Meteoritics & Planetary Science 39, Nr 10, 1733–1740 (2004)
Abstract available online at http://meteoritics.org

Do comets have chondrules and CAIs? Evidence from the Leonid meteors

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(Received 10 June 2003; revision accepted 3 August 2004)

Abstract–Chondrules, silicate spheres typically 0.1 to 1 mm in diameter, are the most abundant constituents in the most common meteorites falling on Earth, the ordinary chondrites. In addition, many primitive meteorites have calcium-aluminum-rich inclusions (CAIs). The question of whether comets have chondrules or CAIs is relevant to understanding what the interior of a comet is like and what a cometary meteorite might be like. In addition, one prominent model for forming chondrules and CAIs, the X-wind model, predicts their presence in comets, while most other models do not. At present, the best way to search for chondrules and CAIs in comets is through meteor showers derived from comets, in particular, the Leonid meteor shower. Evidence potentially could be found in the overall mass distribution of the shower, in chemical analyses of meteors, or in light curves. There is no evidence for a chondrule abundance in the Leonid meteors similar to that found in chondritic meteorites. There is intriguing evidence for chondrule- or CAI-sized objects in a small fraction of the light curves, but further work is required to generate a definitive test.

INTRODUCTION

Virtually all primitive meteorites have the spherical silicate objects known as chondrules. Chondrules are the most common constituent in the most common types of meteorites falling on Earth, the ordinary chondrites (Grossman et al. 1988b). Although there are variations in the size of chondrules from one class of meteorite to another, the size distribution of chondrules within any given meteorite class has a distinct peak, typically at 0.1 to 1 mm diameter (e.g., Grossman et al. 1988b; Rubin 1989; Fig. 1).

Chondrules are mysterious in that, more than a century after the first model of chondrule formation, there is still no agreement on how they formed. Models that have been suggested include lightning, collisions of various sorts, shocks, and solar heating (e.g., Boss 1996; Jones et al. 2000).

In addition, many meteorites contain calcium-aluminum-rich inclusions (CAIs) consisting of the most refractory oxides and silicates that would form from a cooling, high temperature gas (MacPherson et al. 1988). CAIs are not as round as chondrules nor are they as abundant, but they are common, and their sizes are typically comparable to those of chondrules.

The question we pose is: Do chondrules and CAIs exist in comets? There are several reasons for our interest. First, this question is important for understanding what the interior of a comet is like and what a cometary meteorite might be like. The presence or absence of chondrules could be used as a way to identify cometary meteorites. Several decades ago, comets were considered a possible source of many meteorites, along with the Moon and asteroids. We now have convincing evidence of meteorites from Mars, the Moon, and many asteroids. However, there are no meteorites that are generally considered to be cometary. Researchers studying interplanetary dust particles (IDPs) and micrometeorites believe that many of these particles are cometary, based on various assumptions and observations (Bradley et al. 1988; Engrand and Maurette 1998). There are also occasional suggestions that particular meteorites might be cometary. For instance, Botta et al. (2002) and Ehrenfreund et al. (2001) discussed the possibility that CI chondrites could be cometary, based on the fact that the CI chondrites have different amino acid species than other meteorites, but the CI chondrites are completely hydrated, disagreeing with the expected characteristics of "cometary" IDPs. In addition, the cosmic ray and solar flare tracks in single crystals in CI chondrites indicate exposures at heliocentric distances not very different from other chondrites, unlike what would be expected if CIs had formed at larger heliocentric distances.

