AN ELECTRO-OPTICAL SURVEY OF METEOROID BULK DENSITY: EVIDENCE FOR WIDESPREAD RADIAL MIXING IN THE EARLY SOLAR NEBULA. P. Brown[1,2] , J-B. Kikwaya[3] and M. D. Campbell-Brown[1,2], [1]Dept of Physics and Astronomy, University of Western Ontario, London, Ontario, Canada N6A 3K7, pbrown@uwo.ca. [2]Centre for Planetary Science and Exploration, University of Western Ontario, London, Ontario, Canada, N6A 5B7. [3]Vatican Observatory, V-00120 Vatican, City State

Introduction: One of the major results of the Stardust sample return mission to 81P/Wild 2 was the unequilibirated chondrite-like composition of some analysed grains [1,2]. This has led to recognition that refractory materials may be more common than previously thought in Jupiter-family comets (JFCs). Moreover, as JFCs are believed to have formed in the outer solar system [3], the presence of significant refractory material / high temperature minerals and chondrule-like objects [4] with a possible inner solar system origin has strengthened the notion that large scale radial mixing was an efficient process in the early solar system [5]. However, confirmation of significant refractory material in JFCs has so far been limited to one comet (81P/Wild 2). Here we report on a survey of mm-sized meteoroids with known orbits whose bulk densities were simultaneously measured. Our goal is to establish the broad physical characteristics of small body populations, linking meteoroids with these small body populations via measured orbits. Our approach is to use measured bulk meteoroid density as a proxy for the physical nature of the parent population. In particular, we have isolated and examined a number of well observed meteors produced from JFCs and simultaneously measured their density.

Observations: We have performed high resolution, multi-station, electro-optical video measurements of 92 meteors with complete lightcurves during the period 2006-2009. Three different intensified video cameras were used having image sizes ranging from 640x480 pixels to 1360x1036, with pixel scales from 0.01º per pixel to 0.05º per pixel, and stellar limiting magnitudes ranging from +7.5 to +9. The standard deviation of the trajectory solution residuals perpendicular to the path for three station measurements were typically of order 15-20m, with image cadences from 10 - 30 Hz. Our sampled meteoroid population has a representative mass of ~10^{-6} kg. Of particular importance to our modelling effort is that over 3/4 of our sampled events show clear evidence for deceleration, providing strong constraints on model fits not previously available in earlier faint meteor surveys [6].

Model: We make use of the dustball model of meteoroid structure as numerically implemented in [7] to simultaneously fit the astrometric and photometric data per meteor. This model explicitly allows for fragmentation and treats each meteoroid as a collection of fundamental grains rather than as a single monolithic body. The model has 7 free parameters (grain mass/number of grains, thermal conductivity and specific heat of the bulk meteoroid, average molar mass of meteoroid atoms, heat of ablation plus boiling point of individual meteoroid grains and the temperature at which grains are released into the airstream). The final free parameter, bulk density, is the focus of our study. Several other required input values (eg. atmospheric mass density, emissivity of the meteoroid etc.) are fixed to literature values as described in [8].

Our modelling approach is to find groups of plausi ble solutions with a range of possible densities using the reduced Chi-squared fit between the entry model

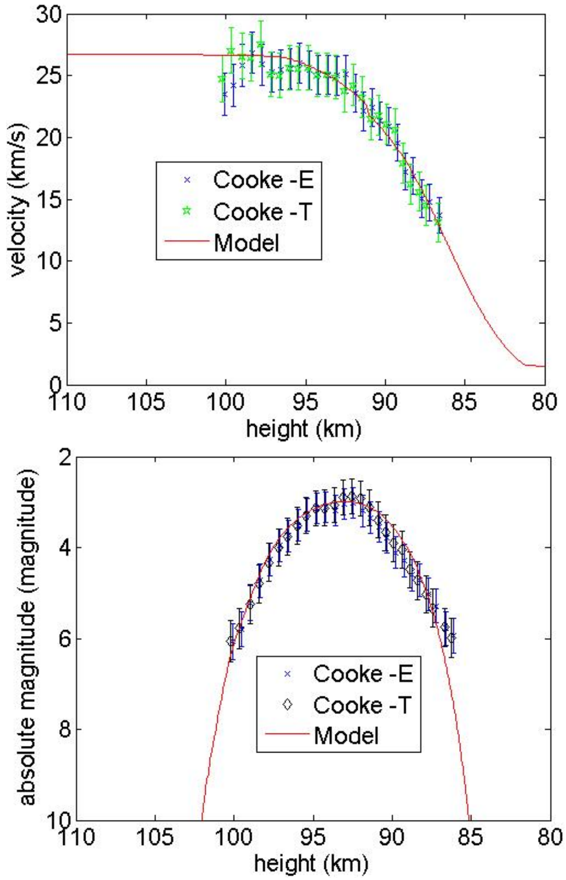

Figure 1. An example meteor observation detected from the Elginfield (E) and Tavistock (T) stations using a pco.1600 Cooke camera showing the apparent velocity (top) and the observed R magnitude lightcurve (bottom) together with the best model fit (red line).

and the kinematic and photometric measurements as a figure of merit. This typically resulted in ~100 acceptable solutions produced from $>10^5$ initial model runs per event. Our final bulk density fits per event are not single values but rather ranges.

