MAKING WATER WORLDS: THE ROLE OF AL 26. **S. J. Desch**[1] and **L. A. Leshin**[2,3], [1] Dept. of Physics and Astronomy, [2] Dept. of Geological Sciences, [3] Center for Meteorite Studies, Arizona State University, Tempe, AZ 85287 (steve.desch@asu.edu, laurie.leshin@asu.edu).

Planets such as Earth are the end products of complex formation histories. These formation histories render some planets habitable, especially if those planets inherit life enablers such as liquid water. We seek to explore important astronomical and planetary factors that affect the likelihood of forming "waterworlds" like the Earth in other solar systems, so that we may better assess the probability that other nominally Earthlike planets may harbor oceans capable of supporting life. In this abstract, we consider the effect of the astronomical setting of a forming solar system, and specifically its effect on the abundance of ^{26}Al, which, we argue, is a significant factor controlling the water content of Earthlike planets. We attribute the source of the short-lived ($t_{1/2} = 0.7\,\mathrm{Myr}$) radionuclide ^{26}Al in our solar system and others to a nearby supernova, so that a solar system's initial abundance of ^{26}Al is set by the essentially random distance to the supernova explosion. Our solar system very plausibly could have received much less ^{26}Al than it did, which would have led to a wetter Earth.

Earth is often perceived as especially wet and life-promoting. In fact, Earth's water makes up a relatively small fraction of the mass of the planet, about $2.8 \times 10^{-4}\,M_{\mathrm{E}}$ of water on the surface, and $0.8 - 8 \times 10^{-4}\,M_{\mathrm{E}}$ in the rest of the planet [1]. We adopt $5 \times 10^{-4}\,M_{\mathrm{E}}$ of water as a reasonable estimate for the "bulk Earth". In recent years, the case has been increasingly made that the Earth's water came from planetesimals in the asteroid belt region [2]. Comets cannot contribute more than 10 % of the Earth's water, due to dynamical constraints [2] and the high D/H ratio of comets [3]. While the late accretion of comets, especially from beyond 20 AU, sets a minimum water content of the Earth as high as 10 % of its present value, the bulk of the Earth's water must have come from the asteroid belt region. Specifically, the water was present as hydrated silicates or ices in either asteroidal bodies ($\sim 10\,\mathrm{km}$ in size) or in planetary embryos (many hundreds of km in size). The accretion of smaller asteroids may have been an efficient process for delivering water to the Earth during the first few Myr of the solar nebula, while the nebular gas was still dense [4], but devolatilization of Earth during later impacts could have removed this water [2]. On the other hand, accretion of planetary embryos from the asteroid belt region is a natural byproduct of planetary accretion that can account entirely for the Earth's water [2].

Spectrophotometry reveals the presence of hydrated silicate absorption features at $3\,\mu$m in asteroids from C class asteroids, which typically orbit at 2.5 - 4 AU [5]. Their spectra are closely related to those of carbonaceous chondrites, which show evidence for only low heating, generally $< 500\,\mathrm{K}$ [6], and contain water up to 10 % by weight [7]. Conversely, S class asteroids, which orbit from about 2 to 3 AU, have spectra that closely resemble those of ordinary chondrites, which show evidence for heating to temperatures in the range 500 - 1400 K, and which contain less than 0.1 % water by weight [8]. All suspected achondrite (differentiated) parent bodies lie inside of 2.7 AU [5], including the HED parent body 4 Vesta, at 2.4 AU. Generally speaking, relatively unheated, water-rich asteroids dominate beyond 2.7 AU, while heated, dry asteroids dominate inside of 2.7 AU. The models of [2] indicate that roughly 15 % of the Earth's mass, and $\approx 90\%$ of its water, derives from planetesimals that resided beyond 2.7 AU. It is tempting to associate the presence of water with a "snow line" in the solar nebula inside of which temperatures exceed 170 K and ice sublimates, which in the standard solar nebula model lies at about 2.7 AU. This simple explanation does not, however, account for carbonaceous chondrites being less water-rich than comets or icy outer planet moons, and it ignores the obviously relevant fact that carbonaceous chondrites are generally not heated, but ordinary chondrites more often than not are. The clear correlation of internal heating with heliocentric distance implicates thermal metamorphism as the determinant of water content.