We reviewed the question of cometary meteorites earlier (Campins and Swindle 1998) and concluded that there are potential sources such as comets with low Earth-encounter

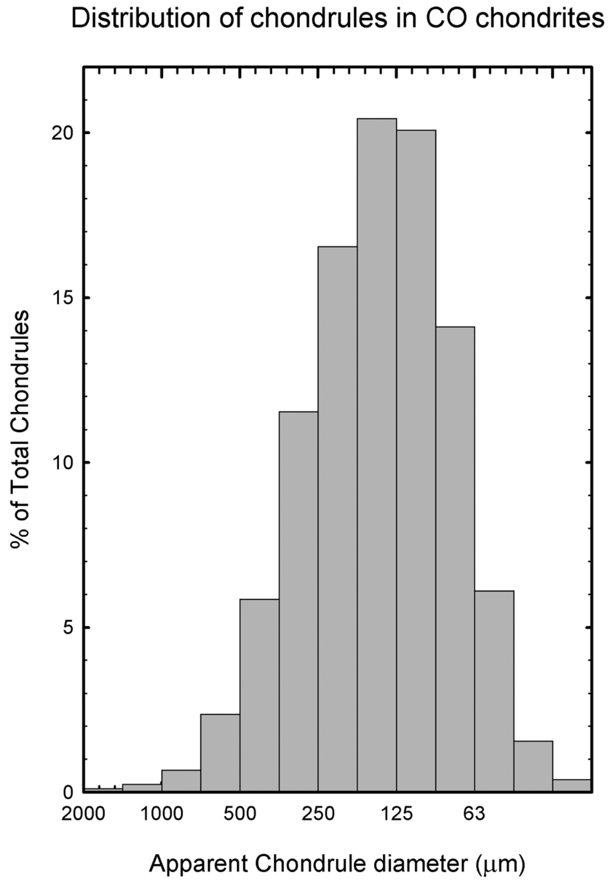

Fig. 1. Size-frequency distribution of 2834 chondrules measured in thin section in 11 CO chondrites by Rubin (1989). The diameters are the maximum apparent diameters (slightly smaller than the true diameters because the thin section may slice a chondrule off-center). Note the strongly peaked size distribution. Chondrules in CO chondrites, with a mean apparent diameter of 148 µm, are the smallest in any of the chondrite groups (Grossman et al. 1988).

velocities that seem to shed coherent pieces that are large enough for some material to survive as meteorites. We attempted to identify the characteristics of cometary meteorites and concluded that they would not have chondrules, since most chondrule formation mechanisms depend on nebular properties such as mass density, number density, or effective solar luminosity (e.g., Boss 1996; Jones et al. 2000), all of which would be expected to fall with distance from the Sun. Hence, we would predict that chondrules (and CAIs) would be less likely to form at the formation distances of comets and, hence, would be less-abundant or absent in comets. Other researchers have also assumed, more or less explicitly, that chondrules are not an important component within comets (e.g., Greenberg 1998; Rietmeijer and Nuth 1998). However, one important recent theory, the X-wind model (Shu et al. 1996, 2001) explicitly predicts that comets do have chondrules.

The X-wind model predicts that chondrules and CAIs are actually formed very close to the Sun (~0.06 AU) but then are entrained in an outflow such as is seen in young stars. Whether a particle is entrained depends on the aerodynamics, which provides a method of size sorting. Millimeter-sized objects are the ones most likely to be entrained in such a wind but then dropped farther out in the solar nebula (Shu et al. 1996). This model seems to satisfy the astronomical observations and theoretical predictions of low temperatures in the nebular disk while also satisfying the meteoritical observation of the abundant presence of chondrules in material from the Main Asteroid Belt (2–3 AU). The model has become quite prominent. Since the beginning of 2001, the model has been referenced in more than 25 articles in *Meteoritics & Planetary Science.* Hence, a second reason to ask whether comets have chondrules and CAIs is to test the X-wind model.

OBSERVATIONAL TESTS OF WHETHER COMETS HAVE CHONDRULES

It is not immediately obvious how to search for chondrules and CAIs in comets. Although there have been suggestions from time to time, we do not have any meteorites that are generally accepted as cometary.

Some interplanetary dust particles are probably cometary, and there is some agreement on which ones those might be, based on observations of the heating caused by atmospheric entry coupled with models of the entry velocities of objects coming from various types of comets and asteroids (Flynn 1989, 1990; Sandford 1986; Sandford and Bradley 1989). However, these arguments are not definitive for any single object. In any case, a cometary chondrule would probably be melted upon atmospheric entry (Fraundorf 1980). There are some Antarctic micrometeorites that have been interpreted as fragments of chondrules (Genge and Grady 2000), but there is no evidence that these are cometary rather than asteroidal.

