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The Dresden (Ontario) H6 Chondrite, Part II: Classification, Estimated Fireball Trajectory, and Possible Origin

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Abstract

The Dresden (Ontario) meteorite fell in southwestern Ontario on the early evening of July 11, 1939. We re-examine this historic Canadian fall, consider the mineralogy, physical properties, and bulk chemistry of the meteorite, and estimate its trajectory and pre-atmospheric orbit based on visual accounts of the event. Mineralogical examination of several fragments of the meteorite reveals poor definition of chondrule margins, lack of glass, and the presence of minor feldspar, confirming Dresden (Ontario) to be an H6 ordinary chondrite. The bulk of the stone has undergone a low level of shock (S2) as indicated by generally clean extinction of silicate grains. A 12-g bulk sample of the Dresden (Ontario) main mass has elemental abundances that agree well with the H-chondrite average. The bulk density for Dresden (3.48+/-0.07 g/cm^3) and porosity (4.9%) are also typical of H chondrites. Several accounts of the fall event constrain the Dresden fireball to have had a ground projection azimuth of ~050, passing from north of London, Ontario southwestwards toward Dresden. The tightly grouped strewnfield of fusion-encrusted fragments recovered ~10 km southwest of Dresden, Ontario suggests that the fireball trajectory was steep. Dark-flight simulations using the 050 azimuth best reproduce the recovered strewnfield distribution with an entry angle of >70°. The range of potential orbits derived from this inferred steep trajectory is consistent with previous orbits measured for meteorite-producing fireballs, and suggest that the Dresden meteoroid had an Apollo asteroid-type orbit, with a perihelion just inside that of the Earth's and a low-to-moderate inclination. The Dresden (Ontario) H6 chondrite is thus petrologically and dynamically similar to other H chondrites with known orbits. A comparison of the known H-chondrite orbits with a modelled debiased distribution of near-Earth objects indicates that the H chondrites were most likely delivered to the Earth via the ν6 and the 3:1 resonances, thus strengthening the dynamical case for the linkage of H-chondrite meteorites with the S-type asteroid 6 Hebe as suggested by Gaffey *et al.* (1993).

Résumé

Le météorite Dresden (Ontario) est tombé dans la région sudouest de l'Ontario au début de la soirée du 11 juillet 1939. Une réévaluation de cette chute historique canadienne a considéré la minéralogie et la chimie globale du météorite. Nous ré-examinons cette chute historique canadienne, en considérant la minéralogie, les caractéristiques physiques et la chimie globale du météorite. Basée sur les observations visuelles de l'événement, nous évaluons la trajectoire du météorite et l'orbite pré-atmosphérique. L'examen de la minéralogie de plusieurs fragments du mériorite indique la faible définition de la marge de chondres, le manque de verre et la présence mineure de feldspath, ce qui confirme que Dresden (Ontario) est un chondrite ordinaire H6 (S2). Le grade pétrologique 6 a été alloué sur la base de la faible définition de la marge de chondres, le manque de verre et la présence mineure de feldspath. La masse de la pierre a subi un taux de choc (S2) plutôt faible tel qu'indiqué par l'extinction généralement nette de grains de silicate. L'analyse multi-éléments d'un échantillon de 12g de la masse principale de Dresden (Ontario) démontre une abondance d'éléments qui s'accorde bien avec celles de la moyenne des chondrites de type H. La densité estimée de la masse de Dresden (3,48+/-0,07 g/cm^3) est aussi typique des chondrites H. Plusieurs rapports de la chute indiquent que le bolide Dresden aurait été limité à une projection terrestre de l'azimuth de ~050. Le bolide a passé au nord de London, Ontario et a poursuivi une direction sudouest. Selon le groupement serré du champ d'éparpillement des fragments récupérés à environ 10 km au sudouest de Dresden, Ontario, une trajectoire raide semble indiquée. Plus particulièrement les simulations de vols en noirceur utilisant l'azimuth 050, avec une pente raide d'entrée dépassant 70 degrés, reproduisent le mieux la distribution du champ d'éparpillement des fragments recouverts. La gamme d'orbites potentielles provenant de cette trajectoire raide est consistante avec les autres orbites mesurées de bolides de météorites. Ceci fait croire que le météorite Dresden avait une orbite de type astéroïdale Apollo, avec périhélion juste à l'intérieur de celle de la Terre et une inclinaison faible à modérée. Le chondrite Dresden (Ontario) H6 est donc semblable dynamiquement et pétrologiquement aux autres chondrites H avec orbites connues. Une comparaison d'orbites de chondrites H mesurées à l'aide d'instruments avec une distribution modelisée d'objets proches de la Terre indique que les chondrites H ont plus probablement été déposées sur la Terre par les résonances v6 et 3:1. Ceci met nettement en valuer leurs liens avec les astéroïdes de type S Hebe 6, tel que suggéré par Gaffey *et al.* (1993).

Keywords: Dresden (Ontario) meteorite, H6 chondrite, density, porosity, bulk chemistry, fireball trajectory, near-Earth objects, 6 Hebe

1. Introduction

A spectacular fireball, resulting in the fall of the Dresden (Ontario) H6 chondrite, occurred on the evening of July 11, 1939. It was seen from a wide area of southern Ontario and the northeastern United States (Colgrove, 1939). During the following days several fragments of the meteorite totalling ~48 kg were recovered ~10 km southwest of Dresden, Ontario by local residents and passers-by. Other museums and private collections account for the remainder (see Appendix in Plotkin, 2006). All of the known fragments were collected shortly after the fall and have a characteristic well-preserved black fusion crust (Fig. 1).

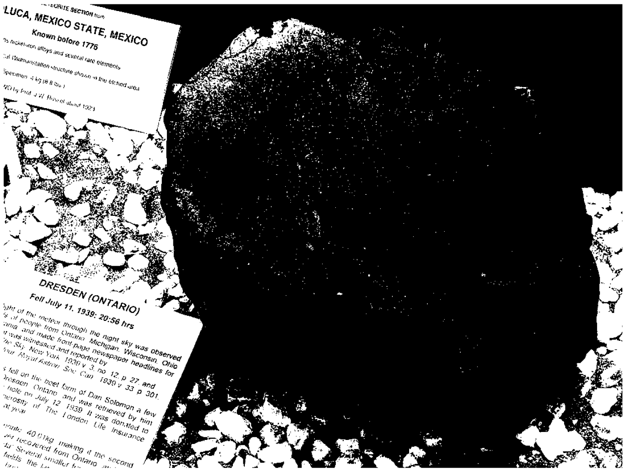

Figure 1 — The Dresden (Ontario) 40.01 kg main mass, with cut face displayed. The meteorite's dark fusion crust is ~1 mm thick and well-preserved. Internal brecciation is clearly visible, defined by dark hairline fractures which envelop centimetre- to decimetre-size chondritic clasts. Width of the cut surface is 32 cm.

