IDENTIFICATION OF REFRACTORY-RICH ASTEROIDS: EVIDENCE FOR THE EARLIEST ACCRETED BODIES IN THE SOLAR SYSTEM.

J. M. Sunshine[1] (jess@astro.umd.edu), H. C. Connolly, Jr.[2, 3], T. J. McCoy[4], S. J. Bus[5], and L. La Croix[4] [1]Dept. of Astronomy, Univ. of Maryland, College Park, MD, 20742; [2]Dept. of Physical Sciences, Kingsborough College of the City University of New York, Brooklyn, NY, 11235; [3]Lunar and Planetary Institute, Univ. of Arizona, Tucson, AZ 85721; [4]Dept. of Mineral Sciences, Smithsonian Institution, Washington, DC, 20560, USA; [5]Institute for Astronomy, Univ. of Hawaii, Hilo, HI, 96720.

Introduction: Refractory inclusions in chondritic meteorites are the oldest rocks in our collections and define the start of the Solar System [1, 2]. These objects also contain minerals that are the first phases predicted to condense from a gas of solar, or enhanced solar, composition and their formation period is argued to have lasted for <1Ma [3]. Refractory inclusions occur in all classes of chondrites with concentrations up to 13% in the CV3 chondrites [4]. The CV3 meteorites are the only chondrites to contain the cm-sized igneous type B Calcium-Aluminum-Rich Inclusions (CAI's) [4] that are the focus of many detailed investigations. Essentially all other refractory inclusions (excluding type B and the related type C) are found within all classes of chondrites. Thus, unlike type B and C inclusions, all other refractory inclusions were widely distributed within the asteroid accretion zone.

Minerals that comprise refractory inclusions were first suggested to exist on asteroid surfaces based on general spectral similarities between two anomalous asteroids, 387 Aquitania and 980 Anacostia, and an inclusion of unknown petrography from the Allende CV3 chondrite, all of which are dominated by absorptions due to FeO in spinel [5]. Refractory minerals similar to those found in refractory inclusions have also been identified in a Stardust sample from comet 81P/Wild 2, suggesting that these materials were widely distributed throughout the Solar System [6].

In this study, we validate the identification of spinel absorptions in Aquitania and present new evidence of additional spinel-rich asteroid surfaces in the Henan family and on the asteroid 234 Barbara. Based on these discoveries, spinel-bearing asteroids can no longer be thought of as rare. If, as discussed below, the spinel in asteroids can confidently be linked to refractory materials, then these asteroids must be among the oldest accreted bodies in the Solar System.

Allende CAI's Spectra: In order to explore the compositional link between these asteroids and refractory materials, we initiated a program to collect representative spectra from fully petrographically characterized and controlled CAI's within Allende. A sample (USNM 3509) was sectioned into large slices and refractory inclusions were identified and cored. Thin and thick sections were made from half the objects with reference materials preserved. While avoiding contamination from the matrix, material from the other half of the objects were cored out, ground into powders, and sent to Brown University for spectral measurements at the Keck-NASA Reflectance Experiment Laboratory (RELAB) facility.

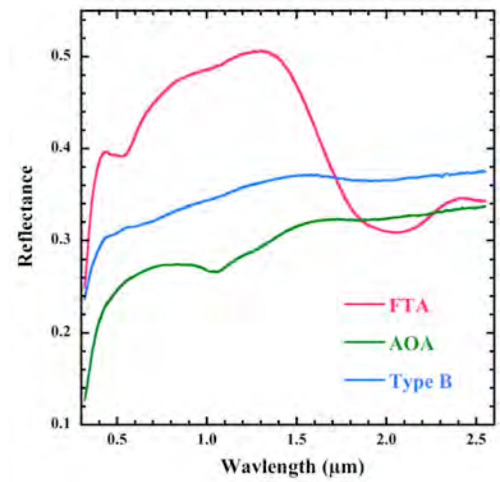

***Fig. 1**: Spectra of CAI's from Allende*

To date, our sample base for spectra includes three type B's, three fluffy type A's (FTA) and one amoeboid olivine aggregate (AOA). Major minerals in FTA's are melitite, and spinel, while type B's also include fassaite and anorthite. Both types have minor amounts of perovskite, hibonite, and metal phases. Of these, only spinel has NIR absorptions, but only if it includes FeO, which occurs via alteration. In general FTA's exhibit varying but greater degrees of alteration, and thus have larger amounts of FeO and stronger spinel absorptions, than type B's (see **Fig. 1**). AOA's include olivine, anorthite and calcic pyroxene. Minor alteration leads to FeO in the olivine and a weak 1 μm feature as seen in the AOA spectrum and perhaps some spinel-rich asteroids (*e.g.*, Aquitania, see **Fig. 2**).

Asteroid Spectra: Currently available telescopic instruments have substantially greater signal-to-noise and spectral resolution than the 52-color data used to initially identify spinel in Aquitania and Anacostia [5]. In this study, spectra combining visible (VIS) observations from the SMASS surveys [7, 8] and near-infrared (NIR) data from SpeX [9] are used to verify the initial identifications from the 52-color data and locate additional spinel-rich asteroids.