The spacecraft missions that studied Comet Halley in 1986 were able to detect mm-sized objects—the DIDSY dust collector onboard the GIOTTO spacecraft analyzed material up to a few times 10^{-5} kg (McDonnell et al. 1991), which would correspond to chondrules of ~2 mm in diameter. Unfortunately, the mass distribution measured by the DIDSY experiment is not sufficiently well-constrained to be diagnostic of the presence or absence of chondrules in Comet Halley (Fulle et al. 1995). The Stardust spacecraft will return cometary dust samples to Earth, but it is not well-equipped for chondrules (Brownlee et al. 2003). A chondrule would pass completely through the aerogel collection medium, although there are dust flux monitors that could detect the impact of a chondrule-sized object. Sometime in the next decade (2014), the European Space Agency's ROSETTA mission plans to land on the surface of a comet; returning material from the surface of a comet to Earth for study is probably more than a decade away.

Although we do not currently have the ability to search for cometary chondrules in either the collected samples on Earth or in the materials around comets, there is a way to test whether comets contain chondrules—we can study meteor showers produced by comets. Essentially, we can use ground- (or airborne-) based techniques to search for chondrules and CAIs in the cometary debris that is large enough to be visible as it ablates while entering the terrestrial atmosphere.

The Leonid meteor storms provide the best opportunity to search for cometary chondrules and CAIs for several reasons. First, the Leonids are faster, at 71.6 ± 0.3 km/sec (e.g., Betlem et al. 1999) and, hence, brighter than any other regular meteor shower. Second, although the Leonids normally consist of only about 10 meteors per hour on mid-November nights, there has been a series of Leonid "storms" since 1998, with more than 1000 meteors per hour in several cases. These storms occur as the Earth passes through dust streams ejected by the Leonids' parent comet, 55P Tempel-Tuttle, on perihelia during the last few centuries (e.g., McNaught and Asher 2002). Since Tempel-Tuttle has a 33-yr period, the storms recur on roughly that timescale. However, the exact positions of the orbits mean that some sets of storms are better than others, and recent storms have been extremely good, well-predicted, and hence, well-studied (Jenniskens and Butow 1999; Jenniskens et al. 1998). Other long-period comets can produce similar storms, and recent improvements in prediction of the storms (Lyytinen and Jenniskens 2003) may make it possible to observe many more meteors from known comets in the future, but at the moment, the Leonids provide by far the best data set.

The Leonid source, Comet 55P/Tempel-Tuttle, is an Oort Cloud comet. Its near-retrograde orbit, though fortuitous for our purposes, is only at the extreme of the continuum of inclinations in such comets. There is no agreement on exactly where Oort Cloud comets formed, but it is generally believed that these icy bodies formed somewhere between the present locations of Jupiter and Neptune (Weissman 1999) and then were ejected, by gravitational interactions with one or more of the jovian planets, to semi-major axes of more than 10^5 AU in many cases, only to be returned to the inner solar system billions of years later. The location of the formation of Oort Cloud comets is actually critical to arguments about how many chondrules and CAIs, and of what size, a comet should have in the X-wind model, since larger objects should fall out of the wind at distances closer to the Sun. We will return to this point later.

We note that an Oort Cloud comet such as Comet 55P/Tempel-Tuttle is unlikely to be a source of meteorites, even if there are cometary meteorites, for the simple reason that the encounter velocity is too high for material to survive. Rather, if there are cometary meteorites, they are more likely to come from "Jupiter-family" comets (Campins and Swindle 1998). These comets have low inclinations, which can lead to extremely low Earth-encounter velocities after sufficient evolution. Although they are known as Jupiter-family comets, they probably formed in the Kuiper Belt (30–50 AU), farther from the Sun than Oort Cloud comets. These differences in orbital histories lead to differences in the likelihood of the two types of comets containing chondrules or other high temperature material.