The fall was documented by Colgrove (1939), Pleva and Colgrove (1939), and Millman (1940), but an anticipated mineralogical follow-up never materialized. Dresden (Ontario) has languished relatively unstudied for six decades. It appears in meteorite catalogues (*e.g.* Grady, 2000), and is featured together with many other chondrites in synoptic surveys of olivine composition (Mason, 1963), rare-gas measurements for cosmic-ray exposure (CRE) ages (Graf and Marti, 1995), and abundance and isotopic composition of boron (Zhai and Shaw, 1994). Two undergraduate B.Sc. honours theses (Rhodes, 1975; Sibbick, 1986) at the University of Western Ontario have been written on Dresden (Ontario), featuring petrographic analyses of samples from the main mass along with measurements of elemental abundances for selected olivine and pyroxene grains and for chondrules.

In this contribution we present new observations on the mineralogy, bulk chemistry, and bulk-material properties of the meteorite, to update the basis for its H6 chondrite classification. We also attempt to constrain the Dresden meteoroid trajectory and its range of most-likely pre-atmospheric orbits based on reported visual accounts of the event and the strewnfield mass distribution. Finally, we compare the handful of known H-chondrite orbits with a modelled debiased distribution of near-Earth objects (Bottke *et al.* 2002) to assess more generally the relationship of the H chondrites with possible source regions in the main belt of asteroids.

2. Dresden (Ontario): the meteorite

The Dresden (Ontario) meteorite is not widely distributed: approximately 90 percent of the recovered mass from the fall resides with the main mass at the University of Western Ontario, with smaller fragments in the Canadian National Collection (Ottawa), and with the Royal Ontario Museum (Toronto). Other museums and private collections account for the remainder (see Appendix in Plotkin 2006). All of the known fragments were collected shortly after the fall and have a characteristic well-preserved black fusion crust, even on recently rediscovered fragments (Fig. 1).

2.1 Specimen appearance

An 1885-g sample in the Canadian National Collection at the Geological Survey of Canada (sample 0408.002) displays faces varying from rounded (gently convex) to uneven, with numerous shallow imprints 0.5 to 4 cm in diameter. In a few small areas the otherwise-intact black fusion crust has been abraded sufficiently to reveal abundant metal grains, each no more than 1 mm in size. The crust is quite typical for an ordinary chondrite, with no prominent flow lines. The crust is locally granular, presumably where it has flowed over and around hackly, protruding metal grains. Sample 11870 in the Royal Ontario Museum collection, mass 1814 g, reveals a brecciated internal texture with light and dark silicate-dominated clasts (maximum dimensions 0.5-10 cm). Metal grains are mostly <1 mm in size. Similar features were found in the previously unknown 252 g "Cumming" fragment (Plotkin, 2006).

2.2. Sample preparation and bulk properties

The Dresden (Ontario) main mass at the University of Western Ontario was sampled in 1973 with a 2.0-cm diameter coring device (Rhodes, 1975), producing three cores that penetrated to the centre of the meteorite (core samples 7612-101, -102, and -103). Two polished sections were available, one each from 7612-101 and -103, and these were gently re-buffed for the present study. Two additional polished specimens (a third thin section and a thin, but still opaque, slice in a 25-mm mount) were prepared from 7612-102, and a portion of this sample was reserved for bulk chemical work. The polished surfaces examined in this study total 8.8 cm^2 (in transmitted light) to 11.9 cm^2 (in reflected light).

Samples 7612-101 and -102 were measured with digital micrometer and laboratory balance, their cylindrical form allowing for a ready estimation of bulk density. Sample 7612-101 weighed 15.700 g, volume 4.593 cm^3 (density 3.418 g/cm^3); 7612-102 weighed 21.632 g, volume 6.263 cm^3 (density 3.454 g/cm^3), for an overall estimated bulk density of 3.44 g/cm^3. Bulk density for a 157-g "McKim" fragment was measured directly via the Archimedean method using a "liquid" of 40-μm glass beads (method of Consolmagno and Britt, 1998) in a repeatable fashion. We obtain a density of 3.48 ± 0.07 g/cm^3, in good agreement with the estimated bulk density from the other two samples. A helium-gas Quantachome Multipycnometer was used to determine the grain density, and hence the porosity of sample 7612-103: the grain density is 3.66 ± 0.10 g/cm^3, yielding a porosity of 4.9% for the meteorite.

Most stony meteorites have densities in the range 3-4 g/cm^3, with lower values for carbonaceous meteorites and higher densities for stony irons. In a review of 265 pieces of 157 H chondrites, measured densities vary from 2.80 to 3.80 g/cm^3, with a mean of 3.40±0.18 g/cm^3, and the average porosity for H chondrites is 6.4±4.2 % (1σ, Britt and Consolmagno, 2003). Dresden (Ontario) is therefore quite typical of H-chondrite density and porosity.

2.3. Dresden (Ontario) mineralogy and textures

The Dresden (Ontario) meteorite is an ordinary chondrite with abundant visible metal, poorly defined chondrule margins, minor coarse feldspar in the matrix, and an apparent absence of glass. These petrographic features suggest significant metamorphism of an H chondrite and are the hallmarks of the highest petrologic grade, H6. The visually estimated mineralogy for four samples, in area (volume) percent includes 12% metal (Ni-Fe alloys kamacite and taenite), 7% troilite (FeS), 3% coarse olivine crystals, 14% moderately to rather ill-defined chondrules, accessory chromite, 1% feldspar, minor secondary Fe oxide, and a granular, silicate-dominated matrix (63%) of grain size <0.1 mm, in which are dispersed angular masses of metal, troilite, and smaller grains of chromite.

The coarse olivine grains are generally subhedral, angular, unstrained, and up to 1 mm in maximum dimension. As is typical of H chondrites, Dresden (Ontario) has magnesium-rich olivine of Fa20 composition (Mason, 1963 and Rhodes, 1975; Fa19 based on two analyses in Sibbick, 1986). Matrix pyroxene is low-calcium orthopyroxene ($Of_{17}En_{82}Wo_1$) based on the recalculated mean of electron-microprobe analyses of four grains; Sibbick, 1986), a form of pyroxene typical for H6 chondrites. Plagioclase feldspar is found throughout the matrix as interstitial-unstrained to slightly strained grains that are often albite-twinned and as large as 0.1 to 0.4 mm. Rhodes (1975) used X-ray diffraction to obtain a sodium-rich plagioclase composition of $Ab_{86}Or_{14}$. Chondrules are mostly 0.2-2.0 mm in diameter, and exhibit five common morphological types (porphyritic olivine, excentroradial pyroxene, orthopyroxene, and fine-grained and barred olivine chondrules; Hutchison 2004).

