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I am submitting herewith a thesis written by Karla Elizabeth Kuebler entitled "A test of nebular sorting mechanisms: Are chondrules and metal-troilite grains in ordinary chondrites mass equivalent?" I have examined the final copy of this thesis for form and content and recommend that it be accepted in partial fulfillment of the requirements fro the degree of Master of Science, with a major in Geology.

Dr. Harry Y. McSween, Major Professor

We have read this thesis and

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Accepted for the Council:

Associate Vice Chancellor and

Dean of The Graduate School

A TEST OF NEBULAR SORTING MECHANISMS: ARE CHONDRULES AND METAL-TROILITE GRAINS IN ORDINARY CHONDRITES MASS EQUIVALENT?

A Thesis
Presented for the
Master of Science
Degree
The University of Tennessee, Knoxville

Karla Elizabeth Kuebler

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DEDICATION

This thesis is dedicated to my twin sister

Kelly Irene Reeder

deceased, December 20th, 1996

"I love you going and never stop, and there's nothing more than that!"

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ABSTRACT

Chondrite groups have distinct size-frequency distributions of chondrules, commonly attributed to mass or aerodynamic sorting in the solar nebula. The concept of sorting has also been extended to other chondrite constituents (metal chondrules and metal-troilite grains), which have similar size-frequency distributions but smaller mean sizes. The different mean sizes of the chondrules and metal-troilite grains have been attributed to their varying densities in support of the concept of sorting, according to which the two populations should be mass equivalent. However, mass equivalence has never been demonstrated for chondrules and metal-troilite grains in the same meteorite.

I present the results of a comparison of chondrules and metal-troilite grains from three ordinary chondrites: Kelly (LL4), Bjurböle (L/LL4), and Hammond Downs (H4). The two populations are not mass equivalent in these three meteorites, and therefore do not provide compelling evidence for nebular sorting. However, trends in my data suggest that sorting did occur, but was inefficient, and imply that the efficiency of sorting varied between the populations, and also between the ordinary chondrite groups.

In each meteorite the average chondrule outweighs the average metal-troilite grain, but the two populations are the most similar in Hammond Downs. The average masses become increasing dissimilar in Bjurböle and Kelly, the average chondrule becoming heavier and the average metal-troilite grain lighter. The observed range in mass of the chondrules is narrower than that of the corresponding metal-troilite grain populations in each sample, suggesting that the chondrules were more efficiently sorted (2σ for the chondrules in each meteorite: Kelly, +0.93mg, -0.41mg; Bjurböle, +0.73mg, -0.31mg; Hammond Downs, +0.28mg, -0.13mg; 2σ for the metal-troilite grains: Kelly, ±0.91mg; Bjurböle, ±0.43mg; Hammond Downs, ±0.34 mg). The sorting efficiency also appears to vary between the ordinary chondrites, the mass

distributions of both populations being relatively narrow in Hammond Downs and increasing in Bjurböle and Kelly.

Because they are not mass equivalent my data fit aerodynamic sorting models better than those which infer sorting by mass alone. Aerodynamic stopping times were found to increase with particle size and mass between the three meteorites. Because of this, the aerodynamic stopping times of the two populations are the most similar in Hammond Downs and the most disparate in Kelly. Significantly, the mean chondrule and metal-troilite grain diameters in Hammond Downs most closely approximate the size of particles which Cuzzi et al. (1996) argue would be the best sorted. The relatively poor sorting of the metal-troilite grains may result from their irregular shapes. The greater abundance of small grains may have also influenced the sorting efficiency of this population because small grains are more easily mobilized by turbulence than large particles.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

FIGURE PAGE

I. INTRODUCTION

Various chondrite groups have been demonstrated to have different chondrule size populations (Dodd, 1976; Hughes, 1978; King and King, 1979). Among the ordinary chondrites, chondrule size progressively decreases from the LL to L to H groups (Rubin, 1989). Although size limitations may have been imposed during chondrule formation, the different chondrule size distributions are usually attributed to sorting mechanisms in the solar nebula. Mass sorting hypotheses suggest that sorting results from the differential settling rates of metal-rich and silicate-rich material to the midplane of a quiescent nebula (Wasson, 1985). Complimentary to mass sorting is the idea of aerodynamic sorting, whereby particles are concentrated between vortices in a turbulent nebula as a function of their stopping times (Cuzzi et al., 1996). While the inferred aerodynamic sorting mechanism differs from that of mass sorting, particle stopping times are related to particle radius and density (Paque and Cuzzi, 1997) so that mass is a significant factor in both hypotheses.

Recently the idea of physical sorting has been extended to other chondrite constituents, such as metal chondrules (Skinner and Leenhouts, 1993) and composite metal-troilite grains (Scott and Haack, 1994). Skinner and Leenhouts produced cumulative size-frequency distribution curves for silicate and metal chondrules from the Acfer 059 carbonaceous chondrite (CR2). The shapes of the size-frequency distribution curves were found to be similar, but were offset because of the difference in their mean sizes. This offset was attributed to the distinct densities of the two populations (Skinner and Leenhouts, 1993). Scott and Haack (1994) conducted a similar study of the Lancé carbonaceous chondrite (CO3) and proposed that sorting may have influenced the size distributions of all chondritic components (matrix, metal-troilite spherules, chondrules). While these studies implied that particle mass was significant in sorting, the mass equivalence of chondrules and metal-troilite grains in a single chondrite sample has never been demonstrated quantitatively. Furthermore, each of the studies comparing chondrules to other chondrite component populations has been based on a single meteorite (Skinner and Leenhouts, 1993; Scott and Haack, 1994). Whether metal-troilite grain sizes follow the same generalized trend established for chondrules in ordinary chondrites is not yet known. According to these accretionary models, chondrules and metal-troilite grains were sorted together and should have equivalent masses. If the masses of two populations follow the established trend for chondrule sizes their masses should decrease in the order LL to L to H (Rubin, 1989).

Companion to chondrule and metal-troilite grain sorting is the concept of metal-silicate fractionation. It is widely maintained (Larimer and Wasson, 1985; Newsom, 1994) that metal-silicate fractionation was an important process in the solar nebula and was largely responsible for the observed chemical variations in the chondrite groups (Urey and Craig, 1953) and possibly the planets (Anders, 1977). The sorting mechanisms described above are also believed to have caused metal-silicate fractionation in chondrites (Wasson, 1985), although concomitant variations in oxidation state suggest that the process was more complex (Kerridge, 1993).

In this study I test the idea of mass equivalence between chondrules and metal-troilite grains by determining the variations in size and mass of these coexisting components in representative meteorites of the ordinary chondrite groups. Thin section measurements were used to estimate the volumes of the chondrules, and X-ray tomographic images were employed to analyze the volumes of the metal-troilite grains. Technological advances have only recently adapted the latter technique to geological materials. The volumes were then combined with compositional data to determine the average masses of the two populations in each meteorite.

II. SAMPLES AND EXPERIMENTAL METHODS

The three ordinary chondrites chosen for this project were Kelly, Bjurböle, and Hammond Downs (Table 1). Although type 3 meteorites are considered to have undergone the least thermal modification since accretion, these meteorites are all petrologic type 4. Fuji et al. (1982) argue that metal-troilite grains show a slight coarsening even by type 4, but these effects are more predictable than those of shock metamorphism which may result in the flattening of chondrules and the mobilization of metal and sulfide. Because meteorites with spherical chondrules and low shock grades were necessary to minimize errors in calculating chondrule and grain volumes I opted for samples with low shock grades and believe the small trade-off in petrographic type is justified. At any rate, the three meteorites are of the same petrographic type and the degree of thermal alteration presumably equivalent.

Two of the meteorites chosen had previously been determined to contain nearly spherical chondrules with less than 5% flattening (Sneyd et al., 1988). Bjurböle was chosen because it lacks a preferred chondrule orientation (Dodd, 1965), which was determined by Sneyd et al. (1988) to be related to the degree of chondrule flattening; consequently Bjurböle was presumed to also contain nearly spherical chondrules. These samples are all of a relatively low shock grade (Kelly and Bjurböle by Stöffler et al., 1991; Bjurböle by Bennett and McSween, 1996; and Hammond Downs by my own analysis), a necessary characteristic because shock distorts the size and shape of metal-troilite grains (Fuji et al., 1982; Willis and Goldstein, 1983; Bennett and McSween, 1996). Shock effects tend to be distributed heterogeneously, so I used the same samples and thin sections previously analyzed by Sneyd et al. (1988) to the extent possible.