In the X-wind model, it would seem that Oort Cloud comets are more likely to have chondrules and CAIs than are Jupiter-family comets. If the X-wind ejected chondrules and CAIs to the location of the formation of the Oort Cloud comets (somewhere among the orbits of the giant planets), it is not necessarily true that these objects were ejected to the Kuiper Belt, although that possibility is raised by Shu et al. (2001). Hence, the absence of chondrules and CAIs in Oort Cloud comets would suggest they are also absent in Jupiter-family comets, although the opposite is not necessarily true. In addition, Oort Cloud comets are probably more likely to have clasts made of the kind of carbonaceous material believed to dominate the outer asteroid belt, since they formed so much closer to the outer belt.

On the other hand, Jupiter-family comets have probably experienced much more extensive collisional histories (Farinella et al. 2000). This provides a heat source for potential lithification processes. This, in turn, means that Jupiter-family comets might have coherent mm-sized fragments that Oort Cloud comets would lack. In other words, not only are Oort Cloud comets more likely to have chondrules and CAIs, but these objects are more likely to separate cleanly, making it more likely to see a pristine chondrule or CAI in a meteor from an Oort Cloud comet like Comet 55P/Tempel-Tuttle.

LEONID EVIDENCE ABOUT CHONDRULES

There are three primary ways in which chondrules and/or CAIs might be identified from Leonid meteors.

Mass Distribution

Based on the total amount of light from a meteor, coupled with assumptions about the meteor's structure and density, it is possible to estimate the mass of that meteor. Combining all the meteors from a shower or storm leads to a mass distribution. These mass distributions are generally assumed to be power laws and are fit as such, but chondrules or CAIs should show up as a peak in the distribution. No such peaks are seen in the Leonids (Fig. 2; Brown et al. 1998). There are, however, some problems with looking at overall mass distributions.

First, the size range of chondrules is near the lower limit of what is observable, so it is possible that, if Comet 55P/Tempel-Tuttle simply contained chondrules that are smaller than those in meteorites, they could not be observed. A 0.2 mm-diameter chondrule would have a mass of only $\sim 10^{-5}$ gm, and even though the high velocity of Leonids

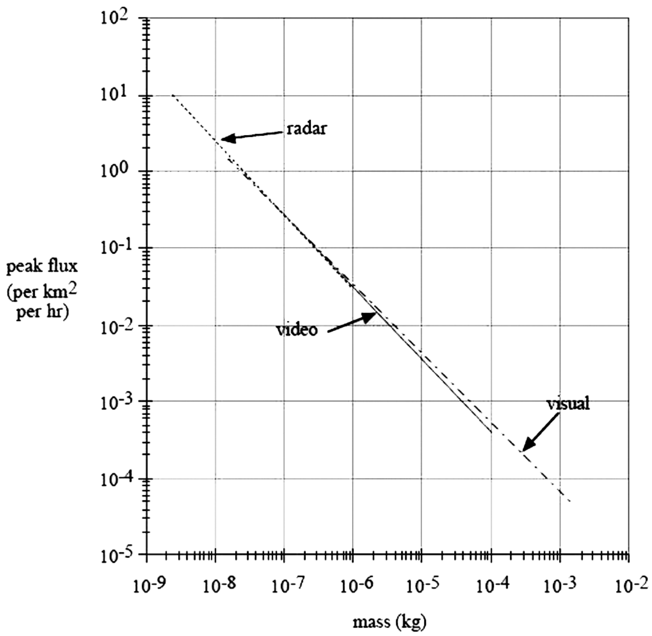

Fig. 2. Mass-frequency distribution of meteors in the 1999 Leonid shower, as measured by a variety of techniques. (From Brown et al. 1998.)