In the VIS-NIR, spinel spectra are dominated by absorption in the 2 μm region. This is in contrast to other common Fe-bearing silicates that have strong absorptions in the NIR [10]. Although pyroxene spectra have absorptions in the 2 μm region, they have even stronger features near 1 μm. On the other hand, olivine spectra lack 2 μm absorptions and are instead characterized by a complex feature at 1 μm. It is on this basis, a strong 2 μm absorption in the absence of a stronger 1 μm feature, that led to the spectral identification of spinel [5]. With the current generation of asteroid spectra we can more confidentially evaluate the identification of spinel and infer the composition of spinel, which is known to vary between spinel ($MgAl_2O_4$) and chromite ($FeCr_2O_4$), and as a function of FeO content [11, 12].

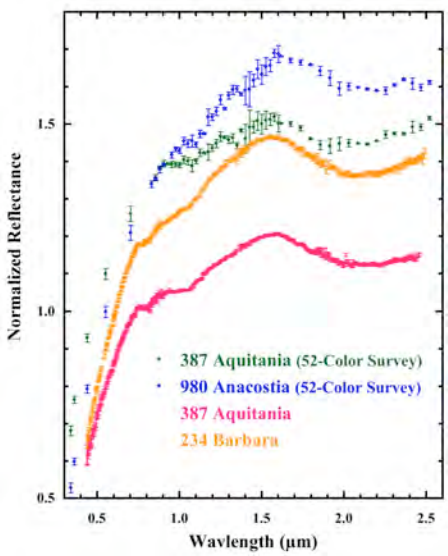

Fig. 2. *52-Color [5] and SpeX asteroid spectra, which are all dominated by spinel absorptions at 2 μm*

SpeX data of Aquitania are clearly dominated by a strong absorption feature near 2 μm and confirm the previous 52-color data (**Fig. 2**). Although Anacostia has not yet been measured with SpeX, comparisons to Anacostia imply that it is also spinel-rich. Based on their unique compositions and general location, these two asteroids (85 and 100 km diameters) were initially proposed to be genetically related [5]. Visible spectra suggest a larger number of similar (L-type) asteroids and on this basis, the Watsonia family at 2.7 AU was proposed [8]. SpeX data of other members of the Watsonia family include spinel absorptions, which support the hypothesis of a break-up of a larger body.

Visible data suggest a second L-type family, the Henan family [8], which was originally proposed on dynamical grounds [13]. NIR SpeX data contain absorptions that, while not as strong as those of Anacostia or Aquitania, are due to spinel. These data of ~10 Henan members suggest that a second spinel-rich asteroids also exists near 2.7 AU. Finally, among our current collection of SpeX data, we have identified a third spinel-rich body, 234 Barbara, a 45 km asteroid located at 2.4 AU. The spectrum of Barbara is dominated by spinel absorptions and is very similar to Anacostia and Aquitania (see **Fig. 2**).

Comparisons with previous research on spectra of terrestrial spinel-group minerals [12, 13] show that the absorptions in the asteroid spectra are due to FeO in spinel rather than chromite. The distinct spinel absorptions in spectra of these asteroids does not require that they be physically dominated by spinel, but rather that spinel be the only mineral with significant absorptions in the NIR. The only known meteoritic materials with significant fractions of spinel are CAI's.

Implications: The presence of FeO in refractory minerals is a critical link between CAI's and spinel-rich asteroids and requires an alteration event. Alteration may have occurred in the nebula. Alternatively, co-accretion of some FeO-rich matrix is needed, which was then exposed to alteration and mobilization of FeO in the parent body. As we continue our efforts to understand the effects of alteration in CAI's types, it may be possible to determine if the asteroids contain type A or B materials. If they are type A, which is widespread in chondrites, then the asteroids are typical of refractory materials throughout the early Solar System. If instead they are type B, which are unique to CV3's, these asteroids represent localized events, but at several places throughout the inner belt, as we have observed these asteroids both at 2.7 and 2.4 AU.

In either case, our results show that spinel-bearing asteroids can no longer be thought of as rare. If accretion began at very early times when refractory materials still dominated, asteroids in which refractory minerals are a significant component should exist. Based on similarities to refractory materials in CAI's, these oldest accreted bodies are likely spinel-rich asteroids.

References: [1] Allegre, C. J. et al. (1995) *Geo. Cosmo. Acta*. [2] Amelin, Y. et al. (2002) *Science*. [3] Beckett et al. (2006) *Meteor. Early Sol. Sys., II*. [4] MacPherson et al. (1988) *Meteor. Early Sol. Sys.*. [5] Burbine, T. H. (1992) *Meteor*. [6] Zolensky et al. (2006) *Science*. [7] Xu. S et al. (1995) *Icarus*. [8] Bus, S. J. (1999) *Ph.D. Thesis, MIT*. [9] Rayner (2004) *SPIE*. [10] Adams, J. F. (1975) *IR. Raman Spec. Lun. Ter. Mats.* [11] Cloutis, E. A. et al. (2004) *MAPS*. [12] Sunshine, J. M. and Cloutis, E. A. (1999) *LPSC*, #1640, 1999. [13] Zappala, V. et al. (1995) *Icarus*.

Acknowledgements: This research funded in part by NASA Grant NNX06AH69G (JMS), NNG05GF39G (HCC), and NSF Grant AST-0307688 (SJB). Thanks to T. Hiroi for carefully collecting our spectra of CAI's.