that 15 % of the solar mass was affected by the material fractionation (Lee et al. 2007). As seen, the oxygen isotope anomaly depends on the external radiation field strength. It is difficult to infer the original radiation environment of the Solar system based on these calculations of $\delta^{18}O$ solely in the proto-Sun since the recent two measurements of the Solar values are very disparate as −50 and +50 permil. However, we can use $\delta^{18}O$ measured from planets, meteorites and comets as additional constraints.

Fig. 2 shows the evolution of $\delta^{17}O$ versus $\delta^{18}O$ calculated from water ice at the disk edge after the proto-Sun achieved its final mass, 1 $M_\odot$. The δ−values follows well the mass-independent fractionation line as shown in CAIs (Clayton et al. 1973). At the final stages of collapse, the water ice in the disk must be highly enriched in heavier oxygens to compensate for their deficiency at the outer nebula, where the water ice becomes deficient due to the material fractionation. $\delta^{17,18}O$ in terrestrial rocks is about 0 permil, but $\delta^{17,18}O$ in meteorites distributes from −80 (Kobayashi et al. 2003) to a few tens permil. $\delta^{18}O$ in the comet Halley is 12 ± 75 per-

TABLE 1.
$\delta^{18}O_{SMOW}$[a] IN THE PROTO-SUN

G_0[b]	$\delta^{18}O_{SMOW}$ (PERMIL)
1	-47
10	+3
25	+40
10^2	-48
10^3	-46
10^4	-8
10^5	-50

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[a] Assumptions in the calculation are 1) grains drift inward 10 times faster than gas in the disk and 2) 15% of the solar mass is affected by the material fractionation.

[b] The enhancement factor, which is a measure of the strength of the local FUV radiation field relative to the standard interstellar radiation field.

mil (Eberhardt et al. 1995). According to Sakamoto et al. (2007), $\delta-$values for inferred H_2O in nanocrystal aggregates in Acfer matrix are $\sim 150 - 200$ permil. The nanocrystals are a poorly characterized phase of an Fe-Ni-O-S bearing mineral that probably formed by oxidation of Fe metal or FeS by water in the solar nebular or in planetesimal. As seen in Fig. 2. the model of $G_0 = 10^5$ presents a wide range $\delta^{18}O$ to support the $\delta^{18,17}O$ values measured within meteorites, comet Halley, and the nanocrystal aggregates in Acfer matrix. Therefore, the results of Lee et al. (2007) suggest that the Sun formed near a massive star in a large stellar cluster, which is consistent with the inferred presence of ^{60}Fe, and support the inference that the bulk Sun has $\delta^{18,17}O = -50$ permil.

ACKNOWLEDGEMENTS

This work was supported by the faculty research fund of Sejong University in 2007.

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