No straightforward method exists for determining the mass of either the chondrules or the metal-troilite grains. Because disaggregation is a destructive process

Table 1. Meteorites used in this Study

samples	classification	thin sections used*	cat scan samples	# chondrules	# metal-troilite grains
Kelly	LL4 (S3) [1,3]	USNM 1240-4, 5, 6	USNM 1240, 5.5 g	222	1923
Bjurböle	L/LL4 (S1) [2,3]	USNM 610-2, 6, 7, USNM 2258-1, AMNH 4474-1	USNM 695, 4.0 g	210	1342
Hammond Downs	H4 (S3) [2]	USNM 2473-1, 2, 3, 16	USNM 2473, 23.8 g	261	3174

1. VanSchmus and Wood (1967), 2. Mason (1973), 3. Stöffler, Keil, and Scott (1991)

*USNM Smithsonian Institution; AMNH American Museum of Natural History and may be biased against small chondrules, the chondrule sizes were determined in thin section and the measurements converted to their disaggregation equivalents according to the method of Eisenhour (1996) (see Appendix 1). The generally irregular shapes of metal-troilite grains are unfavorable for thin section analysis and so were analyzed using computed X-ray tomography (cat scans). These three-dimensional images are based on density variations within the meteorites, so that the metal-troilite grains stand out clearly from the silicate matrix.

Chondrules. For the chondrule size analyses at least 200 chondrules were measured for each of the three meteorites (Table 1). Chondrule diameters were measured in reflected light, first across the long dimension of the chondrule (where distinguishable) and then perpendicular to this axis. These two measurements were averaged, and the assumption of sphericity was made for the following corrections and calculations. Because of the low degree of flattening I believe this to be a valid assumption. Broken chondrules, chondrule fragments, and lithic clasts were excluded from the data set. Although I cannot exclude the possibility that chondrule fragments were sorted along with whole chondrules in the nebula, asteroid accretion and regolith processes offer ample opportunities to break chondrules after sorting. In any case, I could not adequately determine the size of chondrule fragments so their exclusion was necessary. Chondrule rims are believed to have accreted onto some chondrules in the presolar environment prior to the accretion of the meteorite parent bodies (Allen et al., 1980) and so were included where present. However, rims were rare and their inclusion had little effect on the results.

Because the evaluation of chondrule sorting depends upon the successful conversion of the apparent size distribution to the true size distribution (that measured in disaggregation experiments), empirical corrections must be employed to correct for the biases encountered in thin sectioning. Corrections were made using a spreadsheet template provided by D.D. Eisenhour and the steps used in these corrections (Eisenhour, 1996) are briefly described below and more thoroughly in Appendix I. I then compared the results from one of the meteorites, Bjurböle, to the disaggregation data of Hughes (1978).

Because thin sections are random slices through a sample, the chondrule diameter measured in thin section is rarely the true diameter. The corrections for this bias are based on a set of algebraic equations and are similar to those made by Hughes (1978). These equations are derived from the hypothetical distribution (statistically determined) of chondrule sizes cut from a population of chondrules whose sizes are known. The equations used in this step of the procedure assume that all chondrules are sampled randomly. Large chondrules, however, are actually sampled preferentially over small ones. Further corrections eliminate this bias, and this is the primary difference between the models of Eisenhour (1996) and Hughes (1978). To obtain the representative proportions of the chondrules in a given size range (the Eisenhour model uses the ϕ scale; where $\phi = -\log_2$diameter), the chondrule abundances were divided by the mean size in the bin (range in size). Last, because the observed chondrule diameter varies between transmitted and reflected light, Eisenhour (1996) recommends that all chondrule measurements be made in reflected light. This eliminates the error between measurements made in thin sections of different thickness. Eisenhour (1996) combined these steps into the following equation:

$$N_0' = \frac{2}{(d_u + d_l)} \frac{d_u}{(d_u^2 - d_l^2)^{\frac{1}{2}}} \left[N_0 - \sum_{i=1}^{\infty} N_i' \left\{ \frac{(D_i^2 - d_l^2)^{\frac{1}{2}} (D_i^2 - d_u^2)^{\frac{1}{2}}}{D_i} \right\} \right]$$

where N_o is the uncorrected number of chondrules in each bin, N_o' is the corrected number of chondrules, D_i and N_i are the mean diameters and corrected abundances, respectively, of larger bins, and d_u and d_l are the upper and lower boundaries, respectively, of bin N_o. The data were corrected bin by bin, starting with the largest bin and proceeding to the smallest. All summations were truncated at $i = 5$ (Eisenhour, 1996). The chondrule size distributions of each meteorite are given in Table 2, both before and after the corrections were made.

Disaggregation data exist for only one of the meteorites, Bjurböle. Because the Eisenhour model corrects for the disproportionate sampling of large chondrules over small, the mean chondrule diameter that we determined for Bjurböle is smaller than those previously reported, including the disaggregation data of Hughes (1978). A comparison of the mean and median chondrule diameters from the raw thin section measurements is presented in Table 3 along with corrected mean and median sizes, and the disaggregation data of Hughes (1978). Some of the discrepancy between my data and Hughes' may be attributed to the destruction of smaller chondrules during disaggregation, but the average chondrule diameter of our thin section data is also smaller than that of Hughes (1978).

After corrections, the mean chondrule diameters were determined graphically and their volumes calculated. The density used to determine the chondrule masses is based on a CIPW norm calculation of the average chondrule composition in ordinary chondrites (Table 4) reported by Grossman and Wasson (1983). The mineral densities used to determine the average chondrule mass are those reported in the Manual of Mineralogy edited by Klein and Hurlbut (1985); when a range in density was given end-member compositions were used to estimate the appropriate density for that mineral. Gooding et al. (1980) determined that chondrule composition does not vary significantly between the ordinary chondrite classes, and Gooding and Keil (1981) concluded that the ordinary chondrite groups contain similar abundances of the primary chondrule textural types. For this reason, I believe that minimal error has been

Table 2. Chondrule size distributions before and after corrections

chondrule diameters		Kelly				Bjurböle				Hammond Downs			
		thin section		corrected		thin section		corrected		thin section		corrected	
(phi)	(mm)	population	%	population	%	population	%	population	%	population	%	population	%
d-1.5 to -1.0	2.828 to 2.000	1	0.45	0.3	0.15	1	0.48	0.3	0.14	0	0.00	0.0	0.00
d-1.0 to -0.5	2.000 to 1.414	10	4.50	4.6	2.07	4	1.90	1.6	0.77	2	0.77	0.6	0.25
d-0.5 to 0.0	1.414 to 1.000	18	8.11	10.4	4.70	11	5.24	6.1	2.91	6	2.30	2.6	0.98
d 0.0 to 0.5	1.000 to 0.707	39	17.57	32.4	14.57	31	14.76	24.3	11.59	17	6.51	10.1	3.87
d 0.5 to 1.0	0.707 to 0.500	65	29.28	73.3	33.03	65	30.95	69.8	33.24	46	17.62	38.5	14.74
d 1.0 to 1.5	0.500 to 0.354	51	22.97	64.3	28.96	48	22.86	54.6	25.98	79	30.27	88.1	33.75
d 1.5 to 2.0	0.354 to 0.250	29	13.06	36.7	16.52	29	13.81	35.6	16.94	65	24.90	82.3	31.55
d 2.0 to 2.5	0.250 to 0.177	7	3.15	0.0	0.00	15	7.14	17.7	8.43	34	13.03	38.8	14.86
d 2.5 to 3.0	0.177 to 0.125	2	0.90	0.0	0.00	5	2.38	0.0	0.00	11	4.21	0.0	0.00
d 3.0 to 3.5	0.125 to 0.088	0	0.00	0.0	0.00	1	0.48	0.0	0.00	0	0.00	0.0	0.00
d 3.5 to 4.0	0.088 to 0.063	0	0.00	0.0	0.00	0	0.00	0.0	0.00	1	0.38	0.0	0.00

Table 3. Mean and median chondrule diameters from Bjurbole. Comparison of thin section measurements to corrected and disaggregated values

data set	mean diameter	median diameter
raw thin section data	0.573 ± 0.32 mm	0.522 mm
data after corrections	0.59 ± 0.25 mm	0.59 mm
disaggregation data from Hughes (1978)	0.750 mm *	0.688 ± 0.003 mm