makes it possible to probe to smaller sizes than other meteors, 10^{-5} gm is roughly the lower limit to what has been observed (Fig. 2). Such a suggestion does not appear to be inconsistent with the X-wind model since the aerodynamic size-sorting mechanism might be expected to drop smaller chondrules after a longer trip, hence, farther from the Sun. Furthermore, there is at least one meteorite, Allan Hills 85085 with chondrules that have a mean diameter of only 15–20 μm (Grossman et al. 1988a; Scott 1988; Weisberg et al. 1988), corresponding to ~10^{-8} gm. However, if the chondrules in comets were common and were very much smaller than those in typical meteorites, we might expect some of these microchondrules to have been found as IDPs—Fraundorf (1980) calculated that roughly 50% of 10 μm particles of 3 gm/cm^3 density (i.e., small microchondrules) would be heated to less than 800 °C.

Another possible problem with looking at the mass distribution is the problem of material attached to chondrules. In Fig. 2, it is clear that most of the observed meteors are far bigger than chondrules, even though the constituent material is expected to have grain sizes no larger than chondrules, and probably much smaller, as discussed below. Hence, there is clearly material sticking together (as will be discussed later, this material is also often assumed to have its own power law size distribution). Furthermore, the fragments of a meteorite that is destroyed by an impact will follow a power law and will not show any peak at the size of the constituent chondrules or CAIs (Durda et al. 2002). The latter argument, however, is not really applicable to the Leonids since the meteorite has undergone various lithification processes, including heating from impacts and aqueous alteration, while an Oort Cloud comet is expected to have escaped those, as discussed above.

Finally, we have not considered the question of whether meteors are representative samplings of the material in cometary nuclei. Since meteoroids are presumably launched off comets as a result of gas pressure (e.g., Jones and Brown 1996), the force and, hence, acceleration would be proportional to the area, and acceleration would be inversely proportional to the mass. This means that higher-density material, such as chondrules or CAIs, would be more difficult to launch. However, since some meteors have masses in the kg range, orders of magnitude larger than the expected sizes of chondrules and CAIs, we would expect to have the smaller high-density particles included within these larger meteors, even if individual chondrules and CAIs are not launched.

Chemical Composition

Although they are less abundant than chondrules, CAIs would be easier to identify by their chemical composition because they are greatly enriched in refractory elements such as Ca, Al, and Mg compared even to Si and Fe. Chondrules are also somewhat refractory compared to bulk primitive meteorites, but the differences tend to be subtler since the volatiles in which they are depleted are elements such as Na and organic compounds.

Chemical compositions of meteors have been determined in two ways. First, spectroscopy on the meteor itself or on a persistent train (if it leaves one) can be used to identify many elements. However, converting the strength of a particular line from a given element into an abundance is not simple since it depends on both the line strength and the presence or absence of nearby lines from other elements.

Another complication is that meteors have been shown to ablate heterogeneously (Borovička et al. 1999; Murray et al. 1998; von Zahn et al. 2002). For example, Na, which is relatively volatile, ablates relatively early, a result that is not terribly surprising but does make analysis more difficult.

However, chemical compositions have been determined in many cases. Borovička et al. (1999) showed that the Ca/Mg and Ca/Fe ratios of 119 Leonids were typically within a factor of three of CI compositions. This is certainly not consistent with CAIs, which are Ca-rich, but the measurements are not sensitive enough to compare with chondrules. However, if the chondrules or CAIs make up only a small portion of the material within a given meteor, their chemical compositions might not produce measurable anomalies in the bulk chemical composition. In this regard, it is worth noting that 30 years ago, Harvey (1974) noted that some high-velocity (cometary?) meteors had spectra apparently lacking Na and Fe. At the time, Wilkening (1975) interpreted these as cometary CAIs, but we are not aware of any further related observations.