Models of asteroid heating [9] indicate that for asteroids larger than about 100 km in diameter (i.e., planetary embryos), will either differentiate completely or be severely heated (e.g., to 500° C), and presumably devolatilize and lose their water, if the abundance of radioactive ^{26}Al is high enough: $^{26}\mathrm{Al}/^{27}\mathrm{Al} > 6.5 \times 10^{-6}$. These bodies form the very dry parent bodies of achondrites and ordinary chondrites. The same models show that even a slightly lower ^{26}Al abundance leads to heating no greater than a few hundred ° C. These bodies form the wet parent bodies of the carbonaceous chondrites. Our solar system began with ^{26}Al/^{27}Al $\approx 5 \times 10^{-5}$, as measured from calcium-aluminum-rich inclusions or CAIs [10], so any asteroids that accreted within 2.1 Myr of CAI formation would be dry, and bodies that formed later could retain water. As accretion timescales scale as the cube of heliocentric distance [11], early accretion is favored closer to the Sun. Accretion of planetesimals in just 2.1 Myr at a distance of 2.7 AU seems reasonable: the initial ^{26}Al/^{27}Al in the eucrite Piplia Kalan has been constrained at $\approx 7 \times 10^{-7}$ [12], implying that 4 Vesta (at 2.4 AU) differentiated, and its crust resolidified, all within 5 Myr.

What if the solar system's initial ^{26}Al abundance was a factor of 10 higher? Planetary embryos that accreted within the first $2.1 + t_{1/e} \ln 10 = 4.5\,\mathrm{Myr}$ of the CAIs would then be dry. Given the cubic dependence on heliocentric distance of the accretion timescale, we estimate that the boundary between the ordinary chondrites and carbonaceous chondrites would be pushed out to $2.7(4.5/2.1)^{1/3} = 3.5\,\mathrm{AU}$. As the Earth is very unlikely to accrete planetary embryos from beyond 3.5 AU [2], the Earth would essentially gain no water from the planetary embryos it accreted from. The Earth's water would consist only of what would be accreted from comets, about an order of magnitude less than the Earth's current water content.

What if the solar system's initial ^{26}Al abundance was a factor of 10 lower? All planetary embryos accreted at any time in the solar system would then by water-rich, since they would not have enough ^{26}Al to be significantly heated. The boundary between ordinary and carbonaceous chondrites would have been pushed in much closer to 1 AU, and the amount of carbonaceous chondrite material the Earth accreted would necessarily increase by a factor of at least 5. From these estimates we conclude that the Earth could have been an order of magnitude drier than it is if ^{26}Al was more abundant, or it could have been an order of magnitude wetter if ^{26}Al was less abundant.

Which is the more likely outcome? Meteoritic evidence suggests strongly that the solar nebula probably had already formed and was creating CAIs when a nearby supernova exploded, injecting the solar nebula with ^{26}Al [13]. This is consistent with estimates that $\approx 85\%$ of all solar-type stars form in clusters large enough to contain a star massive enough to supernova [14]. A plausible analog for the early solar system is a proplyd in the Orion nebula, which will intercept the radioactive elements ejected when the O6 star $\theta^1\,\mathrm{Ori}\,C$ goes supernova in a few Myr. A $25 M_{\odot}$ supernova ejects about $7 \times 10^{-5}\,M_{\odot}$ of ^{26}Al [15]. If this ejecta intercepts a solar-composition disk with surface density Σ at a distance r, the resulting ^{26}Al/^{27}Al ratio $= (1.9 \times 10^{-5})\,(r/10^{17}\,\mathrm{cm})^{-2}\,(\Sigma/1000\,\mathrm{g\,cm^{-2}})^{-1}$. The surface density at 3 AU in a minimum mass nebula is $300\,\mathrm{g\,cm^{-2}}$ [11], so the solar system ^{26}Al/^{27}Al ratio is reproduced if it was $1 \times 10^{17}\,\mathrm{cm}$ from the supernova.

The parameters that can reproduce the initial ^{26}Al/ ^{27}Al ratio of the solar system (distance $r < 10^{17}\,\mathrm{cm}$ from the supernova, and surface density at 3 AU of $\Sigma \sim 300\,\mathrm{g\,cm^{-2}}$) happen to be representative of about 25 % of the proplyds in the Orion Nebula [16]. However, the majority of the proplyds, and the vast majority of protoplanetary disks in the Orion Nebula that are not photoevaporating, should lie at distances $> 3 \times 10^{17}\,\mathrm{cm}$ from $\theta^1\,\mathrm{Ori}\,C$. After $\theta^1\,\mathrm{Ori}\,C$ supernovas, these newly forming solar systems should form planets with insufficient ^{26}Al to melt the ice in their asteroids. Any Earths that form in these solar systems should be considerably wetter (by an order of magnitude) than our own Earth. Further analysis of the injection of short-lived radionuclides into disks in the Orion Nebula is clearly warranted to better quantify these trends. Additionally, it is known that a fraction $\sim 15\%$ of solar systems form in regions without massive stars, such as the Taurus-Auriga molecular clouds. These systems would acquire no ^{26}Al at their births, and any Earths to form in these regions would almost certainly be significantly more water-rich than our own Earth.

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