The overall order of formation of the opaque minerals is first chromite, then metals, then troilite. The chromite is generally well-formed and fine-grained, at 0.08-0.10 mm in diameter. The metal alloy kamacite forms embayed grains <1 mm in diameter, and thin veinlets typically 0.2-0.3 mm wide. Taenite metal occurs as an accessory phase, forming thin lamellae and small granules in both disseminated and veinlet kamacite. The sulphide troilite occurs as a dusting of minute (1-5 μm) blebs in some chondrules, and as larger anhedral masses up to 200-400 μm in the matrix. Some coarser sulphides exhibit polygonal domains consistent with recrystallization.

Despite the presence of minor hairline veinlets infilled by metal (Figs. 2, 3), the small compass of the polished samples provides little evidence for the brecciation seen in larger pieces of the stone (Fig. 1). Troilite occasionally penetrates fractures in silicate chondrules (Fig. 4). The shock state is assigned as S2, as olivine is generally unstrained, plagioclase only locally strained, and the metal veinlets are of restricted occurrence (see Stoffler *et al.* 1991). Many ordinary chondrites are breccias, and Dresden (Ontario) is no exception, hence it remains possible that sections from other parts of the mass would reveal higher degrees of shock.

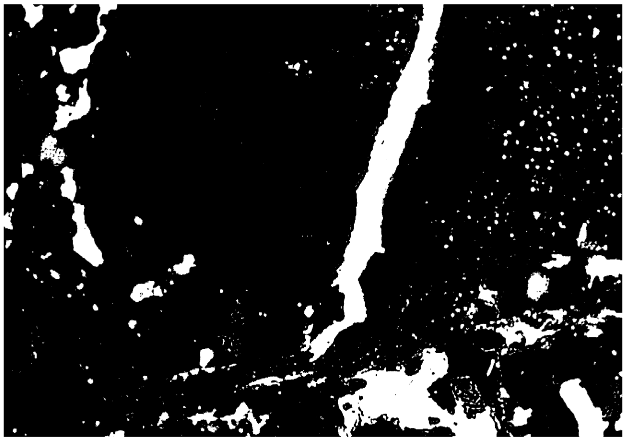

Figure 3 — A veinlet of kamacite, cutting the margin of a very-fine-grained chondrule, which lies adjacent to a pyroxene chondrule speckled by tiny troilite blebs (top right), is itself truncated and offset by a later fracture that contains traces of metal and troilite. Metal, sulphide, and chromite are all visible in the fine granular groundmass of the chondrules (*e.g.* left margin). Photomicrograph in plane-polarized reflected light, long-axis diameter of field of view *ca.* 1.4 mm. Section 7612-102, D-4.

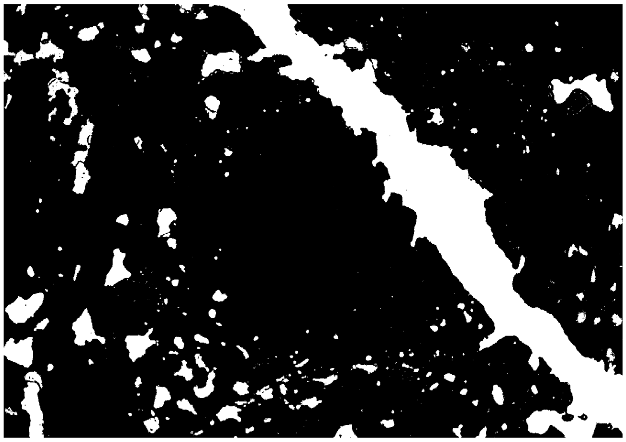

Figure 2 — A veinlet of kamacite traverses the fine-grained, sulphide- and metal-flecked groundmass of the meteorite, skirting a barred olivine chondrule. Photomicrograph in plane-polarized reflected light, long-axis diameter of field of view *ca.* 1.4 mm. Section 7612-102, D-4.

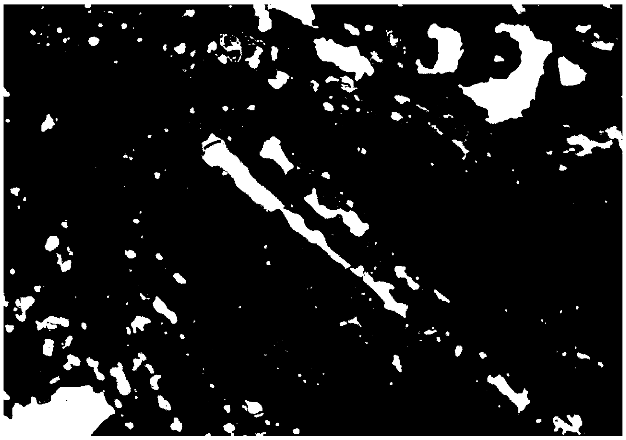

Fig. 4. A barred chondrule invaded by troilite parallel to the bladed fabric (most probably olivine crystallites with interstitial planes of devitrified glass). Coarser kamacite and fine-grained troilite and chromite are visible in the groundmass. Photomicrograph in plane-polarized reflected light, long-axis diameter of field of view *ca.* 1.4 mm. Section 7612-101, D-2.

2.4. Bulk chemistry

Analytical work by Activation Laboratories was conducted with an 11.63-g slice of core 7612-102. The procedures were as follows: 1) The sample was pulverized with agate pestle and mortar; 2) The abundances of major and trace elements were determined by inductively-coupled plasma atomic-emission spectroscopy and mass spectrometry (ICPAES, ICPMS) and instrumental neutron-activation analysis (INAA); 3) FeO was determined separately by titration; 4) The high Ni content was assayed separately; 5) A separate digestion was employed with the ICP analyses to ensure quantitative recovery of chalcophile elements. The largest uncertainty concerns the treatment of iron which, in contrast to most terrestrial rocks, is present in three valence states (Fe^{2+}, Fe^{3+}, and as metallic Fe). Measured elemental abundances are presented in Table 1.