* no standard deviation reported

Table 4. Normative chondrule mineralogy, mineral densities, and the density calculation for the average chondrule

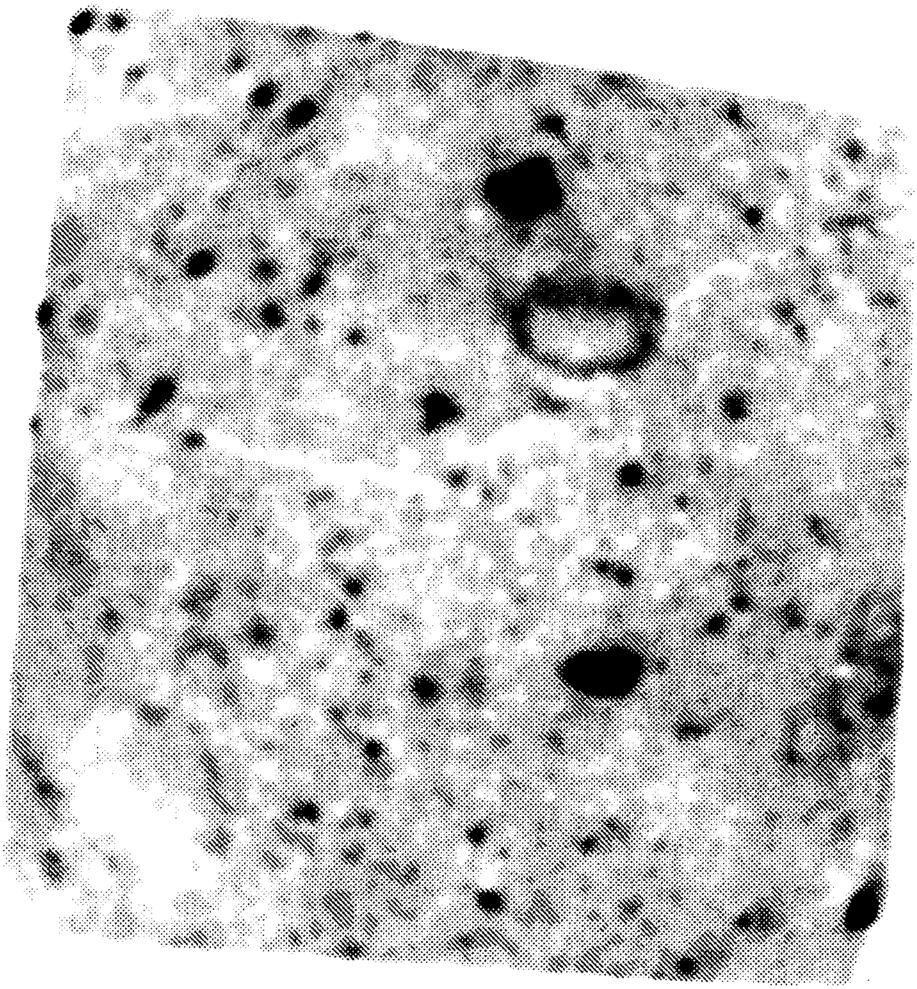
Oxides [1]	Analysis	Mineral	CIPW NORM	norm mineral density (g/cm^3) [2]	abundance x density
SiO_2	46.28	Orthoclase	0.41	2.59	0.01
TiO_2	0.15	Albite	9.47	2.63	0.25
Al_2O_3	2.90	Anorthite	2.67	2.76	0.07
Cr_2O_3	0.00	Diopside	5.65	3.30	0.19
Fe_2O_3	0.00	Wo	2.93		
FeO	16.42	En	1.94		
MnO	0.38	Fs	0.78		
MgO	30.54	Hypersthene	22.3	3.42	0.76
CaO	2.06	Hy	22.3		
Na_2O	1.12	En	15.93		
K_2O	0.07	Fs	6.38		
P_2O_5	0.08	Olivine	59.03	3.58	2.11
		Fo	40.94		
		Fa	18.09		
		Ilmenite	0.29	4.75	0.01
		Apatite	0.17	3.15	0.01
sum=	100	sum =	99.99		3.41
					= ave. density (g/cm^3)

1. Grossman and Wasson (1983)

2. Klein and Hurlbut (1985)

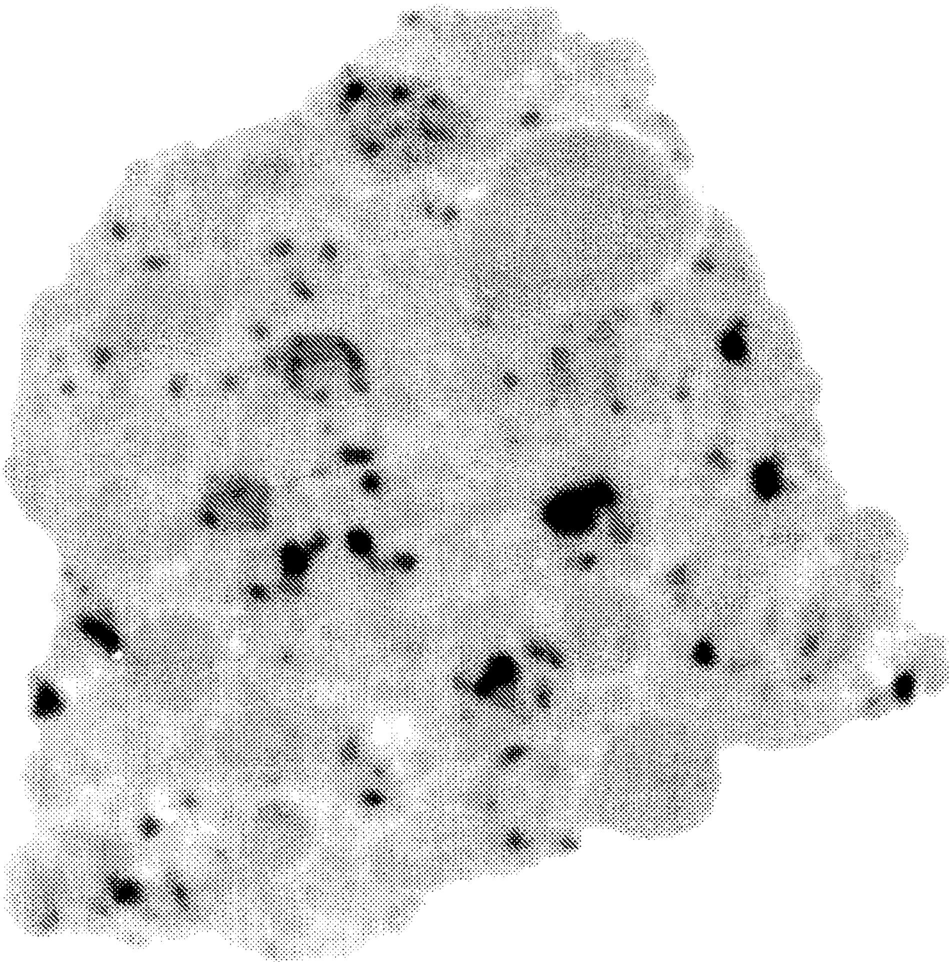
introduced into my calculations by the use of the same mean density for chondrules in all three meteorites.

