THERMAL PROCESSING OF COSMIC DUST: ATMOSPHERIC HEATING AND PARENT BODY METAMORPHISM. Lindsay P. Keller¹, Kathie L. Thomas² and David S. McKay¹ ¹SN14, NASA Johnson Space Center, Houston, TX and ²Lockheed, 2400 NASA Rd. 1, Houston, TX 77058.

Introduction. A major problem in cosmic dust research is differentiating mineralogical and chemical changes that result from deceleration heating in the Earth's atmosphere from those that occur in response to thermal processes on asteroidal parent bodies. Documented changes include melting, the formation of magnetite rims and magnetite precipitates [1, 2], and the loss of volatile elements [e.g. 3]. Theoretical models further suggest that "low-velocity" particles in the 10-20 um range that enter the atmosphere suffer essentially no heating effects [4, 5].

Methods. We studied micotomed thin sections of IDPs in a JEOL 2000FX transmission electron microscope (TEM) using high resolution imaging, electron diffraction, dark-field imaging and energy-dispersive x-ray analysis. We studied 6 IDPs including L2005Y5, U2015C4, L2005Q8, U2015C16, U2015C24, W7029B12. The mineralogy and mineral compositions of the last three IDPs were reported previously [6].

Results. L2005Y5 shows the strongest heating effects of the particles analyzed. The particle is a Fe-rich sphere that consists of μm-sized magnetite plates surrounding a core of fine grained olivine and magnetite. Two compositional groups of olivines coexist in Y5, magnesia olivine grains (Fo90) occur adjacent to more Fe-rich olivines (Fo60). The magnetites are pure Fe oxide and display a lamellar microstructure in TEM images and show streaking along (1 11) in electron diffraction patterns. Solar flare tracks were not observed in any of the olivine grains.

U2015C4 is a strongly heated IDP that has a well-developed rim of fine-grained polygonal magnetite grains surrounding a poorly crystalline core of Fe-rich silicate material. Selected-area electron diffraction patterns of the core material show only diffraction rings that correspond to a spinel-structure (probably magnetite). HRTEM images of the core material show that it consists of small crystalline domains (5 to 10 nm in dia.) that are surrounded by amorphous material. Lattice fringes in the crystalline domains are consistent with magnetite. We interpret the core region as oriented grains of magnetite in an amorphous Mg-silicate matrix. Because of the complex microstructure of the core material, solar flare tracks were not observed. Rare, fine-grained (≤50 nm) Ni-rich sulfides occur near the center of the particle. The magnetite rim consists entirely of well-crystalline grains that are commonly twinned on {111} i.e., spinel-law twinning. The grain size of the magnetites in the rim decreases from relatively coarse-grains on the outside (50 to 70 nm in dia.) grading into the fine-grained magnetite of the core. HRTEM images of some of the magnetites on the outside surface of the particle show larger periodicities along (111) than expected for magnetite. These larger periodicities are consistent with maghemite (γ-Fe₂O₃), although we have no means of determining the valence of Fe in the TEM.

L2005Q8 is a chondritic porous aggregate whose mineralogy is dominated by Fe-bearing olivine (Fo 67). One of the olivine grains is mantled by a poorly-developed magnetite rim. The textures clearly indicate that the magnetite is forming at the expense of olivine. Magnetite platelets form topotactic intergrowths within and on the olivine such that [111]Mt and [110]Mt are parallel to the [010]Ol and [100]Ol respectively. The most distinguishing features of the olivine grains in L2005Q8 are a mottled contrast in dark-field images and a distinctive streaking along c* in SAED patterns. HRTEM images show that the streaking along c* results from the presence of thin lamellae of laihunite (ideally Fe²⁺[2-3x]Fe³⁺[2x]SiO₄, with x = 0.24 or 0.37) that are coherently intergrown with olivine. The degree of laihunite development is gradational; the cores of grains are usually free of lamellae, and the highest density occurs at the rim of the grains. The laihunite-olivine intergrowths are disordered as no distinct satellite reflections occur in the SAED patterns, although some HRTEM images show an ~1.8 nm periodicity along the c-axis suggestive of the 3M polytype of laihunite. No tracks were found in Q8 olivines.
W7029B12, U2015C24, and U2015C16 have been described previously by Klock et al [6] who assigned them to types I, II, and III respectively based on the degree of equilibration of olivine and pyroxene compositions and the presence or absence of solar flare tracks (type I are unequilibrated with tracks, while type III are equilibrated and tracks are absent, type II particles are intermediate). We studied microtomed thin sections of each of these particles looking specifically for magnetite rims and defects in the Fe-rich olivines in order to determine if these particles had been heated during atmospheric entry. No magnetite rims were visible on any of the particles and the olivines were free of lamellar features (e.g. laihunite).

**Discussion and Conclusions.** L2005Y5, U2015C4, and L2005Q8 demonstrate the variety of mineralogical changes that are apparent in IDPs that have been heated during atmospheric entry. Magnetite rims are the most distinctive feature of heated IDPs. Well-developed magnetite rims such as those on Y5 and C4 are thick (> 50 nm) and continuous, while poorly-developed rims (like that on Q8) are discontinuous and are relatively thin. In addition to mineralogical changes, volatile elements are lost during heating, especially Zn [3]. Synchrotron X-ray fluorescence analyses of L2005Y5 and L2005Q8 indicate that both of these particles are strongly depleted in Zn [7].

The alteration of olivine to laihunite that occurs in Q8 is another mineralogical transformation that results from atmospheric heating. Laihunite is a common alteration product of terrestrial Fe-bearing olivines that have undergone subsolidus oxidation at moderate temperatures (400 to 800°C) [8]. The microstructures of the olivine-laihunite-magnetite intergrowths in L2005Q8 strongly resemble those from terrestrial rocks and so we believe that the process of laihunite formation was the same for both (i.e. oxidation of olivine at high temperatures), but the time scales were dramatically different as indicated by the partial laihunitization of Q8 olivines.

The lack of equilibration between adjacent magnesian and Fe-rich olivines in the partly melted IDP L2005Y5, and the absence of heating effects in the type I, II, and III particles of [6] indicate that atmospheric heating is too short in duration to allow for significant Fe/Mg diffusion in the anhydrous silicates. Thus we concur with [7] that the equilibration of olivine and pyroxene compositions in types I-III particles results from parent body processes, not atmospheric heating.