Dresden (Ontario) is of impressively "average" chondritic composition. The INAA result of 28% total Fe agrees well with the estimated H-chondrite mean of 27.5% preferred by Hutchison (2004, p.29). The bulk atomic Mg/Si ratio is 0.858, indistinguishable from a mean value of 0.857 for H, L, and LL chondrites (Berczi and Lukacs, 2003). The total REE (all 14 stable rare-earth elements) content is 3.136 ppm; the chondrite-normalized ratio of representative light and heavy REE, $(La/Yb)_N = 1.07$ (calculated from the values of Anders and Grevesse 1989). Most other abundances agree extremely well with H-chondrite averages, the only significant deviation being the surprisingly low assay for S. Discrepancies may be due in part to the observed metal veinlets and otherwise uneven distribution of metal and sulphide. The measured S/Se ratio is 600, which is low relative to a global average for chondrite (including carbonaceous chondrite) falls of 2500±270 (Dreibus *et al.* 1995). Dresden contains 0.61 ppm Ir (1.27 × chondritic) and 0.297 ppm Au (2.14 × chondritic). Measured boron abundance from the Dresden (Ontario) fragment at the Geological Survey of Canada is 1.13 ppm (Zhai & Shaw 1994), somewhat higher than that found in other H chondrites.

2.5. Dresden (Ontario) classification and context

Taken together, the petrographic observations, bulk elemental abundances, and previously reported compositions of major silicate phases all indicate that the Dresden (Ontario) meteorite is best classified as an H6 [S2] chondrite.

H chondrites are the most "ordinary" of ordinary chondrites, comprising nearly half of the ordinary chondrites and 30.9% of all known meteorites (6962 H chondrites/22507 known meteorites as of December 1999; Grady, 2000). The H chondrites are so named because they are chondrule-bearing meteorites that are "high" in free Fe-Ni metal content (*cf.* Van Schmus & Wood 1967), as opposed to "low" metal (L) and "very low" metal (LL) chondrites. The petrologic grades for H chondrites (ranging from H3 to H6) indicate increasing degrees of thermal metamorphism, with the majority of H chondrites being of the highly metamorphosed grades H5 or H6. Dresden (Ontario) is thus not an exceptional meteorite, but it is nevertheless a significant mass representative of H6 chondrite material that stems from an observed fall.

In one scenario, the H chondrites are thought to represent a parent body of >200-km diameter that underwent internal heating shortly after its formation in the early Solar System, thus creating an "onion-skin" body whose volume was mostly occupied by H6 and H5 chondritic material covered by a thin, less-altered veneer of H4 and H3 chondrites (Binzel *et al.* 1991). Subsequent collisional disruption of this parent body (or bodies) would have made H chondrite of all types available to subsequent collisional ejection even if reassembled into a "rubble pile" of debris, thus accounting for the predominance of the H5 and H6 types among the H chondrites (Gaffey & Gilbert 1998).

If the H chondrites are derived from a particular parent body and delivered to the Earth by some dynamical mechanism(s), then

TABLE 1. BULK CHEMISTRY OF DRESDEN (ONTARIO) H6 CHONDRITE.

Oxide/element (wt.%)	*Dresden*	*H chondrite mean*
SiO_2	35.96	36.15
TiO_2	0.09	0.10
Al_2O_3	1.96	2.14
Cr_2O_3	0.53	0.53
Fetotal	28.00	27.50
MnO	0.26	0.30
MgO	23.92	23.21
CaO	1.68	1.75
Na_2O	0.82	0.86
K_2O	0.08	0.09
P_2O_5	0.24	0.25
Ni	1.90	1.60
Co	0.10	0.08
S	0.46	2.00
Total 1	96.00	96.56
Fe^0	16.80	16.50
$FeO+Fe_2O_3$ as FeO	14.41	14.15
Total 2	99.21	99.71

Analysis of an 11.63-g slice from Dresden sample 7612-102. Mean H-chondrite values are recalculated from Hutchison (2004, p.29). Total 1 is low because O in FeO and lesser Fe_2O_3 is not assigned (there may also be minor losses on ignition due to H_2O in secondary oxyhydroxides, "limonite," plus traces of C). Total 2: content of Fe^0 (Fe in alloy) is estimated as a group average of 60% of the INAA value for total Fe (Hutchison, 2004), and the balance recalculated as FeO (data from Wilson 2004; Activation Laboratories Report A04-0148; FeO and Fe_2O_3 were assayed at 28.24 and 10.02% respectively). Below: selected minor and trace element values (in ppm by weight).

Cr	3600
Co	980
Ni	18990
Cu	89
Zn	111
Ga	7
Ge	11.1
Ba	10
Se	8
Ag	2.7
La	0.31
Ce	0.78
Yb	0.20
Ir	0.610
Au	0.297

it is useful to assess the fireball trajectories of H chondrites so as to constrain the dynamical method of delivery, and possibly identify the source region and parent body for the H chondrites. There are only a few H-chondrite falls with well-constrained, instrumentally measured orbits (Borovicka *et al.* 2003). In the next section we estimate the Dresden fireball trajectory from published eyewitness accounts and constrain the range of possible orbits of the Dresden meteoroid, for comparison with those H chondrites with known orbits.

3. Dresden (Ontario):
FIREBALL TRAJECTORY AND POSSIBLE ORBIT

The fireball associated with the Dresden meteorite fall was witnessed over a wide area of southern Ontario and the northeastern United States (Fig 5a). However, only a few eyewitness accounts are available in the literature with directional information that might help establish the orientation of the fireball path in the atmosphere. As such, the Dresden fireball trajectory cannot be constrained as accurately as has been done for widely seen and instrumentally observed events (*e.g.* Brown *et al.* 1994). Nevertheless the published eyewitness reports for the Dresden event do offer some key constraints upon its possible trajectory.

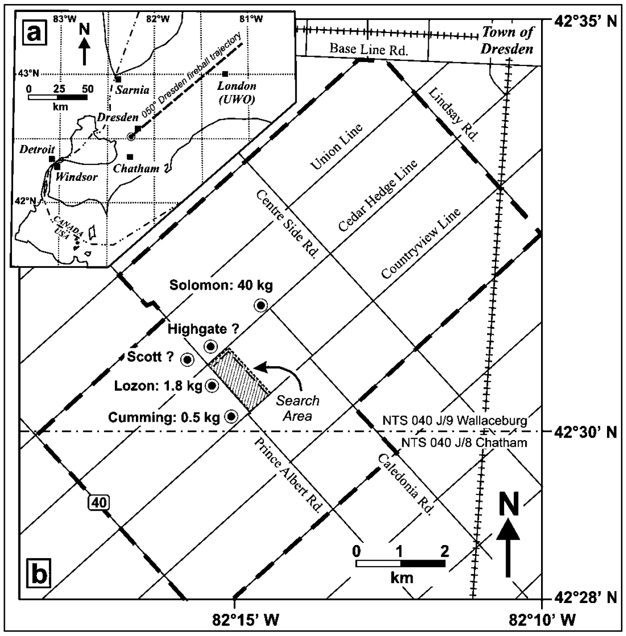

FIGURE 5 a — Inferred ground projection of the July 12, 1939 Dresden fireball over southwestern Ontario. The fireball was observed to pass to the north of London, and headed southwest where it produced meteorites near Dresden, Ontario; b) Inset map of the Dresden (Ontario) strewnfield of the recovered known fragments and their masses. Names with "?" indicate possible small finds that are unconfirmed (Plotkin, 2006). The close proximity of large and small fragment masses suggests a steep entry angle for the meteorite-producing fireball.

