ON THE RELATIONSHIP BETWEEN CHONDRITES, COMETS AND ASTEROIDS, A PETROLOGIC PERSPECTIVE. M. K. Weisberg and H. C. Connolly Jr. Kingsborough Community College, Dept. Physical Sciences, Brooklyn NY 11235 and American Museum of Natural History, Dept. Earth Planet. Sci., NY, NY 10024 (mkweisberg@kbcc.cuny.edu).

Introduction: Asteroids and comets are primitive objects thought to be analogues of the materials that accreted to form the larger bodies in the Solar System. Therefore understanding the relationship between these minor planetary bodies is of great importance for understanding the evolution of the Solar System. The relationship between asteroids and comets has been explored by numerous authors from spectroscopic, dynamical and petrologic perspectives. Samples recently returned by the Stardust mission to Comet 81P/Wild 2 provide us with the first ground truth data for a Kuiper Belt Object and allow us to explore this relationship further. Most striking are the similarities in the silicate and metallic phases in the Stardust samples [1], IDPs [2] (thought to be derived from comets [3]) and chondrites (thought to come from C and S type asteroids [e.g., 4]). Here we review the arguments for a close relationship between Kuiper Belt Objects (KBOs), asteroids and meteorites, with emphasis on petrology, and the implications of this relationship. Our hypothesis is that some carbonaceous (C) chondrites are related to cometary parent bodies.

Spectroscopy: Based on reflectance spectroscopy, ordinary chondrites have been matched with (and predicted to be derived from) spectral type S asteroids [e.g., 4]. However, links between C chondrites and asteroids has been more controversial and less compelling [e.g., 5]. Spectral data suggest that the major part of the non-volatile components of comets is silicate, and the silicate appears to be a mixture of enstatite and forsterite and glass or amorphous material, similar to some IDPs [6] as well as many C chondrites. This conclusion is supported by direct measurement of dust from the coma of Halley's comet by mass spectrometry onboard the USSR Vega-1 mission [7], spectral analysis of "Deep Impact" ejecta from the nucleus of comet 9/P Temple 1 [8], and laboratory studies of comet Wild 2 samples returned to earth by Stardust [1], all of which show the presence of ferromagnesian silicates dominated by Mg-rich varieties. There is no evidence of aqueously altered phases present in the Halley's comet and Wild 2 data. However, some observations from Deep Impact of Temple 1 have been interpreted to be phyllosilicate and carbonate [8].

Dynamical Models: Dynamical studies suggest that many Near Earth Asteroids originated as comets [e.g., 9, 10, 11]. Asteroids that have been linked to C chondrites, such as spectral type C and D have orbital characteristics of comets and have been interpreted to be transitional between comets and asteroids [e.g., 9]. For example asteroid 3200 Phaethon is considered transitional between comet and asteroid. Wetherill [11] suggested that more than half of the Earth-crossing asteroids are extinct comets.

Petrology: Lodders and Osborne [12] gave an intriguing review of the petrologic and chemical characteristics of CI and CM chondrites that support their origin as cometary materials. Here we focus on and summarize data from samples of comet Wild 2 returned by the Stardust mission and compare it to C chondrites. The data we discuss have been previously reported [1]. Stardust samples have been shown to have a preponderance of high temperature and reduced mineral assemblages similar to those interpreted to form through thermal processing in the inner Solar System. Such materials are characteristic of chondrites generally considered to be asteroidal materials from ~2.3 to 3.4 AU. Particles from Wild 2 show mineral assemblages typical of chondrites, with olivine, pyroxene, FeNi-metal and sulfide as common components. Olivine and low-Ca pyroxene have a range of mg# ($Fa_{0.5-41}$ and Fs_{0-48}, respectively), which indicates that the material is unequilibrated, similar to types 2 and 3 chondrites. Some forsterite with <1 wt% FeO has up to 6.4 wt% MnO and 1.4 wt% Cr_2O_3. Other silicates observed are diopside and melilite, typical of some CAIs in carbonaceous chondrites. Additionally, FeNi-metal and sulfides including pentlandite [$(FeNi)_9S_8$)] and Fe-Ni-Cu and Fe-Zn sulfide, phases observed in carbonaceous and enstatite chondrites, are present in some particles. V-bearing osbornite (TiN), a phase also observed in some carbonaceous and enstatite chondrites, has been found in some Stardust samples. It is found in abundance in the CAI-like Stardust particle "Inti" [13].

Discussion: The range of olivine and pyroxene compositions, occurrence of Mn-, Cr-rich olivine, metal and pentlandite in materials from Comet Wild 2 are features consistent with CR and CM chondrites, though other C chondrites cannot be completely ruled out. It has been known for some time that IDPs thought to originate from Oort cloud and Kuiper belt objects [e.g., 3], have petrologic characteristics similar to C chondrites. IDPs show a wide range of olivine compositions [2] similar to that in chondrites and the Stardust samples. Low-iron, Mn-rich forsterite (LIME) is of particular interest. It is interpreted to be a primitive nebular condensate known to occur in IDPs, O and C chondrite matrix, and in amoeboid olivine aggregates in CR chondrites [14, 15] and is found to occur in the Stardust samples [1]. Osbornite grains and osbornite-bearing calcium, aluminum-rich inclusions (CAIs) have been identified in the ALH 85085 CH chondrite [16] and the Isheyevo CH/CB chondrite [17]. However, it should be noted that the osbornite in these chondrites is not known to contain V, like that in the Stardust samples. The lack of V in CH osbornite could be a reflection of differing oxidation state and/or an indication of different source regions for these materials. Thus, the Stardust samples analyzed so far appear to have mineral assemblages similar to some C chondrites particularly CR and CH chondrites (members of the CR clan) and IDPs, with some exceptions. This suggests a possible relationship between the Wild 2 samples, IDPs and the CR clan chondrites. Since IDPs are thought to originate from Oort cloud and kuiper belt objects [3], IDPs are expected to be similar to the cometary materials returned by Stardust.

There are some important differences between samples from comet Wild 2 and chondrites and IDPs. No phyllosilicates or carbonates have yet been found in the Wild 2 samples, whereas they are common in many C chondrites and IDPs. Spectral data from some comets also show the presence of high temperature Mg-rich silicates and amorphous material but no evidence of secondary alteration or hydrated minerals. If this characteristic holds up after further study of Wild 2 samples, it would imply that secondary alteration on comet Wild 2 was not similar to that on C chondrite and IDP parent bodies. The lack of alteration products could be due to evolution of the cometary materials on smaller size parent bodies. However, it should be noted that the Deep Impact data for comet Tempel 1 suggest some phyllosilicate and carbonate may be present. GEMS are present in some IDPs but have not been found in comet Wild 2 and finally no chondrules have yet been found in the comet samples or IDPs, but they are present in chondrites. If chondrules were present the sampling methods for both the Wild 2 samples and IDPs could have resulted in their disaggregation.

More petrologic as well as oxygen isotopic studies of Wild 2 samples and IDPs are needed to further test the relationship between comets IDPs and chondrites. We predict that further study of the Wild 2 samples will continue to support a relationship to C chondrites, specifically members of the CR chondrite clan. Additionally, direct sampling of more comets and asteroids is greatly needed. Our sampling of comets is extremely limited and sparingly little is know about the range of cometary materials and, for example, how it compares to the range of chondrites and asteroids. Sample return from asteroids is also needed to better examine the link between meteorites and asteroids and decipher the evolution of asteroids with respect to comets.

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