The other way to determine chemical composition is through lidar. In this technique, which has been applied by von Zahn et al. (2002), a laser with the wavelength of a spectral line of the atom of interest is pointed at the sky and then the resulting glow, if any, from the species of interest is measured. This technique is specific for a single element, although multiple systems can be, and have been, used simultaneously. So far, Na, K, Ca, and Fe have been studied in this fashion. One of the difficulties of this technique is that it is only sensitive to meteors (actually, the trails left by meteors) that pass through the laser beam at the right altitude (typically 80 to 105 km). The most prominent result from the lidar is the differential ablation of meteors (von Zahn et al. 2002), making the determination of chemical composition extremely difficult.

Light Curves

Probably the most intriguing data at the moment comes from studying light curves to try to determine the internal structure of Leonid meteors. The light curve (the amount of light given off as a function of time) of a meteor depends on the structure of the meteor. Hawkes and Jones (1975) developed a "dustball" model of meteors, in which a single meteor consists of a collection of constituent silicate or metal grains "glued" together by something that vaporizes at lower temperatures. Several predictions of this model were later confirmed (Beech 1984, 1986; Fisher et al. 2000; Hapgood et al. 1982; Jiang and Hu 2001). Intriguingly, the initial dustball model assumed that all the constituent grains are 10^{-6} gm, the size of a chondrule that is roughly 100 μm in diameter. This size was chosen from a range of sizes that had been proposed as the typical size of constituent grains. Although this is smaller than the average chondrule in any class of meteorite, it is only slightly smaller than those in CO chondrites (Rubin 1989) and well within the size range observed in meteorites. This sounds like promising, if indirect, evidence for chondrules in comets. However, Murray et al. (1998, 1999) have published and discussed approximately 100 light curves of Leonids. Murray et al. (1998) argued that the basic dustball model with a single grain size fails to explain the details of most of the light curves, but they were able to do much better by assuming that there is a power law mass distribution of grains within each meteor, with sizes ranging from 10^{-4} gm to 5×10^{-10} gm, a very unchondrule-like mass distribution. There is still some evidence for some harder material within the individual meteors. Murray et al. (1998, 1999) have published several light curves that have a double humped appearance. In general, such curves suggest a harder part that ablates later. In one case (Fig. 3), Murray et al. (1998) have shown how one of these could be matched by a 2×10^{-4} gm (0.2 mg) solid particle coupled with 2.3×10^{-4} gm of fluffier material. The solid particle corresponds to a 500 μm diameter object with a density of 3 gm/cm^{-3}, well within the size range of chondrules and CAIs.

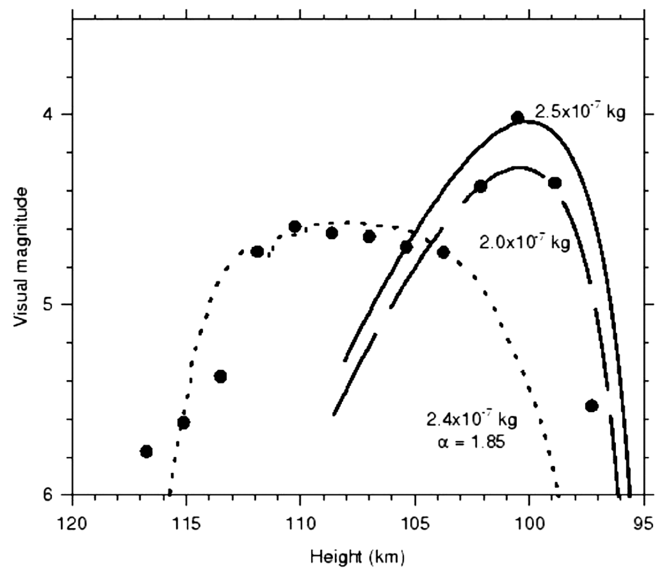

Fig. 3. Light curve of a single 1999 Leonid meteor (circles) compared with a modeled light curve using a "dustball" with a power law distribution of constituent particles (dotted line) coupled with a solid object of either 2×10^{-7} kg (dashed line) or 2.5×10^{-7} kg (solid line). (From Murray et al. 1998.)