3.1 Fireball observations and estimated radiant azimuth

Several eyewitnesses from Wallaceburg (about 10 km northwest from the fall location) reported the fireball as moving to the southeast. Other observers reported the fireball as "laying to the east" of Chatham and Wallaceburg. It was also reported that the fireball left "...a rather short trail of light in the sky" (*Chatham Daily News,* July 12, 1939). Given that the meteorite fall occurred slightly south and east of Wallaceburg, this suggests the fireball azimuth had to be such that the fireball was moving generally from the north to the south. This is further confirmed by the observations of J. Ultviugt of Chatham (almost due south of the meteorite fall location), who states that:

> "From where I was standing the meteor streaked across the constellation of Ursa Major. Sitting on the lawn facing SSW, I was not looking at the exact spot where the celestial wanderer appeared...the bright flash...came from the direction of the setting sun."

The centre of Ursa Major at the time of the fireball (20:45 EDT, July 11, 1939) was at an azimuth of 310° and an altitude of 60° as seen by the observer in Chatham. The sun had set 30 minutes earlier at an azimuth of 302°, consistent with his description. This observation would appear to further rule out a trajectory from the south.

By far the most detailed report, however, is that from W.G. Colgrove, then President of the London Centre of the Royal Astronomical Society of Canada. He observed the fireball from the campus of the University of Western Ontario and describes it as follows (Colgrove, 1939):

> "On the evening of July 11 (1939) at 8:45 [p.m.] a few of us were standing on the upper campus of the University of Western Ontario at London watching the first stars appear when suddenly a great flare from the north-east lighted up the lawns and trees all around us. It was the passing of an unusually bright meteor which immediately exploded high in the air and somewhat behind us and then, shooting a little to the north overhead, whizzed toward the south-west leaving a trail of bluish-green light about 5° wide and extending from north of Vega to near Spica. [...] The main feature lasted only about four seconds, but it was the grandest moving sky picture I have seen since the great comet of 1882."

Colgrove's description establishes that the ground projection of the path went nearly overhead (just to the north) of the UWO campus, moving to the southwest, or from right to left as seen from UWO. Vega at the time of observation was at an altitude of 55° and at an azimuth of 079°. Between Vega and Polaris at this time (still in heavy twilight), only the dim stars of the head of Draco were present, so we may assume the trail began near 50-60° elevation and at an azimuth north of Vega, at an approximate azimuth near ~040°. Spica at this time lay to the southwest (217 azimuth) at an altitude of 29°. Assuming that the trail began near an azimuth of 040° and an elevation of 60°, the approximate lower limit for the maximum elevation (given the other uncertainties in the account) is ~70°. For reasonable first heights of visibility (near 80 km; *cf.* Ceplecha *et al.* 1998), the path was no more than 30 km north of the viewing location, and probably closer. The resulting azimuth for the radiant (using the meteorite recovery location as the other fiducial point along the ground projection of the path) is ~050°, with a line connecting UWO and the fall location giving an azimuth of 054.7°. We thus assume from Colgrove's observation at UWO that the fireball radiant azimuth is constrained to be ~050° and no greater than 054.7°. The short-trail observation at Wallaceburg is also consistent with a 050 azimuth, because such an azimuth would have produced a foreshortened view of the fireball trajectory as seen from Wallaceburg.

The distance between UWO and the fall location is nearly 100 km, so assuming a height at UWO near 80 km, an approximate entry angle of ~40° is obtained. Colgrove (1939) concluded his description of the event by noting that his compilation of other Dresden fall reports (which are not available to us) suggested a trajectory from the northeast towards the southwest, consistent with our path.

3.2 Fireball entry angle

The 050 azimuth determined from the Dresden eyewitness accounts is clearly more reliable than the entry angle, a pattern similar to that found for other fireball events (*cf.* Brown *et al.* 1996). To further refine the entry angle we examine the fall distribution of meteorites recovered on the ground. Figure 5b shows the strewnfield immediately to the southwest of Dresden, giving the locations of recovered fragments and their known masses. Most notably, the smaller fragments lay to the south and south-west of the main (Solomon) 40-kg mass, opposite to the distribution expected for a fireball approaching from the northeast. The most massive fragments are less affected by atmospheric drag, having the smallest surface-area-to-mass ratios, and so usually move further downrange than smaller specimens (Ceplecha *et al.* 1998).

However, two additional observations may explain this puzzling fragment distribution: The smallest fragment (0.5 kg) is located only 2 km to the southwest of the large (40 kg) main mass, a very small ground distance between two fragments of such different masses. As an example, the 1994 St. Robert (Quebec) meteorite fall had a similar spread in surface-area-to-mass ratios across a distance of 8 km with a fireball entry angle of 60° (Brown *et al.* 1996). In addition, all recovered Dresden fragments have well-developed fusion crusts, indicating that the fragmentation event(s) to produce the strewnfield must have occurred before or during ablation in the upper atmosphere, and not close to the ground. The small extent of the ground ellipse for the Dresden fall thus suggests a very steep entry angle.

To switch the mass-sorting order along the ellipse (assuming our 050 trajectory azimuth result is robust), the winds in the upper atmosphere need to have had a significant tail-wind component along the trajectory path. A strong tail wind in combination with a steep trajectory makes it possible for smaller fragments to be "blown" downrange of larger fragments, as has been encountered before with the Johnstown, Colorado and Holbrook, Arizona falls (Nininger, 1963).

A numerical simulation of "darkflight" paths in the atmosphere was performed for fragments from the Dresden fall after ablation ceased (procedure of Brown *et al.* 1996). The winds in the upper atmosphere are unknown at the time of the fall, but in the summer months at this latitude, tropospheric winds are generally from the west or northwest (Beer, 1974). The average winds observed for July 11 over the years 1992-2005 at the fall location are generally from azimuth 300° from ground-level to 30-km altitude and have peak tropospheric speeds near 30 m/s at 12 km altitude. Darkflight runs including masses of 40 kg, 2 kg and 0.5 kg were performed for ejection heights of 25 and 15 km (defined as the height at which the fireball velocity falls below 4 km/s) and for a range of zenith angles. Using our estimated azimuth of ~050° and entry angles from overhead to 30° from the horizontal, it is apparent that the azimuth-300 crosswind would move smaller fragments to the southeast of the main mass, but not further along the trajectory. At entry angles shallower than 60°, the smallest-to-largest observed fragment separations were >6 km, at least three times that observed from the Dresden strewnfield. Entry angles of ~30° produce fragment separations of >10 km.

