WATER WITHIN CERES AND THE QUESTION OF BULK COMPOSITION: CONSTRAINTS AND IMPLICATIONS. M.J. Toplis¹, M. Monnereau², T.H. Prettyman³, J. Castillo-Rogez⁴, H.Y McSween⁵, C.A. Raymond⁶, M.C. DeSanctis⁷, E. Ammannito⁸, R.S. Park⁹, S. Marchi⁹, S. Fabre¹, O. Forni¹, C.T. Russell⁶, ¹Institut de Recherche en Astrophysique et Planetologie, 14 Avenue Edouard Belin, 31400 Toulouse, France; mtoplis@irap.omp.eu, ²Planetary Science Institute, Tucson, AZ 85719, USA, ³Jet Propulsion Laboratory, 4800 Oak Grove Drive, Pasadena, CA 91109, USA, ⁴University of Tennessee, Knoxville, TN 37996, USA, ⁵Istituto di Astrofisica e Planetologia Spaziali, Via Fosso del Cavaliere 100, 00133, Roma, ⁶UCLA, Earth, Planetary and Space Sciences, Los Angeles, CA 90095-1567, USA, ⁷Southwest Research Institute, Boulder, CO 80302, USA

Introduction

In January 1801, the Italian astronomer Piazzi discovered a body orbiting the Sun between Mars and Jupiter, that he called Ceres. While there was early hope that Ceres was the “missing” planet filling the gap in the Titius-Bode law, the subsequent years led to discovery of many more bodies orbiting the Sun in this region. Ceres remains the largest and heaviest of these bodies, constituting approximately one third of the total mass of the main asteroid belt. For this reason, Ceres is of particular interest, a unique window into the history of the early solar system and the premises of terrestrial planets-building.

Ceres acquired the status of dwarf planet in 2006 and has been the subject of considerable study over the years, most recently thanks to the instruments onboard the Dawn spacecraft. The Dawn mission has provided unprecedented insights into the morphology, surface mineralogy, geophysical properties and surface chemistry [1-6]. While there are several striking local features including the bright spots in Occator crater [7] and the pronounced positive topographic feature, Ahuna Mons [8], at a global scale the ceranian surface appears relatively uniform [2-4]. This surface shows no characteristic features of olivine or pyroxene in the 0.5 to 5 micron range accessible to the visible-infrared (VIR) spectrometer onboard, but rather a series of prominent features in the range 2 to 3.5 microns that indicate an altered surface containing Mg-rich serpentine, ammoniated clays and (Ca, Mg) carbonates, in addition to a spectrally neutral, dark component [2-3].

The question bulk composition

Given the low bulk density of Ceres relative to rocky bodies such as Vesta (2.16 g/cm³ for the former vs. 3.46 g/cm³ for the latter), evidence for the action of water (i.e. mineralogical alteration) does not come as surprise. However, the questions remain of how much water ice was accreted to Ceres and how that hydrogen is now distributed, both across the surface and as a function of depth.

The issue of hydrogen content leads to the broader question of Ceres’ bulk composition. While chondritic compositions, in particular carbonaceous chondrites, are commonly used as convenient proxies for primitive materials of the solar system, it should be appreciated that even in this case there is significant chemical variability from group to group. While the ratios of refractory elements are approximately constant across all chondrite groups, this is not the case for rock-forming cosmochemically volatile elements such as chlorine and potassium. In detail, the CI meteorites are significantly richer in these elements than all the other carbonaceous and ordinary chondrite groups [9].

For the most volatile elements such as H, C and N the situation is even more complex, as chondritic compositions may not be the most relevant analogues. In this case, depending on where a given body formed, different volatile species have the possibility of accreting as ices, lower temperature ices being stable further from the Sun. Such volatile-rich ices may interact with primitive metals and silicates on the parent body to be incorporated in secondary silicates and/or oxides, but a fraction may remain in volatile form and not be preserved upon delivery to Earth. For these reasons, the bulk H, C, and N contents of carbonaceous chondrites are a lower bound of initial content of these elements. Furthermore, the observed volatile concentrations are only relevant to the region where the carbonaceous chondrite parent bodies formed. Concentrations may have been higher and elemental ratios different for bodies that accreted in different regions of the solar system.