In addition, there are some cases where a small portion of a meteor continued after the bulk of it apparently ablated. For example, Borovička and Jenniskens (1998) show an image of a magnitude −13 fireball that has a portion that continues after a bright "terminal" burst (Fig. 4). That portion corresponds to 1 mg of a 1 kg meteor, again, roughly the size of a chondrule. Although, at first glance, these two observations seem like evidence for chondrules or CAIs within comets, there are two things that should be kept in mind.

First, since an Oort Cloud comet such as Comet 55P/Tempel-Tuttle formed somewhere in the region between the current locations of Jupiter and Neptune, these bits could simply represent carbonaceous clasts from the outer edge of the asteroid belt. Determining chemical compositions on the last bits would be difficult but diagnostic.

Second, these do not represent nearly as substantial a fraction of the mass of the meteors as chondrules and CAIs do of chondritic meteorites. In the first case, less than 10% of the light curves published by Murray et al. (1998, 1999) are double humped, and the one analysis suggests that roughly half the mass of the meteor is a high density solid. This would suggest that less than 5% of the total mass is in hard material. In the second case, the solid particle that continues represents 1 ppm of the mass of the meteor. In many chondrites, 50% or more of the material is chondrules (Grossman et al. 1988b), although the number is as low as 5% in a few cases (e.g., Scott 1988). However, there could be many other solid particles that were destroyed earlier by ablation because they were much closer to the edge of the clump that comprised the meteor. And if this is true, would there be a way to find evidence for them?

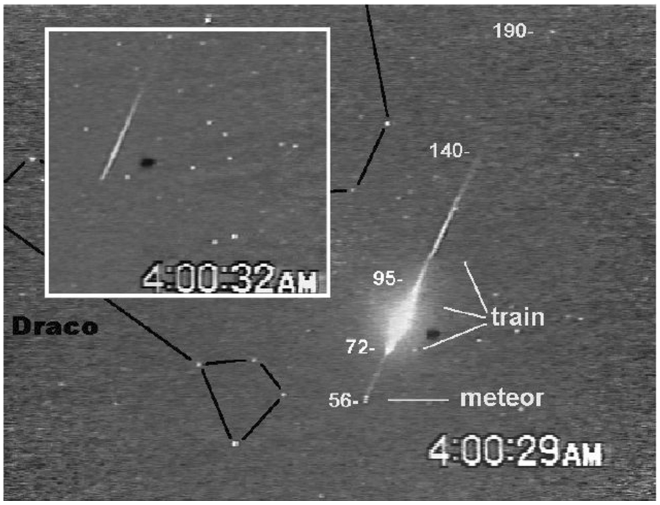

Fig. 4. Video recording of a single Leonid meteor from the 1999 shower. The numbers represent the atmospheric height in km. Note the portion that continued to a height of 56 km after the bulk of the meteor disappeared at 72 km. (From Borovička and Jenniskens 1998.)

Calcium-aluminum-rich inclusions are much less common in most meteorites, making up only 5% by volume of the meteorite in the CAI-rich Allende (McSween 1977) and far less in most meteorites. Furthermore, the size distribution of CAIs is not as restricted as it is for chondrules. Hence, these observations of harder grains within the Leonid meteors are consistent with, though not diagnostic of, the presence of CAIs at the abundances they are found in meteorites. However, the chemical information available is not consistent with CAIs.

FUTURE REFINEMENTS

What would it take to get more meaningful constraints from the Leonids?