The closest fit to the Dresden strewnfield observations is found by assuming a tropospheric wind direction of ~040°, producing a ~30 m/s tailwind relative to the 050 fireball trajectory. In this manner, a near-vertical entry angle allowed the smallest fragment (0.5 kg) to travel 1.8 km further downrange of the largest fragment (40 kg), due to the tailwind. Entry angles of less than 75° result in the larger fragment moving further downrange than the smaller mass. We are thus led to conclude that the entry angle for the fireball was very steep, potentially >70°, suggesting that at the time of the first fireball observation by Colgrove it was encountering atmosphere at >80 km or that the upper atmosphere tail-wind may have been unusually strong, permitting a slightly less-steep entry angle.

3.3 Possible Dresden heliocentric orbit

As noted above, the fireball azimuth is the best-determined parameter from the few observations, and the interpreted steep entry angle requires an additional but reasonable assumption that the tight strewnfield mass distribution rules out a shallow fireball trajectory. The final and least-constrained parameter required to calculate a possible orbit for the Dresden meteoroid is its entry velocity. The possible heliocentric orbit for Dresden assuming a fireball azimuth of 050° and an entry angle of 85°, 75°, or 65° is shown for a range of entry velocities in Table 2.

The steep entry angle of the fireball and its arrival in the early evening, local time, together provide a good constraint on the perihelion distance *(q)* of the Dresden meteoroid orbit. Perihelion is the most robustly determined feature of the estimated orbit for Dresden because the fall geometry is largely insensitive to entry velocity (possible q in Table 2 has a narrow range from 0.96028 to 1.0145 astronomical units for reasonable entry velocities). The unknown entry velocity mostly affects the estimated orbital eccentricity *(e)* and semi-major axis, which for low entry velocities of ~12 km/s is closer to circular with a perihelion (Q) just slightly greater than 1 AU, and for higher velocities becomes more eccentric with perihelia well beyond Jupiter (Table 2).

Entry velocity is dynamically constrained to be less than 21 km/s for Dresden to have had an asteroidal-like orbit (with a Tisserand parameter >3; *cf.* Bottke *et al.* 2002) and to be consistent with the expectation that meteorites could be produced (*cf.* Wetherill & ReVelle 1981). For steep trajectories the entry velocity maximum cut-off is even lower, close to 18 km/s.

The range of potential orbits are consistent with previous orbits measured for meteorite-producing fireballs (Borovicka *et al.* 2003), and suggest that the Dresden meteoroid encountered the Earth pre-perihelion at the descending node of its Apollo asteroid-type orbit. The Dresden orbit most likely had a

TABLE 2. REPRESENTATIVE POSSIBLE ORBITS FOR THE DRESDEN (ONTARIO) METEORITE.

Fall location: 42.5 deg N; 82.25 deg W (Fig. 5). Symbols are: *alt* altitude of the radiant (in°), *azm* azimuth of the radiant, best estimated as 050, *vel* is entry velocity in km/s, *RA* and *Dec* are the apparent right ascension and declination of the radiant, *a* is the semi-major axis in AU, *e* is the eccentricity, *i* is the inclination of the orbit, ω is the argument of perihelion, Ω is the longitude of the ascending node, *Q* is the aphelion distance in AU, *q* is the perihelion distance, and *T* is the Tisserand parameter.

alt	*Azm*	*vel*	*RA*	*Dec*	*a*	*e*	*i*	ω	Ω	*Q*	*q*	*T*
85	50	12	241.5	47.1	1.18	0.141	8.1	190	109.678	1.35	1.01453	5.3
85	50	13	240.6	46.7	1.32	0.232	11.2	189	109.678	1.63	1.01422	4.9
85	50	14	240.1	46.5	1.48	0.314	13.5	188	109.678	1.94	1.01399	4.5
85	50	15	239.8	46.3	1.67	0.393	15.4	188	109.678	2.33	1.01380	4.1
85	50	16	239.6	46.2	1.92	0.471	17.1	188	109.678	2.82	1.01364	3.7
85	50	17	239.4	46.1	2.25	0.549	18.7	188	109.678	3.48	1.01349	3.4
85	50	18	239.3	46.1	2.72	0.628	20.0	187	109.678	4.43	1.01336	3
85	50	19	239.1	46.0	3.46	0.707	21.3	187	109.678	5.90	1.01324	2.6
85	50	20	239.1	46.0	4.77	0.788	22.5	187	109.678	8.53	1.01312	2.2
85	50	21	239.0	45.9	7.79	0.870	23.6	187	109.678	14.58	1.01302	1.8

alt	*Azm*	*vel*	*RA*	*Dec*	*a*	*e*	*i*	ω	Ω	*Q*	*q*	*T*
75	50	12	261	53.4	1.09	0.071	9	207	109.678	1.16	1.00922	5.7
75	50	13	258.1	52.7	1.17	0.137	12.5	199	109.678	1.33	1.00967	5.4
75	50	14	256.5	52.4	1.26	0.201	15.1	196	109.678	1.52	1.00969	5
75	50	15	255.5	52.1	1.37	0.265	17.4	195	109.678	1.74	1.00961	4.7
75	50	16	254.7	51.9	1.5	0.328	19.3	194	109.678	2	1.0095	4.4
75	50	17	254.2	51.7	1.66	0.393	21.1	193	109.678	2.31	1.00938	4.1
75	50	18	253.8	51.6	1.86	0.458	22.7	192	109.678	2.72	1.00925	3.8
75	50	19	253.4	51.5	2.12	0.525	24.2	192	109.678	3.24	1.00912	3.4
75	50	20	253.2	51.4	2.48	0.593	25.6	191	109.678	3.95	1.009	3.1
75	50	21	252.9	51.4	3	0.663	26.9	191	109.678	4.98	1.00888	2.7

alt	*Azm*	*vel*	*RA*	*Dec*	*a*	*e*	*i*	ω	Ω	*Q*	*q*	*T*
65	50	12	285.2	55.6	1	0.041	9.3	295	109.678	1.04	0.96028	6.1
65	50	13	279.7	55.5	1.04	0.057	13.3	245	109.678	1.1	0.98524	5.9
65	50	14	276.7	55.4	1.1	0.094	16.3	223	109.678	1.2	0.99332	5.6
65	50	15	274.7	55.3	1.16	0.137	18.9	213	109.678	1.31	0.99652	5.4
65	50	16	273.3	55.1	1.22	0.184	21.1	208	109.678	1.45	0.99812	5.1
65	50	17	272.3	55.1	1.3	0.233	23.2	205	109.678	1.61	0.99904	4.9
65	50	18	271.5	55	1.4	0.284	25.1	202	109.678	1.79	0.99961	4.6
65	50	19	270.9	54.9	1.51	0.337	26.8	201	109.678	2.02	0.99999	4.4
65	50	20	270.3	54.8	1.64	0.392	28.5	199	109.678	2.29	1.00024	4.1
65	50	21	269.9	54.8	1.81	0.448	30	198	109.678	2.63	1.00041	3.8

perihelion just inside that of the Earth's and had a low to moderate inclination.