Metal-troilite grains Because of the irregular shapes of metal-troilite grains, a three-dimensional method for analyzing the grains was necessary. Recent modifications in computed X-ray tomography have expanded the potential applications of this technique (Carlson and Denison, 1992), previously limited to medical research and metallurgy. Because meteorite samples are precious, this non-destructive technique is ideally suited to this study. These images are based upon variations in density (related to X-ray absorption) at each of several thousand points in a two-dimensional slice of the object (see Appendix II for additional details on how computed tomographic scans are produced and their limitations). Multiple slices are used to create the continuous three-dimensional image. I used a spacing of 100 μm between slices for my cat scans. Examples of individual slices of the Kelly, Bjurböle, and Hammond Downs meteorites are shown in Figure 1a, b and c. A composite cutaway image of the Hammond Downs meteorite is shown in Figure 2a. Such imaginary cuts into these computer images can be made so that the interior can be analyzed without damaging the sample. Figure 2b is another image of the Hammond Downs sample where the silicate material has been removed so that only the metal-troilite grains are visible. The irregular shapes of the grains are apparent in this image and emphasize the need for three dimensional analyses. Using Adobe Photoshop, the metal-troilite grains were highlighted by selecting a threshold grayscale value. It was then possible to calculate the area of each grain in pixels and to convert this value to cm^2. After the area had been calculated for each grain in every slice, the area of the grains was integrated over multiple slices and the intervening spaces to determine the volume (Kuebler et al., 1997). Grains visibly associated with chondrules and chondrule rims were omitted from the data set. One egregiously large vein-like grain from Hammond Downs



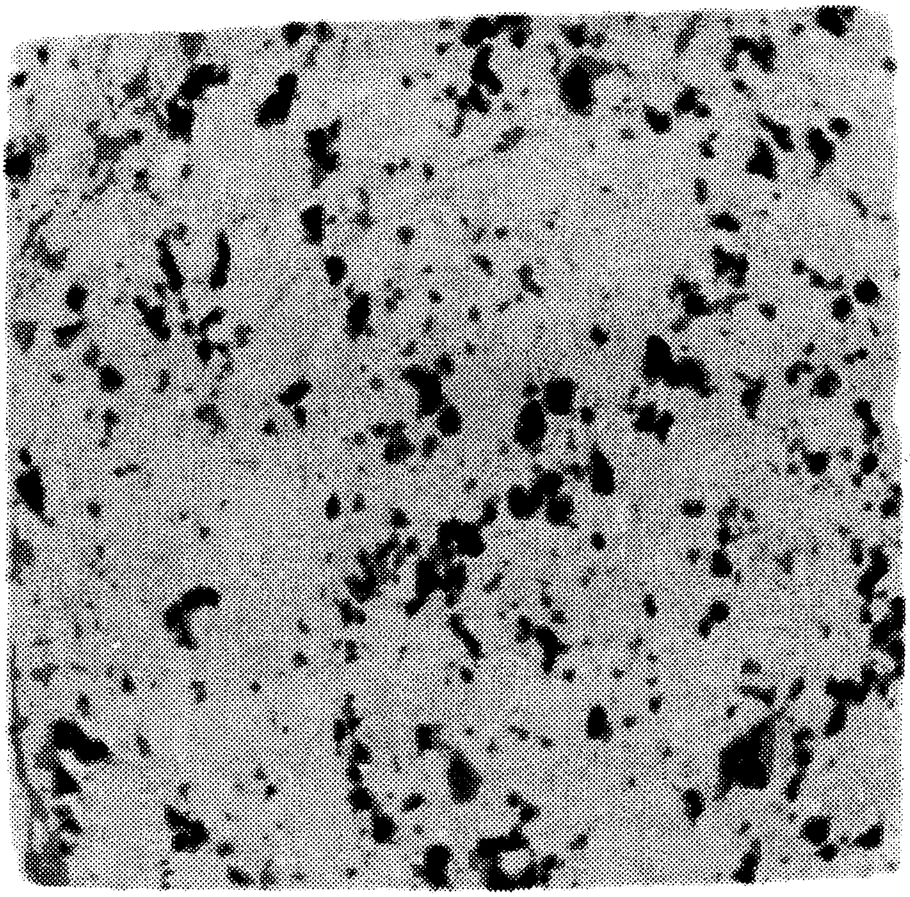
a. Kelly: 13 x 13 mm; only one chondrule is visible in the image because it has a metal and sulfide-rich rim.

Figure 1. X-ray images or "slices" of the Kelly, Bjurbole, and Hammond Downs meteorites. The denser metal and troilite phases (black) stand out from the silicate matrix which is lighter gray.



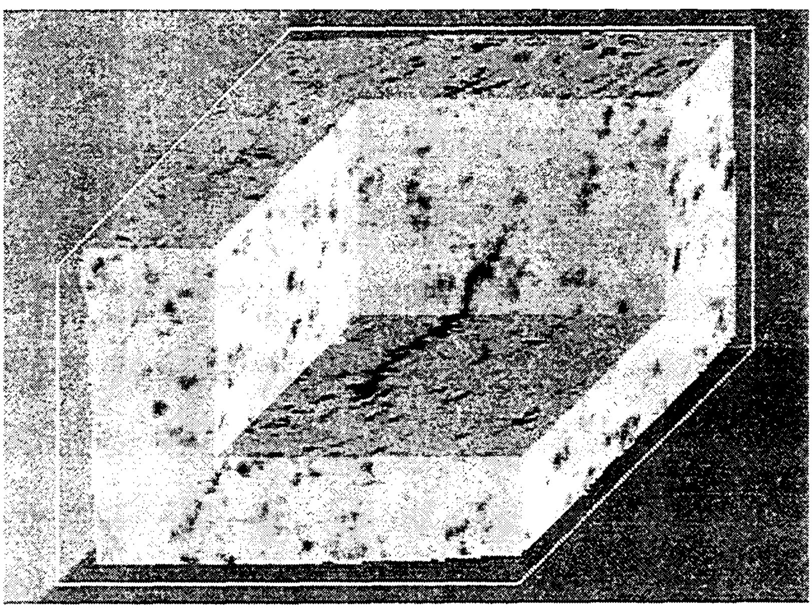
b. Bjurbole: approx. 15 x 15 mm. Chondrules stand out more clearly in this tomographic image because they are denser than the surrounding matrix.

Figure 1. (continued)



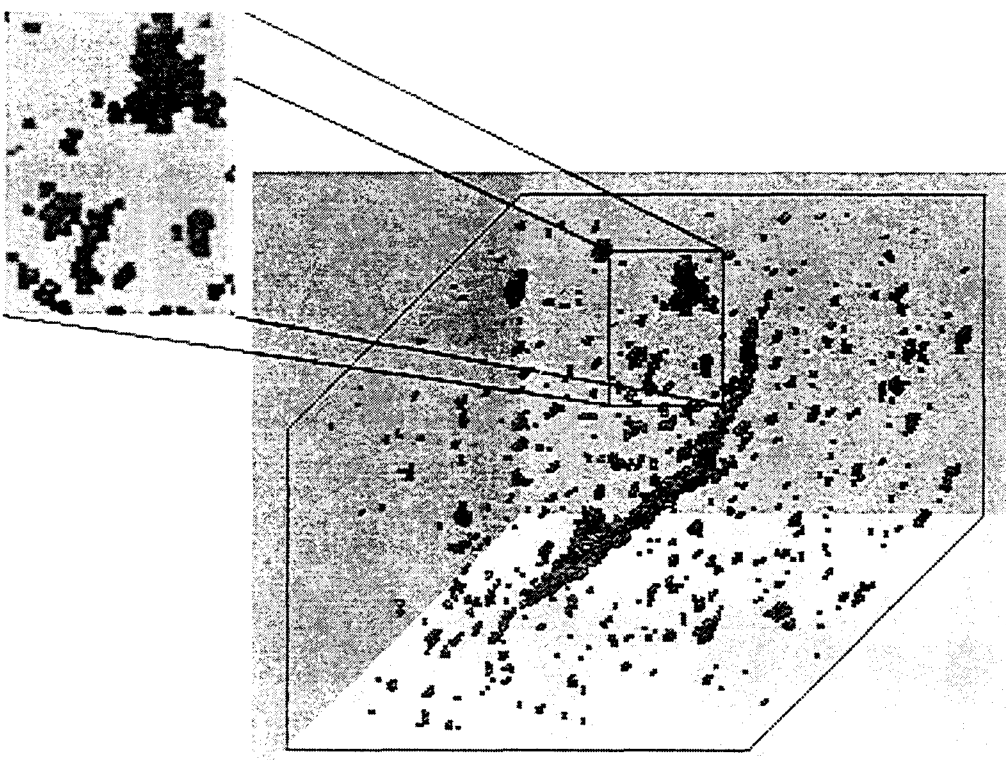
c. Hammond Downs: 13 x 13 mm. Metal-troilite grains in this meteorite are abundant and some appear to be fused together, the result of low levels of shock metamorphism. Shock effects were compensated for during grain-size analysis by separating or combining the affected grains.

Figure 1. (continued)



a. One vein-like grain apparent in this cutaway image is presumably the result of low-level shock metamorphism and was excluded from the data set for this meteorite. The size of this grain is anomalous considering the low levels of shock apparent in silicates of the sample, and may indicate the inhomogeneous distribution of shock in this meteorite.

Figure 2. Composite three-dimensional cutaway image of the Hammond Downs meteorite. Cube is 13x13x8mm.



b. The silicate material was removed from the previous image so that only the metal-troilite grains remain. The irregular shapes of the grains emphasize the need for three dimensional size analyses.

