ICY EXOMOONS EVIDENCED BY SPALLOGENIC NUCLIDES IN POLLUTED WHITE DWARFS.

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Introduction: White dwarfs (WDs) represent the last stage of stellar evolution. These stellar remnants are extremely dense and have extraordinary gravity such that elements heavier than helium sink rapidly below their surfaces. One would expect to observe only H and He at the surfaces of WDs. However, 25 to 50% of WDs exhibit elements heavier than helium. These white dwarfs are polluted by heavy elements resulting from accretion of asteroid-like or comet-like rocky bodies [1]. The geochemical compositions of extrasolar rocky bodies accreting onto WDs provides surprisingly detailed information about the geochemistry of extrasolar rocky bodies [2].

Recently, exceptionally high abundances of Be ($\sim 500\times$ chondritic) relative to other rock-forming elements (e.g., Fe, Mg, and O) were discovered in two polluted WDs, GALEX J2339-0424 and GD 378 [3], and by inference in the planetary materials polluting them. We present evidence that these excesses in Be in polluted WDs are the result of accretion of icy exomoons that formed in the radiation belts of giant exoplanets [4]. Here we use excess Be in the white dwarf GALEX J2339-0424 as an example.

Composition of Accreted Body: Differential settling through the WD envelope may cause lighter elements to appear in excess, altering the apparent composition of the accreted body. Because Be is among the lightest metals discovered in a polluted WD, we evaluated whether a high beryllium concentration in the atmosphere of the WD could be due simply to the higher rates of gravity-driven settling for heavier elements, compared to Be. We calculate the composition of the accreted parent body as a function of the duration of the accretion event, $T_{\rm acc}$, given known e-folding times for settling, τ_z, and a value for the lifetime of the exponentially decaying debris disk around the star, $\tau_{\rm disk}$. Solving for the mass of element z of the parent body accreted by the WD, $M^{\rm o}_{{\rm PB},z}$, as a function of accretion timescale $T_{\rm acc}$, yields

$$M^{\rm o}_{{\rm PB},z}(T_{\rm acc}) = \frac{M_{{\rm CV},z}\left[\tau_{\rm disk} - \tau_z\right]}{\tau_z\left[e^{-T_{\rm acc}/\tau_{\rm disk}} - e^{-T_{\rm acc}/\tau_z}\right]}. \quad (1)$$

We compare inferred abundances of z/Fe in GALEX J2339-0424, to z/Fe in CI chondrite, bulk silicate Earth and continental crust [5, 6, 7]. Figure 1 shows that the best fit to the composition of the accreted body is a CI-like carbonaceous chondrite; the accreted body was a chondrite-like body similar to those in our solar system.

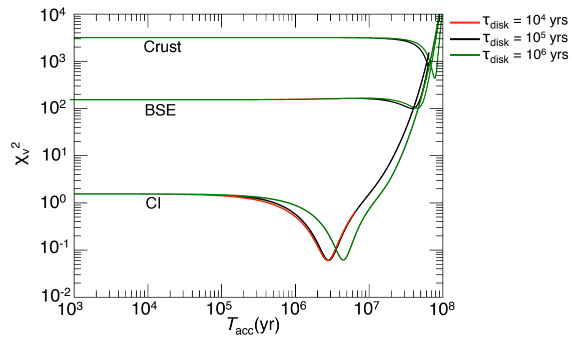

Figure 1: Reduced chi-squared, χ^2_ν, vs. $T_{\rm acc}$ for fits to average continental crust, bulk silicate Earth, and CI chondrite for the body accreted by WD GALEX J2339-0424. Various disk e-folding timescales, $\tau_{\rm disk}$, are shown for comparison. The fits are for the rock-forming elements Mg, Si, Fe, Ca, Ti and Mn. The best-fit $T_{\rm acc}$ is about 2 to 3 Myr.

Accounting for settling decreases the excess in Be from $\sim 500\times$ to $\sim 200\times$ chondritic, but does not remove it. This Be-rich, chondrite-like parent body was water ice-rich. Three-quarters of the oxygen comprising the parent body accreted by GALEX J2339-0424 was in excess of that required to form the oxides of the rock-forming elements. The excess oxygen was presumably accreted as water ice, and the parent body that accreted onto GALEX J2339-0424 was approximately 85% water by volume.

The failure of relevant geological materials enriched in Be relative to chondrite to fit the observed relative concentrations of the rock-forming elements in the WD demonstrates that the excess of Be cannot be explained by geochemical processes that might concentrate Be.