4. ORIGIN OF THE DRESDEN (ONTARIO) H6 CHONDRITE

The Dresden (Ontario) meteorite is an H6 [S2] chondrite, an exemplary representative of the H-chondrite group. It was collected immediately after its arrival and remains available in several research collections for further study (Plotkin 2006). Based on the limited reported observations of the 1939 fall, a range of possible orbits has been estimated for the Dresden meteoroid. In this section we consider the possibilities for the origin of the Dresden (Ontario) meteorite and for other H chondrites.

In the past 20 years significant advances have been made in exploring the linkages between types of meteorites and with their possible parent bodies in the Solar System (McSween 1999). Attempts to link meteorite classes with possible parent bodies in the Solar System can be made by matching the measured spectral reflectance of asteroidal (and other) bodies with those properties in the meteorites (Gaffey *et al.* 1993), and by dynamical modelling of the delivery of meteoritic material from different regions and source bodies in the inner Solar System (Farinella *et al.* 1993; Gladman *et al.* 1997).

The major planets (primarily Jupiter) largely control the orbital distribution of the main-belt asteroids through gravitational perturbations, producing regions in orbital element *(a,e,i)* space that are either swept virtually clean or show concentrations of asteroids due to resonant interactions with the major planets (Nesvorny *et al.* 2002). In addition, recent work (Gladman *et al.* 1997; Vokrouhlický & Farinella 2000)

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suggests that the orbits of sub-metre to km-size bodies within the main belt can undergo slow diffusion over some millions of years via non-gravitational effects (*e.g.* the Yarkovsky force) until such a dynamical "escape-hatch," like the 3:1 mean-motion resonance with Jupiter, is encountered. Transfer to an Earth-crossing orbit due to gravitational perturbations is then relatively rapid, and the average lifetime of these objects in Earth-crossing orbits is 2 to 7 million years (Gladman *et al.* 1997; Bottke e*t al.* 2002).

Using a numerical simulation of transfer rates from the main-belt asteroids, Bottke *et al.* (2002) have derived the probability in *a,e,i* space of transfer from specific dynamical "escape-hatches" for any given Earth-crossing orbit. It may thus be possible to place dynamical constraints upon the tentative linkages of meteorites classes with potential source asteroids by identifying the most likely delivery mechanisms that would produce a population of Earth-crossing meteoroids that match known meteorite orbits.

Ordinary chondrites have been suggested to be related to a subset of S-type asteroids, called S(IV), based on similarities in their reflectance spectra (Gaffey *et al.* 1993). The S(IV) subtype asteroids are concentrated near the 3:1 mean-motion resonance with Jupiter, at 2.5 AU. A prominent member of the S(IV) subtype, asteroid 6 Hebe, has an orbit that is close to both the 3:1 mean-motion resonance and the ν6 secular (orbital-inclination) resonance with Saturn, located near i=15-16 deg for a=2.426 AU (Bottke *et al.* 2002). Asteroid 6 Hebe has been proposed to be the probable parent body of the H chondrites, based on its proximity to both 3:1 and ν6 resonances, and on its similarity with the reflectance spectra of H chondrites (Gaffey and Gilbert, 1998). Modelling of the dispersal of collisional fragments from 6 Hebe indicates that >1 million years after the initial fragment-producing collisional event, the diffusion of fragments into the ν6 resonance is heavily favoured over their migration into the 3:1 mean motion resonance, and that the flux of meteoroids from 6 Hebe to the Earth should therefore be dominated by delivery via the ν6 resonance (Vokrouhlický & Farinella 2000). If 6 Hebe is the parent body for H chondrites, then the known orbits of H chondrites should demonstrate a dynamical affinity for the 3:1 and especially ν6 resonances.

Of the seven known orbits for meteorite-producing fireballs, four of them produced H chondrites (Pribram, Lost City, Peekskill, and Moravka; Borovicka *et al.* 2003). Another H chondrite fall (St. Robert; Brown *et al.* 1996) has a somewhat less-constrained orbit that is nevertheless useful for comparison with the debiased distribution of near-Earth objects (Bottke *et al.* 2002). All five of these H-chondrite known and "most likely" orbits are given in Table 3, along with the possible Dresden orbits from Table 2 with reasonable entry velocities of 14 to 18 km/s. We then apply the numerical simulation of transfer rates from the main-belt asteroids of Bottke *et al.* (2002) to assess the probability in *a,e,i* space of the transfer from specific "escape-hatches" for each of the known or inferred H-chondrite orbits.

For the known H-chondrite orbits in Table 3 the greatest transfer probabilities are typically from the ν6 secular resonance (60-65%, excepting Moravka and Pribram), whereas the 3:1 mean-motion resonance has a relatively low transfer probability (5-17%, excepting Pribram). The orbit for Pribram is distinct from the other H chondrites in *a,e,i* space, and shows a high transfer probability from the 3:1 resonance and a much lower probability from the ν6 resonance (55% and 14%, respectively). Also of note is the significant transfer probability for all H-chondrite orbits from Mars-crossing resonances (MC; 18-32%, and dominantly so for Moravka at 69%), which reflects the possibility for the passage of asteroids related to the H-chondrite complex through orbits having intermediate dynamical interactions with Mars before achieving Earth-crossing status.

The family of Dresden orbits calculated for an 85° entry angle and a range of possible entry velocities has a large transfer probability from the ν6 secular resonance, echoing those for the known orbits of Lost City, Peekskill, and St. Robert (Table 3). Collectively, the calculated H-chondrite orbits given in Table 3 suggest that the ν6 secular resonance may be the dominant "escape hatch" for delivering H chondrites from the main-belt into Earth-crossing orbits.

Pribram's orbit implies that the 3:1 resonance may also be an important delivery mechanism, suggesting that there may be (at least) two dynamically distinct pathways for generating Earth-crossing bodies of H-chondrite composition. The existence of two H-chondrite

TABLE 3. KNOWN H-CHONDRITE ORBITS AND THEIR POSSIBLE SOURCE REGIONS.