Figure 2. (continued)

(presumably affected by shock metamorphism) was also omitted. The grains are typically intergrowths of metal and troilite, and the two phases could not be adequately distinguished in the cat scans; therefore, it was necessary to use whole-rock, wet-chemical analyses (Fredriksson et al., 1979, Jarosewich, 1990) to determine the average proportions of Fe-Ni metal and troilite present in each meteorite and to estimate their respective grain densities (Table 5). The density of the metal phase in the sample was first determined according to the weight percent of Fe and Ni and this was combined with the weight percent and density of troilite to calculate the mean density of the average metal-troilite grain in each sample. A wet-chemical analysis for the Kelly meteorite was unavailable so that it was necessary to use the average composition of LL chondrites to determine grain density for this sample.

Table 5. Density calculations for metal-troilite grains

meteorite	wt% Fe*	wt% Ni*	wt%FeS*	density of Fe-Ni metal	density of ave. grain
Kelly	2.44	1.07	5.79	8.19 g/cm^3	6.10 g/cm^3
Bjurböle	3.53	1.12	5.35	8.13 g/cm^3	6.36 g/cm^3
Hammond Downs	5.33	1.59	4.91	8.11 g/cm^3	6.75 g/cm^3

*Bjurböle data from Fredriksson, et al. (1979),

Kelly and Hammond Downs data from Jarosewich (1990)

III. VARIATIONS IN TOMOGRAPHIC IMAGES OF THE THREE METEORITES

Considerable variation was found between the tomographic images. Only in the Bjurböle cat scan were many of the chondrules obvious (Figure 1b). This may be attributed to the high abundance of matrix material in Bjurböle (Dodd, 1976), but the chondrules in Bjurböle seem to contain more metal and sulfide grains than do the other meteorites. I cannot be sure on the second point, however, because the only apparent chondrules in Kelly and Hammond Downs were those surrounded by rims rich in metal and sulfide (Fig. 1b and c). Because the chondrules stood out better in the Bjurböle scan, it was easier to omit those metal-troilite grains associated with the chondrules than for the other meteorites. It is difficult to estimate how much of an effect this may have had on the data set, but is presumably negligible as no incongruities are apparent in the final mass calculations.

According to the shock classification scheme of Stöffler, two of the meteorites, Kelly (Stöffler et al., 1991) and Hammond Downs (our own analysis), are S3 shock grade. Olivine crystals in these two meteorites contain planar and irregular fractures and have undulatory extinction, but lack mosaicism. Although the two meteorites are of the same shock stage, the effects of shock on the metal-troilite grains are much more apparent in the Hammond Downs cat scan. The metal-troilite grains in Hammond Downs appear to be fused together in the tomographic image (Figure 1c). A vein-like grain whose proportions are irreconcilable even with extreme grades of shock metamorphism (Bennett and McSween, 1996) was also discovered in the Hammond Downs cat-scan (Figure 2a). Shock is often distributed heterogeneously in meteorites, however, so it is possible that the metal and troilite in this vein may have been injected from elsewhere in the meteorite which was more heavily shocked. Kelly, on the other hand, contained the least massive metal-troilite grains, and shock appears to have been insignificant. I suspect that the greater abundance of metal-troilite grains in Hammond

Downs (roughly three times that of the Kelly meteorite, although the samples are equivalent in size) also influenced the apparent degree of communication between grains.

The annealing of grains as the result of shock may have narrowed the apparent grain size distribution in Hammond Downs slightly by fusing together small grains, and may also have contributed to the greater average mass determined for the metal-troilite grains in Hammond Downs. We were able to minimize this source of error during grain size analysis, however, by separating those metal-troilite grains which appeared to be affected and doubt that the data was greatly influenced. Attempts to omit grains that may have been affected by shock only increased the difference in the average masses of the metal-troilite grains and chondrules for this meteorite.

IV. COMPARISON OF CHONDRULES AND METAL-TROILITE GRAINS

Previous studies have suggested that chondrules, metal chondrules, and other chondrite constituents were sorted together in the presolar nebula. The evidence cited for sorting is the similarity in shape of the apparent size distribution curves for the different components made from thin section data. However, the three pairs of size-frequency curves made in this study are only similar in one of the meteorites, Hammond Downs (Figure 3). The size-frequency curves of the metal-troilite grains in Bjurböle and Kelly are more spread out than are their respective chondrule size-frequency curves and have lower slopes. In addition, the average masses of the two populations (Table 6) indicate that chondrules and metal-troilite grains in the same meteorite are not mass equivalent. Because they are not mass equivalent, the two populations have different average stopping times.

The observed trend in the average sizes and masses of metal-troilite grains between chondrite groups is opposite that of the chondrules (Table 6). While the masses of the chondrules were found to vary between chondrite groups similar to the trend established for chondrule sizes by Rubin (1989), i.e. decreasing from LL to L to H, the sizes and masses of the metal-troilite grains were found to increase in this sequence. The average masses of the metal-troilite grains and chondrules are closer in Hammond Downs than in either of the other two meteorites (Table 6). The average metal-troilite grain from Bjurböle has a mass slightly more than a third that of the average chondrule, and for Kelly the difference increases so that the average metal-troilite grain is roughly a fourth that of the average chondrule. The abundance of light metal-troilite grains increases from H to L to LL chondrites, but differences in the grain densities for these meteorites account for most of this discrepancy.

Cumulative size-frequency curves for metal-troilite grains and chondrules are shown in Figure 3 for each meteorite. The size distribution curves of the two

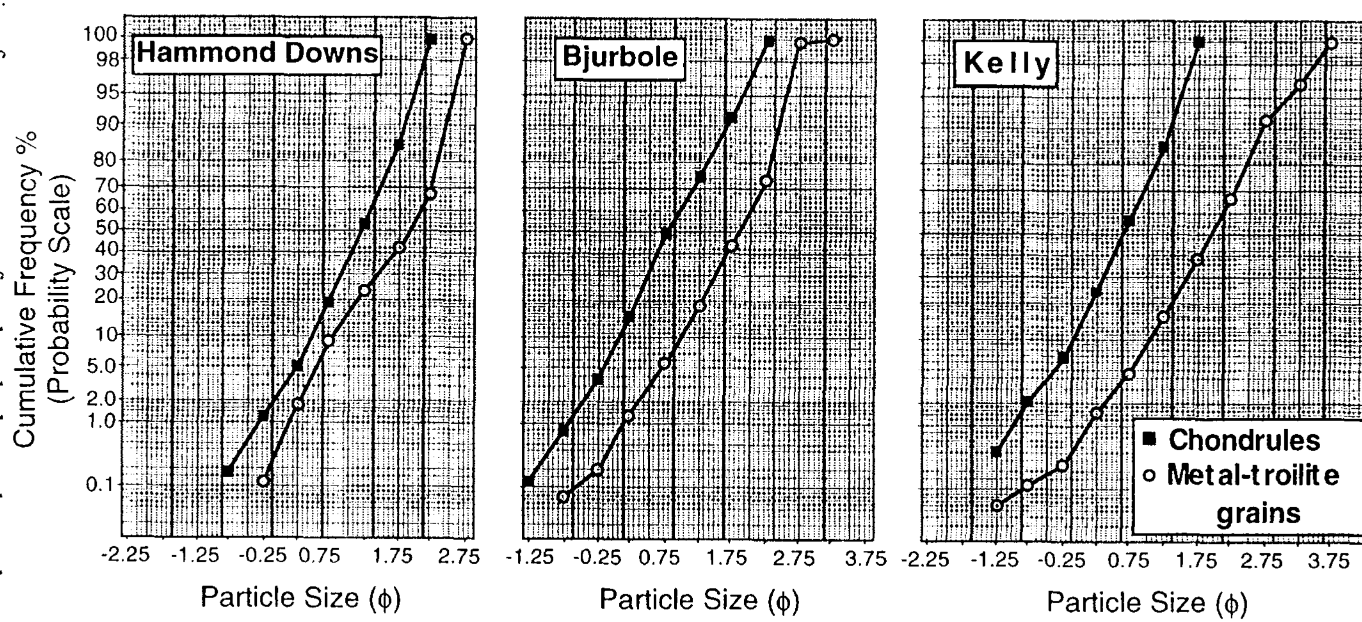


Figure 3. Cumulative size-frequency curves for chondrules and metal-troilite grains.

