

PHOEBE'S CARBON ISOTOPE COMPOSITION AS EVIDENCE FOR SELF-SHIELDING IN THE SOLAR NEBULA. M. Neveu^{1,2}, C. H. House³, and S. T. Wieman^{2,4}. ¹Department of Astronomy, University of Maryland, College Park, MD 20742, USA. ²Planetary Environments Laboratory, NASA Goddard Space Flight Center, Greenbelt, MD, 20770, USA (marc.f.neveu@nasa.gov). ³Department of Geosciences, Pennsylvania State University, University Park, PA 16802, USA (chrishouse@psu.edu). ⁴Center for Space Sciences and Technology, University of Maryland, Baltimore County, Baltimore, MD 21250, USA (scott.t.wieman@nasa.gov).

Introduction: Unlike hydrogen, nitrogen, and oxygen, solar system carbon isotopic compositions are very uniform: $^{12}\text{C}/^{13}\text{C} \approx 80\text{--}115$ with many near the Earth value of ≈ 90 . Recently, Clark et al. [1] reported an extremely low value of $^{12}\text{C}/^{13}\text{C}=19$ in CO_2 ice on Saturn's moon Phoebe (Fig. 1). Here, we investigate possible interpretations for this observation.

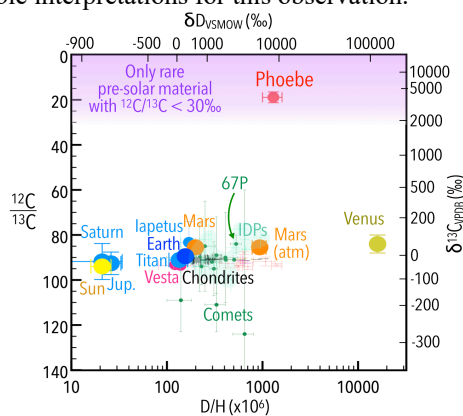


Figure 1. Phoebe's extreme ^{13}C enrichment compared to other measured solar system objects. $\delta^{13}\text{C} (\text{‰}) = (^{13}\text{C}/^{12}\text{C})_{\text{measured}} / (^{13}\text{C}/^{12}\text{C})_{\text{ref.}} - 1 \times 1000$. The reference is Vienna Pee Dee Belemnite ($^{12}\text{C}/^{13}\text{C}=89$). Solar system objects are spread on the x-axis by D/H ratio (ref. Vienna Std. Mean Ocean Water, $\text{D}/\text{H} = 155.8 \times 10^{-6}$).

Origin of Phoebe's CO_2 : Phoebe, a dark object on a retrograde orbit, is very likely a captured moon. Its bulk density $\approx 1640 \text{ kg m}^{-3}$ suggests that it could have formed either in the transneptunian protoplanetary disk [2] or in the giant planets forming region [3], with a bulk ice (mostly H_2O) content of 30-50% by mass and a possible abundance of solid carbon up to 20% [3].

The ^{13}C -rich CO_2 ice could have formed in several ways. CO_2 could predate accretion if it formed via the gas-grain reaction of C or C^+ with O [4]. The reaction of CO with OH in nebular gas [5] or with O on grains [4] is implausible as it would require ^{13}C -rich CO (see end p. 1). CO_2 could also form post-accretion by oxidation of organic compounds condensed in the nebula [6] and seen on Phoebe [7], via space weathering [8] or aqueous alteration [3,7].

Possible sources of Phoebe's ^{13}C enrichment: It is unlikely that Phoebe's carbon became ^{13}C -enriched post-accretion, because other bodies have a uniform

$^{12}\text{C}/^{13}\text{C}$ ratio irrespective of size, state of differentiation, outgassing, or C speciation (Fig. 1).

Unless Phoebe was captured from another planetary system, a pre-solar system origin for its C is unlikely for two reasons. First, most interstellar sources have $^{12}\text{C}/^{13}\text{C}$ ratios higher than Phoebe's [1], save for rare pre-solar grains [9] and sources near the Galactic center [10]. Second, mixing of pre-solar C isotopic reservoirs would distribute $^{12}\text{C}/^{13}\text{C}$ ratios among solar system bodies throughout the range spanning Phoebe to solar-like values (as is the case for D/H ratios; Fig. 1), rather than cluster them within a tight range with the outlier Phoebe value suggesting a distinct reservoir.

Phoebe itself could have formed outside the solar system in a dense, ^{13}C -rich region. Such conditions could be met around an asymptotic giant branch star dredging up and ejecting ^{13}C -rich material [10]. This material could condense and either coat Phoebe as a remnant planetesimal, or form Phoebe as a 2nd-generation planetesimal, prior to ejection due to dynamical disturbances caused by the star shedding mass or gravitational interactions with surviving or newly formed planets [11]. The plausibility of these scenarios would need to be quantified. Dating of Phoebe material could indicate whether it predates the solar system.

If Phoebe formed in the solar system, we find that its $^{12}\text{C}/^{13}\text{C}$ ratio can only result from accretion of carbon in a region of the protoplanetary disk where CO (the prime carrier molecule of C in the solar nebula) was abundant enough to be opaque (self-shielding) to far-UV wavelengths able to photolyze ^{12}CO , but still transparent to wavelengths able to photolyze rarer ^{13}CO . This model, applied to C^{16}O and $\text{C}^{17,18}\text{O}$, can explain the distribution of O isotopes in the solar system [12,13]. C differs from O by its propensity to be ionized and undergo fast C^+ exchange with unfractionated CO, which can erase the fractionation induced by CO photolysis depending on total carbon abundance and far-UV flux. Simulations tracking these reactions show that the fractionation can persist in some nebular regions but be erased in others, with $^{12}\text{C}/^{13}\text{C} \approx 15\text{--}130$ depending on the disk region and the C species [5].