Fall	*type*	*a*	*e*	*i*	*Q*	*q*	***OB***	***3:1***	***MC***	**ν6**
Moravka[1]	H5	1.85	0.470	32.2	2.71	0.9823	0	14.1	**68.8**	17.1
Pribram[2]	H5	2.40	0.671	10.48	4.01	0.7894	7.0	**55.1**	24.2	13.8
Lost City[3]	H5	1.66	0.417	12.0	2.35	0.9670	0	8.5	31.4	**60.0**
Peekskill[4]	H6	1.49	0.410	4.9	2.10	0.8860	0	16.8	18.2	**65.0**
St. Robert[5]	H5	1.90	0.480	0.7	2.86	1.0158	9.5	5.3	20.2	**65.0**
Dresden 14	H6	1.48	0.314	13.5	1.94	1.0140	0	11.6	34.2	**54.2**
Dresden 15	H6	1.67	0.393	15.4	2.33	1.0138	0	2.6	38.7	**58.7**
Dresden 16	H6	1.92	0.471	17.1	2.82	1.0136	0	17.1	14.1	**68.8**
Dresden 17	H6	2.25	0.549	18.7	3.48	1.0135	0	29.9	6.1	**64.0**
Dresden 18	H6	2.72	v8	20.0	4.43	1.0134	23.1	**42.8**	17.4	11.4

Symbols are: *Fall* - meteorite fall with calculated orbit and reference, *type*, petrologic type of H chondrite, *a* is the semi-major axis in AU, *e* is the eccentricity, *i* is the inclination of the orbit, *Q* is the aphelion distance in AU, *q* is the perihelion distance. The probability of delivery (in %) to a given H-chondrite orbit from various dynamical regions in the main belt (in bold) are: ***OB*** - outer main belt; ***3:1*** - the 3:1 mean motion resonance with Jupiter; ***MC*** - Mars crossing; **ν6** - the "nu-6" sidereal-motion resonance with Jupiter and Saturn. This work is adapted from Bottke *et al.* (2002). References: [1]Borovicka *et al.* 2003; [2]Ceplecha, 1977; [3]McCrosky *et al.* 1971; [4]Brown *et al.* 1994; [5]Brown *et al.* 1996. Dresden 14 through 18 represent orbital solutions that vary the entry velocity from 14 km/s to 18 km/s for an entry angle of 85°.

populations has been determined on the basis of time-of-day fall statistics and cosmic-ray exposure (CRE) ages (Graf *et al.* 2001). Most H chondrites fall in the afternoon or evening, local time, and exhibit a range of CRE ages with a peak at ~7.6 Ma. A subset of H5 chondrites do not show this prevalence of afternoon falls relative to morning falls, and show a distinct peak of CRE ages at 7.0 Ma as well as greater tritium (^{3}H) loss, indicating that these meteorites may come from the disruption of a distinct "H5" parent body at 7.0 Ma and that they collectively may have had greater exposure to solar heating in orbits with lower perihelia than is experienced by most H chondrites.

From their simulations, Vokrouhlický and Farinella (2000) note that fragments derived from an initial collision-ejection at 6 Hebe typically undergo several further fragmentation events before arriving at Earth. Dynamical considerations are consistent with the idea that the H-chondrite meteorites encountered by the Earth do not come directly from a parent body like 6 Hebe, but were ejected from some intermediate body, possibly already in an Earth-crossing orbit. The existence of distinct H-chondrite populations (Graf *et al.* 2001) also suggests that the Earth is encountering meteoroids from compositionally distinct fragments of the H-chondrite parent body, and not directly from the parent body itself.

Taking 6 Hebe to be the initial source of H chondrites, there would be an expected "background" population of meteoroids that have undergone many collisional events prior to their delivery to the Earth via the ν6 secular resonance (Vokrouhlický & Farinella 2000). In this scenario, these meteoroids would be expected to exhibit a wide range of CRE ages and petrologic types. Punctuating this background H-chondrite meteoroid population could be a subset of H chondrites with a distinct H_5 composition and CRE age that would reflect the recent disruption of a substantial fragment from 6 Hebe. These meteoroids would on the whole have experienced fewer collisional events, and could be delivered by the 3:1 mean-motion resonance, especially if their parent fragment had already encountered the 3:1 resonance prior to its disruption. In the initial million years following ejection directly from 6 Hebe, fragments will encounter the ν6 and 3:1 resonances more or less equally (VVokrouhlický & Farinella 2000), so the injection of a fresh, short-lived stream of H-chondrite meteoroids via the 3:1 mean-motion resonance appears possible.

We emphasize that the transfer probabilities cannot uniquely identify the region in the main belt from which the H chondrites emerged, but taken as a whole they do suggest that the H-chondrite parent asteroid is located near the ν6 and the 3:1 resonances, and that the ν6 resonance may be the dominant delivery mechanism, at least for the handful of H chondrites with known orbits to date. These findings are consistent with the proposition that asteroid 6 Hebe is the probable parent body for the Dresden (Ontario) meteorite and the majority of the H chondrites.

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APPENDIX 1: GLOSSARY OF MINERALOGICAL TERMS

Here is a quick guide to some mineralogical terms commonly applied to meteorites and found in this article: for concise explanations of many more terms, see the glossary in Norton (1994).

Chromite – a common, chromium-rich member of the *spinel* family of cubic oxides, with essential components Fe, Cr, and O, generally with appreciable Mg and Al.

Crystal form – increasingly perfect developments of crystal form may be termed *anhedral* (shapeless) to *subhedral* or *euhedral* (with ideal form, *e.g.* cubes of chromite). Reaction of a crystal with its surroundings may result in corrosion, such that its faces become *embayed.*

Metal – the Ni-Fe alloys most often found in meteorites are *kamacite* and *taenite,* typically with about 5 and 30 weight percent Ni, respectively.

Olivine – a *silicate* mineral with essential Mg and Fe (plus Si and O). The most iron-rich compositions are termed *fayalite.*

Orthopyroxene – a subset of the *pyroxene* silicate family, with orthorhombic symmetry, possessing essential Mg and Fe. *Enstatite* refers to the most magnesium-rich compositions.

Plagioclase – a common silicate of the *feldspar* family, with exchangeable Ca and Na, frequently characterized by repetitive side-by-side stacking of crystals known as "*albite twinning*."

Extra reference:

Norton, O.R. 1994, Rocks from Space: Meteorites and Meteorite Hunters. Mountain Press Publishing Company, Missoula, Montana, 449pp.