Table 6. average radius, volume, density, and average mass

A. Chondrules

meteorite	average radius	average volume	density	average mass	average stopping times*	average (radius x density)*
Kelly	0.33 mm ± 0.14 mm	0.149 + 0.272 mm^3 - 0.119 mm^3	3.415 g/cm^3	0.51 + 0.93 mg - 0.41 mg	5600 seconds	0.122 g/cm^3
Bjurböle	0.30 mm ± 0.13 mm	0.108 + 0.214 mm^3 -0.089 mm^3	3.415 g/cm^3	0.37 + 0.73 mg - 0.31 mg	5050 seconds	0.101 g/cm^3
Hammond Downs	0.23 mm ± 0.09 mm	0.051 + 0.081 mm^3 - 0.038 mm^3	3.415 g/cm^3	0.17 + 0.28 mg - 0.13 mg	3930 seconds	0.079 g/cm^3

B. Metal-troilite grains

meteorite	average radius	average volume	density	average mass	average stopping times	
Kelly	0.124 mm ± 0.072 mm	0.0211 ± 0.135 mm^3	6.098 g/cm^3	0.129 + 31.7 mg - 0.128 mg	3780 seconds	0.076 g/cm^3
Bjurböle	0.134 mm ± 0.068 mm	0.0213 ± 0.068 mm^3	6.362 g/cm^3	0.135 + 0.845 mg - 0.129 mg	4265 seconds	0.085 g/cm^3
Hammond Downs	0.138 mm ± 0.074 mm	0.0232 ± 0.051 mm^3	6.750 g/cm^3	0.157 + 6.433 mg - 0.148 mg	4658 seconds	0.093 g/cm^3

* calculated according to Cuzzi, et al. (1996)

populations are the most similar in Hammond Downs, the curves of both populations spreading out over the same number of phi scale bins, and having similar slopes. The metal-troilite grain populations in Bjurböle and Kelly, however, are spread out over a greater number of bins so that they have shallower slopes than their coexisting chondrule populations. This distinction in the size-distribution curves of the two populations can be made because the metal-troilite grains were analyzed using X-ray tomography. The true size of some large, rare metal-troilite grains are apparent in the tomographic images which cannot be fully appreciated in thin section. I concede that some distortion in the grain size curves may also result from the combination of the metal and sulfide phases. Although the two phases are usually intergrown, individual metal or sulfide grains are not uncommon and their combination may account for some of the spread observed in grain size distributions. For the same reason, the use of a single grain density may have spread out the grain mass distributions by overestimating or underestimating the density of some single-phase grains. Considering the greater abundance of small grains, I presume the underestimation of grain masses poses a greater uncertainty.

The histograms in Figure 4 represent the range in mass of the chondrules and metal-troilite grains versus the percentage of constituents present in each bin. The ranges in mass of both populations are considerable, but are greater for the metal-troilite grains. The bins used for in this figure are based on the phi-scale presented in the Eisenhour model, accounting for their irregularity. As was found for the size-distribution curves the two mass distribution histograms are the most similar for Hammond Downs. The average masses of the chondrules and metal-troilite grains become increasingly dissimilar in Bjurböle and Kelly, the average chondrule becoming heavier and the average metal-troilite grains lighter. Light metal-troilite grains are common in each meteorite, but are the most abundant in Kelly.

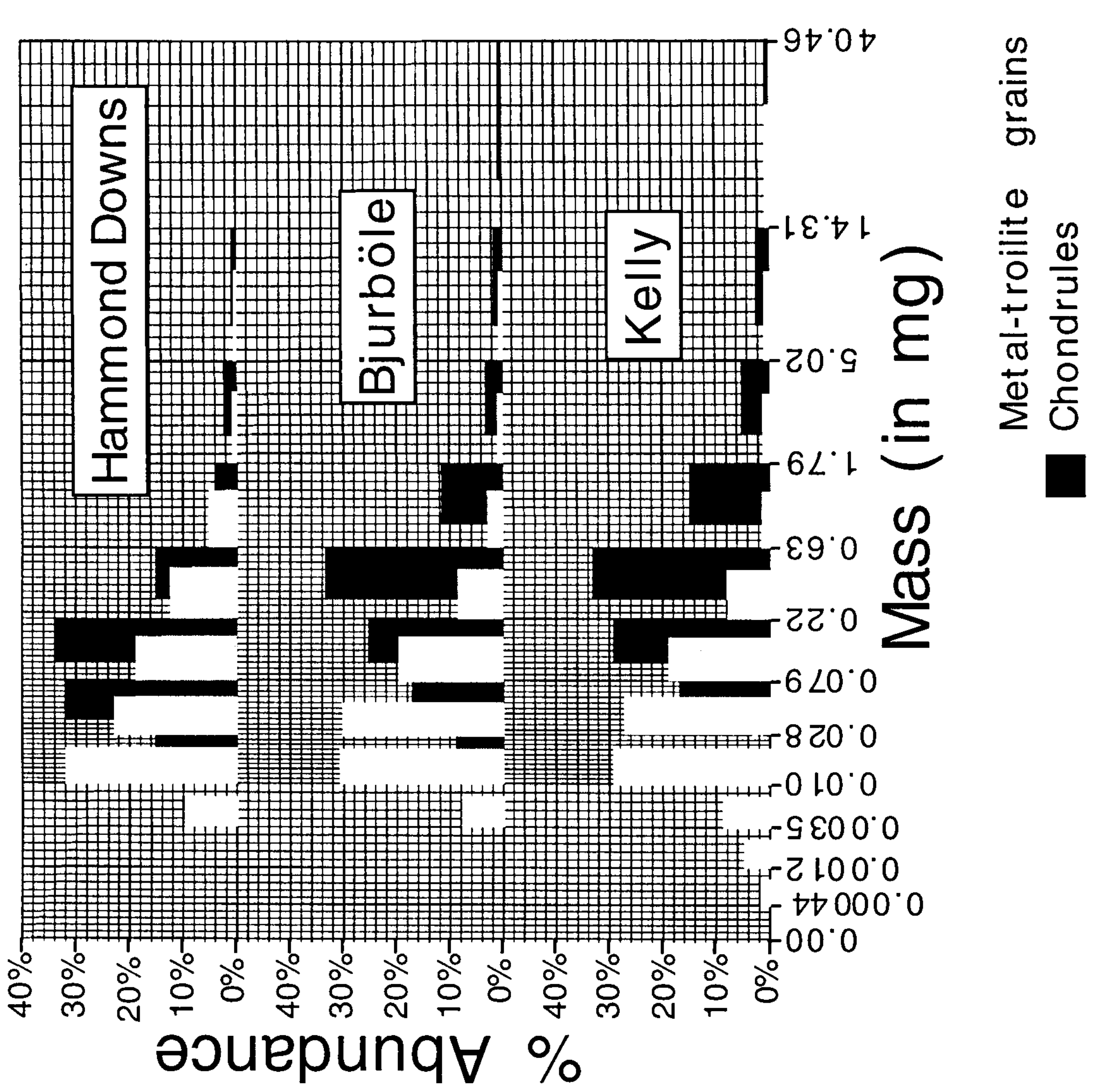


Figure 4. Range of masses observed in chondrules and metal-troilite grain populations. The average metal-troilite grain is lighter than the average chondrule, and the metal-troilite grains are less well sorted. This may result from the smaller sizes and irregular shapes of the grains. The bins used in this figure are based on the phi-scale bins used to plot the cumulative size frequency curves in Figure 3.

Interestingly, the average volumes of the metal-troilite grains are almost identical for the three meteorites, despite the increased spread of sizes in Kelly and Bjurböle. Because of the similarity in the average grain sizes for the three chondrites I presume the primary cause of variation in the grain masses is the different proportions of metal and troilite in the matrices of the meteorites (Table 5). Hammond Downs has roughly equal proportions of metal and troilite and contains the highest weight percent Ni, so that the calculated metal-troilite grain density for this meteorite is greater than that estimated for the other two chondrites. The proportions of troilite and iron in the grain populations increase in Bjurböle and Kelly, and contributes to their successively lower average metal-troilite grain densities.