C^+ -CO exchange can itself enrich CO in ^{13}C , a fractionation that could then be inherited by CO_2 formed from CO without invoking self-shielding. However, the enrichment, given by $^{12}\text{CO}/^{13}\text{CO} = ^{12}\text{C}^+/^{13}\text{C}^+ \exp(-$

35 K / T) [5 and refs. therein], requires $T < 22$ K to obtain a Phoebe-like ratio $^{12}\text{C}/^{13}\text{C}=19$ in CO from a bulk solar system ratio of 90 in C^+ . At 20-30 K, CO freezes out onto grains [14] and cannot undergo exchange.

Nebular location of Phoebe's ^{13}C enrichment: In the simulations of [5], the self-shielded region with $^{12}\text{C}/^{13}\text{C} \approx 15$ is within 10 AU of the Sun, a fraction of an AU thick, and 1-2 AU away from the midplane at 5-10 AU. It should approach the midplane as the gas dissipates. Phoebe could have been coated by ^{13}C -rich CO_2 ice and/or refractory C from this region following early capture by Saturn, then at 5-10 AU [15,16], due to Saturn migration [16], nebular drag [17], and/or a close encounter [18]. Capture could have placed Phoebe on an orbit with an inclination close to today's 152° . A capture orbit eccentricity of ≈ 0.9 has apoapsis in the ^{13}C -rich region at 1.5-3.5 AU distance along the 150° inclined orbital plane. Phoebe would have spent 80% of the time beyond 1 AU from Saturn for an orbit with the current 0.07 AU periapsis and 2 AU apoapsis.

Nebular drag would have partially circularized the orbit [17]. The drag deceleration exerted on Phoebe is $\frac{1}{2} C_D \pi R^2 N/N_A M_{\text{gas}} v^2 / m$, with $R=100$ km the radius of Phoebe, $m=8.3 \times 10^{18}$ kg its mass, v its orbital speed (between 0.1 and 2.6 km s^{-1} for the above capture orbit), N the number density of gas atoms or molecules, N_A Avogadro's number, $M_{\text{gas}}=2.4 \times 10^{-3}$ kg mol^{-1} the molar mass of the H-He gas composition [5], and $C_D=2$ for a high-Mach regime [19] since the sound speed is only tens of m s^{-1} in the <100 K gas along Phoebe's orbit. We adopt an initial gas density profile along the orbit that decreases exponentially between $N=10^{12.5}$ cm^{-3} at periapsis, corresponding to a midplane gas density at 5-10 AU [20] halved due to the gap opened by Saturn [21], and 10^3 -fold lower ($10^{9.5}$ cm^{-3}) at apoapsis [5]. The resulting drag decreases Phoebe's orbital speed by 2.5 mm s^{-1} after the first orbit. Most of the drag happens near periapsis where Phoebe's velocity and the gas density are maximum. This lowers the apoapsis while preserving the periapsis, which we assume remains constant. We assume that densities decrease exponentially with time, ten-fold (peak $10^{11.5}$ cm^{-3}) 2.67 Myr after capture and again (peak $10^{10.5}$ cm^{-3}) 0.87 Myr later, consistently with photoevaporation of the nebula under 600 times today's local interstellar far-UV flux [20]. The deceleration too is 10 and 100 times lower at these respective times if the apoapsis decreases at about the same pace as the disk scale height, which is verified a posteriori as the decay time to the current orbit is a few Myr (Fig. 2). The circularization stops once the gas is gone and Phoebe spends most of the nebular lifetime in the ^{13}C -rich region.

A formation in the first few Myr of the solar system agrees with the need for short-lived radionuclide

heating to aqueously alter Phoebe's silicates [3] and with planetesimal formation mechanisms involving gas [22]. The capture explanation for Phoebe's ^{13}C enrichment implies that other small irregular moons and Triton could be ^{13}C -rich too if captured early.

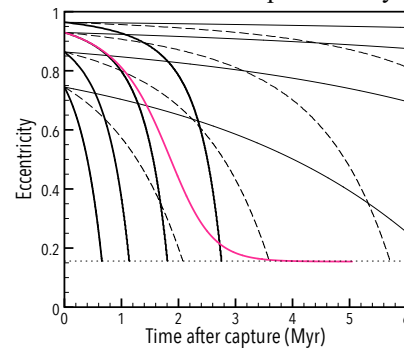


Figure 2. Post-capture decay of Phoebe's orbital eccentricity due to nebular drag. Initial apoapses are 4, 2, 1, and 0.5 AU; the periapsis is assumed to remain constant. Black curves: gas densities constant with time, decreasing exponentially in the Saturn gap from $10^{12.5}$ (thick curves), 10^{12} (dashed curves), and $10^{11.5}$ cm^{-3} (thin curves) to 10^3 times less at apoastron. Pink curve: if the density profile decreases exponentially with time (see text), Phoebe asymptotically reaches its current orbit (dotted line) as the nebula vanishes.

Phoebe could also have formed much farther out at the nebula's outer edge, sampling ^{13}C -rich material there before being tugged inward by the giant planets. This does not explain why no comet has a $^{12}\text{C}/^{13}\text{C}$ composition that comes close to Phoebe's (Fig. 1).

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