Source of Excess Be: Beryllium (as well as B and a significant fraction of Li) forms by spallation rather than stellar nucleosynthesis. Because the excess Be cannot be explained by differential settling in the WD nor by geochemical processes, it is almost certainly due to spallation of heavier nuclei (in particular, O) in rock or ice. Winds from the WD itself would only be efficacious if the star were rapidly rotating, or another mechanism such as a magnetic field were available to capture protons. GALEX J2339-0424 is neither magnetic nor rapidly rotating. We require an environment that can produce the observed Be/O number ratio of approximately 10^{-5}. The required fluence of $10^{21}{\rm cm}^{-2}$ to create the

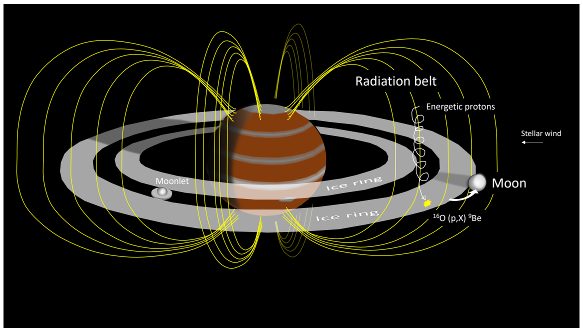

Figure 2: Schematic diagram depicting the proposed environment for formation of ices enriched in spallogenic nuclides. Trapped, high-energy protons migrate along magnetic field lines until they interact with icy rings by the reaction ^{16}O(p,X)^{9}Be. Eventually icy ring material accretes around a rocky core and a moon is formed at the outer edge of the disk that includes the product ^{9}Be [9].

observed Be/O ratio is the primary arbiter for the environment that formed the excess Be (and by inference, Li and B as well).

To reach a fluence of $10^{21}\mathrm{cm}^{-2}$, typical fluxes of ambient Galactic cosmic rays (GCRs) would have to act for 10^{12} to 10^{13} years, an impossibly long timescale. Core-collapse supernovae (CCSN) are one exogenous source of higher proton flux. We calculate that if 10% of the total energy of a SN remnant went towards the production of Be, a generous fraction, the energy fluence necessary to produce the observed Be/O ratio would require the SN source to be 0.025 pc from the planetary system. Not only is this improbable, but at these distances the system is unlikely to survive the CCSN event [8].

The fluence of energetic protons emanating from a protostar in its first $\sim$ 10 Myr, during the lifetime of its protoplanetary disk, is a potential source of irradiation. However, the energy loss of protons due to ionization of hydrogen severely limits Be production in the presence of a protoplanetary gas. This limits the region of sufficient irradiation to within 0.05 AU into the inner edge of the disk. Such a localized environment for rock formation makes this scenario unlikely.

Be Excesses in Icy Moons: Based on the above, the observed excess Be found in GALEX J2339-0424 appears to require that the accreted parent body formed in a local region of unusually high proton flux that was largely free of hydrogen gas. Radiation belts around giant planets satisfy these conditions. Icy rings provide the target. Saturn's inner icy moons formed as the rings viscously spread beyond the Roche limit, allowing cm- to m-sized ice grains to coalesce with ubiquitous silicates into a medium-sized moon [11]. This provides an analogy for the formation of the icy body accreted by the WDs (Figure 2).

We evaluated the plausibility of irradiation of icy rings in the radiation belt of a giant planet as the explanation for the Be excesses in the bodies accreted by the WDs. Using Saturn's rings as the analogy, the ice grain size in the rings was likely similar to the stopping distance of MeV protons in water ice; the process was efficient. The MeV proton flux depends on the stellar wind intensity of the host star at the position of the planet, the efficiency of trapping, and the sink terms for protons. Trapping efficiency depends foremost on the planet's magnetic field, which in turn depends on the mass of the planet, its rotation rate, and the conductivity of its interior. The higher MeV proton flux in Jupiter's radiation belt compared with Saturn is attributable to the higher Jovian magnetic field. The $\geq$ 10 MeV proton flux in the radiation belt of Jupiter is $10^{7}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$ [12]. This flux corresponds to a required radiation timescale of 1×10^{7} years. Estimates for the residence time of ices in Saturn's rings are on the order of 10^{7} to 10^{8} years [11], suggesting that a Jovian-like radiation flux is a plausible source for the irradiation of ices comprising the parent body accreted by GALEX J2339-0424.

Conclusion: Accretion of icy exomoons ejected from giant exoplanets were predicted to be sources of WD pollution [13]. Supra-chondritic Be/O ratios in polluted WDs may be evidence of this process. The masses and densities of the Saturnian mid-sized icy moons are comparable to that determined for the icy parent body accreted by GALEX J2339-0424. As a corollary of this study, we predict that at least some of the mid-sized icy moons of Saturn, e.g., Mimas, should be enriched in Be, B, and Li.

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