Because the average sizes and masses of the two populations differ, their stopping times are also dissimilar (Table 6). Currently accepted aerodynamic sorting models (Cuzzi et al. 1996) explain sorting in terms of particle stopping times (t_s) given by the equation:

$$t_s = r_p \rho_s / c \rho_g$$

where r_p is the radius of the particle, ρ_s is its density, c is the gas sound speed, and ρ_g is the density of the gas. Because the exact value of ρ_g is uncertain, the value more often sited in aerodynamic sorting models is ($r_p \cdot \rho_s$) and these values are also provided in Table 6. The average stopping times of the chondrules and metal-troilite grains increase with the average particle diameter between the chondrite groups. Chondrules in the Kelly meteorite are the largest of the three meteorites, and hence have the longest average stopping time. On the other hand, Kelly's metal-troilite grains are smaller and lighter than those in Bjurböle and Hammond Downs and have the shortest average stopping time. The opposite is true of Hammond Downs, its chondrules have the shortest average stopping time and its metal-troilite grains the longest. For this reason, the average aerodynamic stopping times of the two populations are also the most similar in Hammond Downs and the most disparate in Kelly.

The Eisenhour (1996) method yields smaller average chondrule sizes than do previous models, which translates into smaller calculated chondrule masses. The model of Hughes (1978) would have afforded an even greater disparity between the average chondrule and metal-troilite grain masses. The large standard deviations for the chondrule data set can be attributed in part to the method used to determine the mean diameter and standard deviation. Because the corrected chondrule size distributions are presented as bin populations, it was necessary to determine the mean size and standard deviation graphically using the equations of Folk and Ward (1957). The graphic mean chondrule size (M) is given by the equation:

$$M = \frac{\phi_{16} + \phi_{50} + \phi_{84}}{3}$$

and the graphic standard deviation (C) by:

$$C = \frac{\phi_{84} - \phi_{16}}{4} + \frac{\phi_{95} - \phi_{5}}{6.6}$$

The chondrule sizes are evenly distributed between the 84th and 16th percentiles and are only slightly skewed to smaller chondrule sizes, but the paucity of chondrules at the upper and lower limits of the size-frequency distribution hinder the accurate determination of the 5th and 95th percentiles. Nonetheless, the graphic mean and median chondrule diameters are identical in all three meteorites and are not an artifact of the empirical corrections employed (D. Eisenhour, 1997, personal communication), despite the skewness in the corrected size distributions shown in Table 2.

V. IMPLICATIONS FOR NEBULAR SORTING AND FRACTIONATION

Variations in the uncompressed mean densities of the terrestrial planets have been attributed to their differing accreted proportions of metal and silicate (Larimer and Wasson, 1989). Metal-silicate fractionation has also been recognized among the ordinary chondrites (Urey and Craig 1953). Early in this century it was demonstrated that ferromagnesian minerals in metal-poor meteorites had higher FeO contents (Prior, 1916). This was attributed to variations in redox conditions of the solar nebula, i.e. that more Fe in metal-poor chondrites was present in silicates rather than in metallic form. Urey and Craig (1953) demonstrated this to be an oversimplification, by showing that the overall abundance of Fe (relative to Si) is also higher in the metal-rich chondrites. Since then, the interpretation of siderophile element (Fe, Ni, Co) fractionation patterns in ordinary chondrites has made it possible to link the compositions of the ordinary chondrites to that of the CI chondrites, whose composition approximates that of the bulk solar system. The ordinary chondrites can be modeled from a CI starting composition by the removal of a refractory (Mg-rich) component and the subsequent loss of metal (or silicate enrichment) (Larimer and Wasson, 1989). Metal-silicate fractionation is usually inferred to have resulted from one of several physical processes and has been identified with the phenomena of sorting, although no single process has yet been confidently specified (Larimer and Wasson, 1989). Uncertainties also remain concerning the timing of metal-silicate fractionation relative to chondrule and CAI formation (Newsom, 1994).

Several inferences concerning metal-silicate fractionation can be drawn from my results. The best sorted meteorite, Hammond Downs, is the richest in metal and sulfide grains, has the highest weight percent of Fe, and contains the smallest chondrules. Conversely, Kelly contains the largest chondrules, lightest metal-troilite grains, and the lowest weight percent of Fe. This anticorrelation between the average chondrule and metal-troilite grain masses further support the conclusion that sorting is related to metal-silicate fractionation. The difference in the average masses and stopping times of the populations is problematic, however, and the variations in their mass distributions even more so.

Nonetheless, the average particle stopping times of both populations increase with size and mass between the chondrite groups, supporting the primary premise of sorting models. The degree (or efficiency) of sorting appears to vary between the two populations. The chondrules have narrower size and mass distributions, apparently having been sorted more efficiently than the metal-troilite grains. For this reason, the average volumes, masses, and aerodynamic stopping times of the two populations appear to converge in Hammond Downs.

Because of the apparent difference in sorting efficiency of chondrules and metal-troilite grains, my data are easier to fit into the context of aerodynamic sorting models than those which infer sorting by mass alone. Although the two populations are not mass equivalent, the correlation in particle size, density, and stopping time holds true between chondrite groups, and therefore support aerodynamic sorting models. The small sizes and irregular shapes of the metal-troilite grains may account for their relatively inefficient sorting (see Figure 2b). The most efficiently sorted particles according to Cuzzi et al. (1996) are those whose diameters are approximately 0.3 mm, or about that of a typical chondrule. Small particles are more easily mobilized by turbulence than are large particles (Weidenschilling, 1989). The metal-troilite grain populations are dominated by grains smaller than this optimum size, partly accounting for the greater observed range in mass for this population. The irregular shapes of the grains would have also affected the efficiency with which they were sorted, such that the diameter of the leading edge of the grain would be the most influenced by turbulence (Cuzzi, personal communication). My data also support aerodynamic models in that the corrected mean chondrule and metal-troilite grain diameters of the most efficiently sorted of the three meteorites (0.46 ± 0.09 mm and 0.276 ± 0.074 mm, respectively, for Hammond Downs) most closely approximate the size of particles which Cuzzi et al. (1996) argue would be the best sorted. The mean chondrule diameters are successively larger and the metal-troilite grain diameters successively smaller in Bjurböle and Kelly. Accordingly, these two meteorites are successively less well-sorted (Table 6).

VI. CONCLUSIONS

The two populations are not mass equivalent, and have different mass distributions and average particle stopping times. The average chondrule masses vary between the ordinary chondrite groups similar to the trend in chondrule sizes established by Rubin (1989), decreasing from LL to L to H. The average masses of the metal-troilite grains trend opposite to this, increasing from LL to L to H. The ranges in mass found for the chondrules are smaller than those for metal-troilite grains, presumably related to the efficiency of sorting of the two populations. Chondrules are more efficiently sorted than metal-troilite grains, and the efficiency of sorting of both components also varies between the ordinary chondrite groups. The mass distributions of chondrules and metal-troilite grains are narrowest in the H chondrites and are interpreted to be better sorted. The mass distributions of the two populations are successively greater in the L and LL ordinary chondrites, which are less well-sorted. A correlation between aerodynamic stopping time and particle size is apparent despite the two populations not being mass equivalent.

Because of the discrepancy between the chondrule and metal-troilite grain populations, my data fit into aerodynamic sorting models better than those which depend on sorting simply by mass. Significantly, the average metal-troilite grain and corrected mean chondrule diameters from the most well-sorted chondrite (Hammond Downs) most closely approximate the size of particles which Cuzzi et al. (1996) argue would be the most well-sorted. Finally, I have found X-ray tomography to be a very useful imaging technique for the study of meteorites. By analyzing the meteorites grains using X-ray tomography I found considerable variation in the images, which suggests the that X-ray tomography would be useful for in analyzing other textural features in meteorites.

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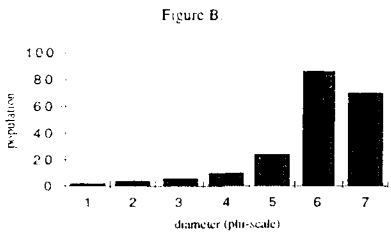
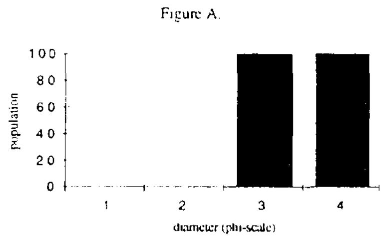
APPENDICES

APPENDIX I. Empirical corrections for thin section measurements (according to Eisenhour, 1996).





Bias #1) Imagine a meteorite containing 200 chondrules, 100 in each of two bins (size ranges). A histogram of the true size distribution would look like Figure A. The apparent size distribution in thin section would most likely yield the distribution shown in Figure B. To restore the thin section data back to its true size distribution use the following procedure.

