SATURN SATELLITE DENSITIES AND THE C/O CHEMISTRY OF THE SOLAR NEBULA.

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Introduction: The composition of material condensed in the outer solar system is very dependent on the state of carbon and oxygen in the solar or circumplanetary nebula, since oxygen is the dominant solid-forming element in a solar composition gas (in the form of silicates and water ice), and carbon is about half as abundant. Past discussions of solid material formed in these regions have focused on differences expected between material formed near giant planets where carbon is generally expected to be in the reduced, CH_4, form and material formed in the outer protoplanetary solar nebula where CO is believed to be the dominant form [1]. The composition and expected density of these materials are quite sensitive to the C and O solar abundances in all these models. We discuss here the effects of recently suggested modifications to solar abundances on the interpretation of the mean densities for satellites in the Saturn system.

Solar Abundances: We have calculated on a uniform basis the expected condensate density as function of carbon partitioning for both the historical and newly proposed solar abundances. For these calculations, the three components are: anhydrous rock (3360 kg m^{-3}), metallic sulfide/oxide phase (4800 km m^{-3}), and water ice (940 kg m^{-3}). The results are plotted in Figure 1.

Historical values. Most early discussions of the composition and density of nebula condensates were based on the solar abundances compiled by Cameron [2] in 1981. With Cameron's C and O abundance values, the expected uncompressed density of condensates ranges from ~ 1300 kg m^{-3} for CH_4 dominated reducing conditions to ~ 1900 kg m^{-3} for CO dominated chemistry. This agreed reasonably well with the range of then known outer planet satellite densities. A major revision to the solar values was proposed by Anders and Grevesse in 1989 [3] and a review of carbon chemistry by Simonelli *et al.* in the same year adopted similar values [4]. Resultant condensate densities for these values are less sensitive to the state of carbon in the nebula, with the highest density for CO rich conditions being ~ 1400 – 1600 kg m^{-3}.

New values. A major re-evaluation of solar photospheric C and O abundances has recently been proposed based on improved spectroscopic modeling and interpretation [5,6]. The oxygen abundance resulting from this analysis is about 50% lower than the previously accepted Anders and Grevesse value and, along with a change in carbon abundance, results in expected condensate densities significantly higher than previous models for both CH_4 and CO rich conditions. The range of density for variations in the carbon chemistry is also larger, from ~ 1500 to 2300 kg m^{-3}.

The new abundances, although based on improved solar photospheric modeling, raise other issues for solar composition and structure modeling, however, and may not represent a true primordial solar value. Lodders [7] has suggested that the primordial values for C and O are higher based on the effects of gravitational settling. This modification lowers the expected condensate densities somewhat but still produces values significantly above those for the older solar values.

Saturn Satellites: Saturn's satellite system consists of one large, planet-sized moon, Titan, a collection of small and medium sized objects usually referred to a the icy satellites, and a retinue of distant irregular, presumably captured objects of which Phoebe is the largest. The range in density among these objects suggests origins in regions of differing carbon chemistry.

Icy satellites. The mass-weighted average of the icy satellites is only 1300 kg m^{-3} [8]. Given the older solar values this material could be consistent with a CH_4 rich chemistry, but the newer values, even as revised by Lodders, are inconsistent with these satellites forming from a solar composition source. One possibility is that Saturn's local environment was oxygen and water rich compared with the proto-planetary nebula. Another is that a significant amount of the carbon might be incorporated as low density solid hydrocarbons, resulting in lower densities.

Phoebe. The Cassini flyby of this outer satellite in June of 2003 resulted in a mean density determination of 1630 ± 33 kg m^{-3} [9,10]. Consistent with the capture origin inferred from its irregular orbit, this high density suggests an origin in an environment different from the inner, regular satellites. For the new solar abundance, Phoebe's mean density is consistent with nebular chemistry from moderately reducing (CO ~ 0.25) to very CO rich values, depending on the (unknown) bulk porosity of this small satellite. If Phoebe is composed of material with the same uncompressed density as other objects formed in the outer parts of the solar nebula, i.e. Pluto and Triton, it would imply a moderate porosity and a CO-rich carbon chemistry.

Conclusions: Newly proposed values for the solar abundances of carbon and oxygen result in a significant increase in the expected density of condensates from a solar composition nebula, regardless of the state of carbon in the system. For the Saturn system, the regular, icy satellites are consistent with a solar abundance only if a significant amount of carbon is incorporated as low-density hydrocarbons. Phoebe's density suggests a very different environment and is consistent with an origin in a CO-rich proto-planetary nebula.

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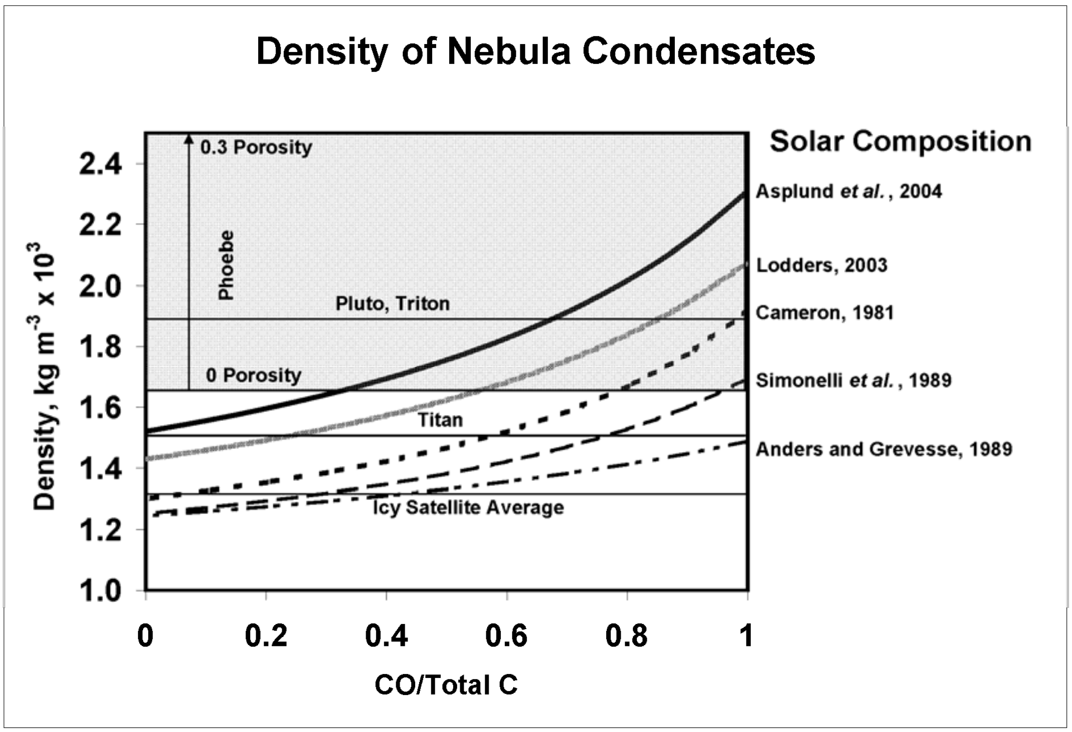

Figure 1: Density of Nebula Condensates. Model uncompressed densities of condensates from a solar composition nebula as a function of carbon partitioning in the gas phase between CO and CH_4. Models for different historical and recent sources of solar oxygen and carbon abundances are shown along with determinations of uncompressed density for Saturn icy satellites, Titan, Pluto/Triton, and Phoebe (for a range of plausible bulk porosity values).