Results and Discussion: Our bulk density distribution shows three peaks: one near 1000 kgm^{-3}, another near 3000 kgm^{-3} and a final high density peak near 5000 kgm^{-3} (Fig 1). We find a clear correlation between orbital class and bulk density (Fig. 2). Based on the Tisserand parameter (T_j) our raw sampled meteoroid population is 26% of asteroidal origin, 14% from Jupiter-family comets (JFC) with the remaining 60% from Halley-type comets (HTC) or nearly-isotropic comets (NIC) **.**

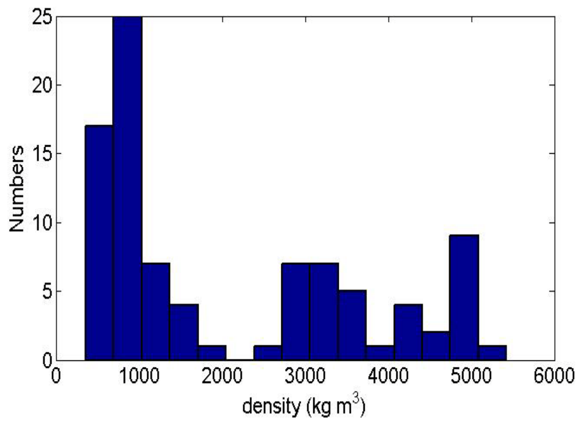

Figure 1. The bulk density distribution of our meteoroid sample using the average of the density range found from the model fit to each of the 92 meteors.

The HTC/NIC population is found to be uniformly of low apparent bulk density (<1500 kgm^{-3}), much as expected for typical unprocessed cometary material [9]. Our asteroidal population has a bimodal density distribution with some chondritic-type densities (~3500 kgm^{-3}) as well as a higher density peak extending to bulk densities >5000 kgm^{-3}. Such high densities are most probably indicative of iron-rich compositions. That mm-sized meteoroids of nearly pure iron may be common (~10% of all meteoroids) has been previously suggested based on a survey of meteor spectra [10] and separate results based on two station faint meteor height measurements [11]. Our results are consistent with these earlier measurements.

For meteoroids with $2<T_j<3$ which are in JFC-type orbits, the density distribution is remarkably distinct from that of the HTC/NIC population. Here densities are more typically chondritic, with a class average density of 3200 ± 500 kgm^{-3}. Such high bulk density is unexpected for mm-sized meteoroids associated with JFCs. As these JFC-type meteoroids are from a variety of radiants spread throughout the year, and hence unlikely to be from a single parent JFC, it suggests high density (and hence potentially high-temperature) mineral assemblages may be common among the JFCs as a population.

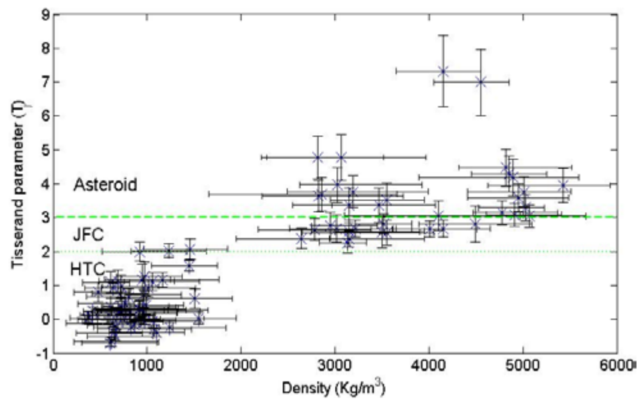

Figure 2. The bulk density for each meteoroid in our survey and its T_j. The uncertainty values in density reflect the range of possible densities based on our modeling while the error in T_j reflects uncertainty in the mesured meteoroid orbit prior to Earth encounter.

Conclusions: Based on precise metric and photometric observations of 92 meteors, we have estimated bulk densities of meteoroids and linked each to a probable parent population based on their pre-atmospheric orbit. We find distinct differences in the bulk density of meteoroids among parent body classes. The average density of meteoroids likely to be of asteroidal origin is between 3000 - 5000 kgm^{-3}, while most of our meteoroids (60%) are from HTC/NIC parents and have a bulk density in the range of $400 < \rho < 1600$ kgm^{-3}.

Our JFC meteoroids show chondritic-like bulk densities, suggesting either evolutionary processes have sintered the original meteoroids raising their bulk density and/or that high density minerals compose a significant fraction of the mass of JFC dust at mm-sizes.

References: [1] Ishii et al. (2008) *Science*, 314, 447–450. [2] Sandford, S.A. (2011) *Proc. IAU Symp. 280,* 275-287. [3] Duncan, M. (2008) *Sp. Sci. Rev.* ,138, 109-126. [4] Nakamura, T. (2008) *Science*, 321, 1664-1667. [5] Ciesla, F.J. (2007) *Science*, 318, 447–450. [6] Sarma, T. and Jones, J. (1985) *Bull. Astr. Inst. Czech.*, 36, 9-24. [7] Campbell-Brown, M.D and Koschny, D. (2004) *A&A*, 422, 751-758. [8] Kikwaya, J.-B., Campbell-Brown, M.D. and Brown, P. (2011) *A&A*, 530, A113. [9] Ceplecha, Z. (1988) *Bull. Astr. Inst. Czech.*, 39, 221-236. [10] Borovička, J. et al (2005) *Icarus*, 174, 15-30. [11] Kaiser, N. Brown, P. and Hawkes, R.L. (2004), *EMP*, 95 579-586