Overall, the question of Ceres’ bulk composition is a fundamental one. First of all, for the most volatile species, elemental ratios are a potential window into the formation region of the material that was accreted. For the more refractory elements distinguishing between a CI-like source or a CM-like source is critical because potassium, a key cosmochemically volatile element, is also a potential heat-source. In this contribution we explore a range of possible bulk compositions, assessing which are capable of producing compositional and mineralogical signatures similar to those observed by the Dawn spacecraft.

Hydrogen and its distribution

Before treating the question of lithophile elements, we begin by considering the question of hydrogen and its distribution. Given the bulk density of
Ceres that is now known with precision [1], it is possible to estimate the amount of water ice that Ceres contains [10]. Performing such a calculation assuming a mixture of dry silicates (of density in the range 3.5 to 3.8 g/cm³ corresponding to that measured for anhydrous carbonaceous chondrite and H-chondrite respectively [11]), results in a calculated bulk ice content of 22.5±1 wt%. This value provides an indication of the amount of water ice that was present at the time of accretion. Alternatively, a similar calculation may be made assuming a mixture of water ice and an altered silicate. Using the measured grain density of CI as a proxy for the latter [2.46 g/cm³; 11], 8 wt% water ice is calculated in this case. This value provides an idea of the current bulk water-ice content of Ceres. Given the measured weight equivalent hydrogen (WEH) content measured by the GRaND spectrometer onboard Dawn in the ice-free equatorial region (17 wt% [4]) and the similarity of the latter to that measured in CI chondrite [12], the present day bulk water content of Ceres can be calculated. This calculation provides a value of ~23.5 wt% H₂O, remarkably close to that calculated for a mixture of ice and anhydrous silicates. This good first order consistency is reassuring and indicates that the overall volume change during alteration may be limited.

Assuming a current value of 8 wt% bulk water ice, the question then becomes where that ice resides. In this respect, gravity data of the Dawn mission indicate a central mass concentration at Ceres, with an outer layer of less than average density [5]. Based upon detailed analysis of the geophysical data and simple geochemical arguments, the average density of the outer layer of Ceres can be constrained to be in the range 1.4 to 1.8 g/cm³. For densities in that range, an average water-ice content can be calculated assuming a mixture of CI-like material (of density 2.46 g/cm³) and water ice (Fig. 1). Alternatively, the gravity data of [3] can be used to estimate the shell thickness for a given value of shell density. Making the extreme assumption that all the available bulk water ice is partitioned into this outer shell, a second value of ice content can be estimated. A third constraint relevant to this question is the ice-content at the poles measured by GRaND, roughly 10 wt% [4].

When taken together it is found that the two calculated estimates of water-ice content are never in mutual agreement (Fig. 1). In this respect we note that partial dehydration of the central region could provide more water to the outer layer, but in this case, the higher density of the shell becomes incompatible with geophysical data. An ice-bearing lower layer decreases the water available for the outer shell, accentuating the difference between the two curves. In light of this discrepancy, it is possible that “free” hydrogen (i.e. that not bound in silicate, carbonate or oxide materials) is in some form other than water ice. Furthermore, in both cases, the calculated values of ice content are greater than those measured by GRaND in the upper meter of Ceres’ regolith at the poles. This observation is difficult to interpret as it may be the result of vertical variations of H-content within the upper 50 km or so.

Figure 1. Estimates of the mass fraction of water ice in the present-day external shell of Ceres calculated using simple mass balance and geophysical constraints on the shell-size (see text for details). The green box is the value measured by the GRaND spectrometer onboard Dawn.

Lithophile elements and thermal modelling

The form and distribution of hydrogen is intimately related to the internal evolution of Ceres since its formation 4.5 billion years ago. To better understand this evolution we are engaged in numerical modelling of Ceres’ evolution, building upon earlier work on this subject [13]. The codes being used are those developed for understanding Vesta [14]. They involve modelling of thermal, physical and chemical aspects of the problem, including explicit consideration of the transport of heat producing elements such as K during chemical alteration and the kinetics of that alteration. More details will be presented at the meeting.