1. More detailed predictions of abundance and size range of chondrules and CAIs in comets formed at various locations. Although we do not know exactly where Oort Cloud comets formed, it was probably between the present locations of Jupiter and Neptune (Weissman 1999). This is a range in heliocentric distance of nearly an order of magnitude; however, it should be possible to set some limits on how many chondrules and CAIs would get that far and what size they would be. Knowing this, it would be possible to turn the Leonids (or a future meteor shower or storm) into a quantitative test of the X-wind model.
2. Better chemical abundance determinations for meteors. Higher spectral resolution and lidars sensitive to more elements would help determine the more elemental abundances. However, since some elements appear to ablate before others (von Zahn et al. 2002), even these steps would not help unless accurate quantitative models of differential ablation can be developed. The five-year run of Leonid storms has presumably ended, so it may not be possible to acquire better data in the near future, but with additional Leonid data not yet published, improvement may be possible.
3. Higher sensitivity for detection of smaller objects in the Leonids and in other meteor showers. If comets do contain sub-mm-sized chondrules and CAIs, present observations barely reach this level, so it might not be as obvious in the size distribution, light curves, or chemical compositions as it would be with the higher sensitivity to smaller sizes. It is possible that even if the X-wind model is correct, few or no chondrules or CAIs would be seen at the sizes that have been probed to date. This is because the entrainment of such particles in the X-wind would depend on the surface to mass ratio, and smaller particles would be likely to remain entrained longer. Hence, comets might have much smaller chondrules and CAIs.
4. Better statistics. If chondrules and CAIs should only be present at the level of, for example, 1–10%, it is clear that we would need observations on more meteors than those published to date to test predictions accurately.
5. Modeling of light curves with the concept of chondrules in mind. Current models of meteor ablation are just beginning to address the grain size distribution at the level needed to determine whether or not there are chondrules within meteors. Most meteors are clearly made up of smaller objects, as required by the double humped light curves (Murray et al. 1998, 1999). However, the models to address such objects are usually either simple power law mass distributions or a combination of a single particle plus a power law. If cometary solids were, like many meteorites, a bi-modal population, consisting of chondrules and/or CAIs with a size distribution narrowly peaked at a given size, plus individual grains ("matrix" in the case of meteorites) with a size distribution peaked at a much smaller size (or perhaps even a power law distribution), what would the light curve of such an object look like as it ablated? Would it be like the double humped light curves presented in Murray et al. (1998, 1999)? There are enough free parameters in these models that it might not be possible to argue that a particular light curve required the presence of chondrules, but it might be possible to develop a strong case that it would be difficult to reconcile chondrules with many or all of the light curves.

SUMMARY AND CONCLUSIONS

The Leonid meteors are the most likely way to address the important question of whether comets contain chondrules. The Leonids' orbit means that the Leonids are fast, enhancing the size of signal for a given mass. In addition, the Leonids have been extensively observed in recent years. Finally, the parent comet of the Leonids, 55P/Tempel-Tuttle, is an Oort Cloud comet, and Oort Cloud comets are more likely to have chondrules than Jupiter-family comets because Oort Cloud comets probably formed closer to the nascent Sun.

So far, the data on Leonids presented gives no strong evidence for the existence of abundant chondrules or CAIs in meteors. The lack of evidence from light curves for a peak in the mass distribution at the sizes of chondrules suggests that perhaps these objects are not a major component of comets, although the sizes of chondrules (and CAIs) in comets could be smaller because comets formed at a greater distance from the Sun than the chondritic meteorites. The presence of double humped light curves (Murray et al. 1998, 1999) and other evidence for mm-sized hard bits surviving (Murray et al. 1998; Borovička and Jenniskens 1998) suggests that there may be some solids of that size, but the suggested abundances range from ≤5% down to ~1 ppm. Whether that abundance is significant is unclear. The limited compositional information available to date (Borovička et al. 1999) shows no evidence for CAIs. Chondrules, which should be more common, would be harder to detect chemically.

Hence, the Leonid meteors contain intriguing hints bearing on the important question of whether comets have chondrules and CAIs. Turning these hints into significant quantitative tests will require coordinated efforts of meteor observers and modelers and astrophysical modelers.

Acknowledgments–We appreciate the discussions with several scientists who patiently explained meteor showers (especially P. Jenniskens, P. Brown, and R. L. Hawkes) and interplanetary and cometary dust (S. Sandford) to us and a review by Associate Editor D. E. Brownlee. We gratefully acknowledge the funding agencies, the support of which helped make this possible: NSF (H. Campins) and NASA (H. Campins and T. Swindle).

Editorial Handling— Dr. Donald Brownlee

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