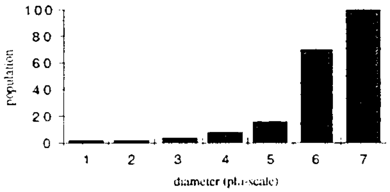
A) The population of the largest bin (y_1) is 100 chondrules, the number of chondrules sampled in the largest thin section bin (x) is 71 so that some of the chondrules have been lost to smaller bins. By using equation:

(# measured in the bin) - (y x % in smaller bin) = # chondrules remaining in bin

the observed chondrule population can be converted back to their true size distribution:

2nd largest bin = 87- (y_1 x 0.16) = 71
3rd largest bin = 23 - (y_1 x 0.07) = 16
4th largest bin = 10 - (y_1 x 0.03) = 7
5th largest bin = 5 - (y_1 x 0.02) = 3
6th largest bin = 3 - (y_1 x 0.01) = 2
7th largest bin = 1 - (y_1 x 0.00) = 1 _
sum = 100

Figure C.



After this first step is complete the resulting histogram is given in Figure C, and the population of the largest bin has been restored. The sum at the end of this step represents the number of chondrules that must be restored to the smaller bin.

B) A similar procedure is used to restore the second bin. Again $y_2 = 100$.

3rd largest bin = 16 - (y_2 x 0.16) = 0
4th largest bin = 7 - (y_2 x 0.07) = 0
5th largest bin = 3 - (y_2 x 0.03) = 0
6th largest bin = 2 - (y_2 x 0.02) = 0
7th largest bin = 1 - (y_2 x 0.01) = 0
sum = 0

No chondrules are left to be restored.

C) In reality, multiple bins would be necessary and this procedure would need to be reiterated until no chondrules remained. This step must precede all other corrections.

Bias #2) The observed diameter of a chondrule varies according to the light used when measurements are made. When the surrounding matrix is opaque, measurements made in transmitted light represent the smallest diameter of the chondrule in the thin section. When the surrounding matrix is transparent the size measured is the largest diameter of the chondrule. Measurements made in reflected light represent the chondrule's diameter at the upper surface of the thin section. The difference in these measurements depends on the size of the chondrules and the thickness of the thin section. The error introduced, therefore, varies from one thin section to another and correcting for this source of error would be complicated. For this reason, it is suggested that all measurements be made in reflected light.

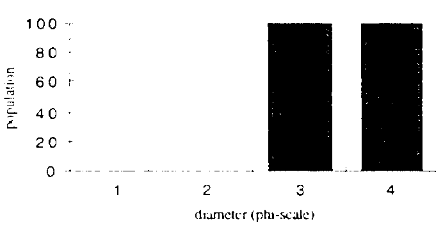
Bias #3) The above corrections assume that all chondrule are sample randomly. Large chondrules, however, are sampled preferentially over small. If ten serial thin sections were made of a sample containing one small chondrule (diameter = 0.1 mm) and one large chondrule (diameter = 1 mm) the small chondrule would be sampled in one of the ten thin sections, and the large chondrule would be sampled in all ten. Therefore, to obtain the representative proportions of the chondrules it is necessary to divide their occurrence by their size:

1 chondrule / 0.1 mm = 10
10 chondrules / 1.0 mm = 10

Because chondrule sizes are often reported according to the phi-scale and because phi-scale distributions are log-normal the method uses bin sizes based on the phi-scale rather than a metric scale. If the observed chondrule distribution in thin section is as shown in Figure D then the average chondrule size in the smaller bin is 70% of the average chondrule size in the larger bin. Therefore to correct for the observed distribution for sampling error divide:

100 chondrules / 0.5 ϕ (or 0.707 mm) = 141 chondrules
100 chondrules / 1 ϕ (or 0.5 mm) = 100 chondrules

Figure D.



APPENDIX II. X-ray tomography, resolution and limitations

Physicians use computed axial tomography (or X-ray CT) to produce three-dimensional images (cat scans) of the brain and other organs. Researchers have modified the technique for other scientific endeavors by intensifying the radiation for use with denser (geologic) materials and by improving the resolution. The images produced are based on variations in density at each point within the object rather than through the object as a whole (as is done for standard X-ray images). The density changes are determined by passing a horizontal fan of X-rays through an object on a turntable (Denison and Carlson, 1997). The intensities of the X-rays are measured before and after passing through the object, and are measured continuously as the object is rotated. This evaluates the attenuation of the X-rays by the object. Because the object is rotated, the X-rays pass through each point in the object several times, making it possible to calculate the attenuation of the beam at each point along its path (Denison and Carlson, 1997).

To produce an image from the X-ray data, Beer's law is used to relate the initial intensity (I_o) and final intensity (I) to a property of the object called the *linear attenuation coefficient* (μ):

$$I = I_o \cdot \exp \int_0^d -\mu(x)\, dx$$

where d is a distance coordinate along the X-ray path (a point within the object for which μ is being calculated) and x is a dummy variable of integration over distance. An equation of this sort is produced for every intensity measurement of each different X-ray path (Denison and Carlson, 1997). The value of $\mu(x)$ is unknown, but can be related to density (r) by the equation:

$$\mu = r\left(a + (bZ^{3.8} / E^{3.2})\right)$$

where a and b are constants, Z is the effective atomic number of the material being analyzed, and E is the energy of the X-ray beam. Larger μ values correspond to denser materials. The attenuation of the beam is calculated at each point along the X-ray path using a process called image reconstruction. One such procedure, "filtered backprojection," is described by Dewdney (1990). From this information an image, or slice, is produced where each pixel represents one μ value. By repeating the procedure and producing multiple slices one can create a continuous three-dimensional image.

The resolution of the X-ray CT image is dependent on several factors including the size of the X-ray source, the geometry of the apparatus, and the signal-to-noise ratio in the attenuated beam. Other factors impinging on the resolution of the image include the efficacy with which the sample being imaged absorbs X-rays and the amount of scatter produced. If the sample imaged is too large or absorbs X-rays too strongly, variations within the sample may be obscured. This may also create differences in the total beam attenuation, even between "equivalent" paths - those traversed at 180° (Denison and Carlson, 1997). The ultimate resolution of a slice depends on the density of pixels (or voxel, for three dimensions) used to create the image, and is usually based on the minimum resolvable unit as determined by the previous factors. The value of μ calculated for each pixel is translated into a greyscale scale value (0 = black, 255 = white), and is used to create the images. Modern CT instruments can discriminate values of μ to about 0.1% under favorable circumstances but are hindered by an increase in the amount of noise. Resolution in the third dimension is dependent on the slice thickness used. X-ray CT images can be produced with a slice resolution of 10 μm, but the time required to produce these images, the memory required to store them, and cost are prohibitive. A resolution range of 100-200 μm is usually reasonable (Denison and Carlson, 1997).

Imaging artifacts, such as an uneven brightness, linear streaking, and apparent gradients across sharp interfaces result from the preferential absorption of X-rays characteristic for the material being analyzed and also from the stronger absorption of low-energy X-rays, a phenomena known as beam-hardening (Denison and Carlson, 1997). This results in the image being slightly lighter at the center of the image. These artifacts can usually be ameliorated by incorporating empirical corrections or by digital filtering during image processing.

VITA

Karla Elizabeth Kuebler was born in Kansas City, KS on July 5th, 1971 and was raised in nearby Overland Park, KS. She attended Trailwood Elementary, Indian Creek Junior High, and Shawnee Mission South in the Shawnee Mission School District, graduating in May of 1989. The following autumn she entered the University of Kansas, Lawrence where she developed interests in both geology and astronomy. In the spring of her graduation, May 1994, the Geology department awarded her the W. A. Tarr Award and the Erasmus Haworth Outstanding Senior Award. She also received the W. Wyman Storer Award from the Physics and Astronomy Department for her two years of service as the President of the Astronomy Associates of Lawrence. Her involvement in the Geology and Astronomy departments led to a summer internship with the Lunar and Planetary Institute/Johnson Space Center in 1994. There she analyzed the minor element chemistries of the minerals in lunar sample 72255 under the direction of Dr. Graham Ryder. She entered the Master's program at the University of Tennessee, Knoxville in January of 1995 where she began studying ordinary chondrites and the origins of the solar system with Dr. Harry "Hap" McSween. The Master of Science Degree was granted in December, 1997.