RECOGNIZING LEONID METEOROIDS AMONG THE COLLECTED STRATOSPHERIC DUST

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Abstract. Three chemical groups of primary "silicate" spheres <30 μm in diameter of cometary origin were collected in the lower stratosphere between 1981 May and 1994 July. The "silicate" sphere abundances represent an annual background from contributions by sporadic meteor and weak annual meteor shower activities. During two collection periods, from 06/22 until 08/18, 1983 (U2015), and from 09/15–12/15, 1981 (W7027/7029), a higher number of spheres was collected compared to other periods of the year represented by the other collectors studied here. This study links two different data sets, viz. the NASSA/JSC Cosmic Dust Catalogs and peak activities of annual meteor showers, and identified high-velocity cometary sources for collected stratospheric "silicate" spheres. The majority of spheres on flag U2015 may originate from comet P/Swift-Tuttle (Perseids), while the majority of spheres on flags W7027/7029 could be from comet P/Halley (Orionids) or comet P/Tempel-Tuttle (Leonids). Variations in relative proportions of the Mg,Si,Ca ± Al, Mg,Si ± Fe and Al, Si,Ca spheres may offer a hint of chemical differences among high-velocity comets. Proof for the findings reported here might be obtained by targeted cosmic dust collections in the lower stratosphere including periods of meteor shower and storm activity.

Key words: Ablation, chemical composition, comets, cosmic dust, Leonids, interplanetary dust particles (IDPs), meteor showers, silicates, spheres

(2000b) showed that within reason we could use the measured physical, chemical and mineralogical properties of the surviving IDPs and micrometeorites to constrain these properties in micrometeoroids that do not survive during atmospheric entry.

Spheres in the NASA Cosmic Dust Program have not received much attention although they may include dust that entered the atmosphere with cometary velocities (i.e. >20 km s^{-1}) from near-Earth asteroids and comets. The surviving dust will most likely be in the form of "silicate" spheres. We use the opportunity of the current Leonid storm activity to review "silicate" sphere data in the NASA Cosmic Dust Catalogs. We will attempt to identify meteor showers, and thus sources, that could have produced these spheres and their precursor fragments.

2. The NASA Cosmic Dust Collection

Since May 1982, the NASA Cosmic Dust Program has routinely collected stratospheric dust at altitudes between 17 – 19 km altitude using silicone oil-coated, inertial-impact, Lexan flat-plate collectors that are housed in pylons mounted underneath the wings of high-flying U2, ER-2 and W57B aircraft. Pressure sensors on the aircraft activate the collectors at the appropriate altitudes to avoid sampling the dirty troposphere. On average each collector is exposed to the stratosphere for an accumulated total exposure time of 30 – 40 hours but longer exposures have occurred (Rietmeijer and Warren, 1994). All pre- and post-flight handling of individual collectors (or flags), as well as sample curation, occurs in a dedicated Class 100 clean-room (Warren and Zolensky, 1994).

The sources used in this study are the Cosmic Dust Catalogs volumes 1 through 15 published by the NASA Johnson Space Center (Appendix). In these catalogs each particle is identified by a scanning electron microscope image (aggregate, sphere, fragment), its physical properties (e.g. size, color, shape), and an energy dispersive spectrum (EDS). The EDS spectrum shows the presence of major rock-forming elements from Na to Ni with abundances above the detection limit (typically a few percent) (Figure 1). These properties can be unambiguously determined, and allow classification of almost every particle in one of only four major groups (Mackinnon *et al.*, 1982). Stratospheric dust classification using these simple properties was proven to be highly accurate, consistent and effective (Rietmeijer, 1998 for a review).

Appendix). The relative peak heights offer a qualitative estimate of the elements present. In this manner, the major elements define three distinct chemical groups for the "silicate" spheres, viz. (1) Mg,Si ± Fe, (2) Mg,Si,Ca ± Al and (3) Al,Si,Ca. Elements with almost equal estimate abundance are listed. The '±' sign indicates elements that occur with variable abundances in a chemical group. Minor amounts of elements from one group may occur in another group, such as small amounts of Mg and Fe in Al,Si,Ca spheres. This chemical grouping is not an exact procedure but is does confirm the presence of only three major chemical groups of collected "silicate" spheres.

Sphere allocation to the TCN group is a default assignment. That is, its elemental composition does not resemble the elemental distribution of particles associated with collected chondritic aggregate IDPs and cluster IDPs that that are proven to be extraterrestrial (Brownlee, 1985; Rietmeijer, 1998; Zolensky *et al.*, 1994). We re-allocated the rare TCN "silicate" spheres in the NASA Cosmic Dust Collection to the C group because there are no known natural terrestrial processes that could produce "silicate" spheres that reach the lower stratospheres by a natural process. Silicate spheres are only known among the shards and spheres in the ejecta plume of the mount Etna volcano (Italy) with activity limited to the troposphere (Lefèvre *et al.*, 1985, 1986). These volcanic spheres contain abundant Al, Mg and Fe, which do not occur simultaneously in the stratospheric spheres, and they have high alkali contents (Lefèvre *et al.*, 1985, 1986).

The numbers of collected "silicate" C-spheres are listed in Table I, which shows the collection periods and number of cosmic "silicate" spheres with three distinct elemental compositions from the NASA Cosmic Dust Collection (Appendix). The actual collection dates are not known for most collectors (or flags) (Jack Warren, NASA-JSC Curatorial Facility, written comm.). All LAC abundances are normalized for comparison with the SAC abundances. This Table I has multiple entries when two or three individual collectors were flown simultaneously on the airplane. The number of particles on simultaneously flown collectors used by the NASA Cosmic Dust Program (see, appendix) are listed separately in Table II and show that variability of collected spheres among simultaneously flown collectors. This variability is an observed fact but it is a not understood phenomenon that might be related to the location of collectors on either the left or right wing of the aircraft (Rietmeijer and Warren, 1994). It is also possible that it reflects small scale, transient heterogeneity in

TABLE II

Collectors	Total number of spheres
W7027	3
W7029	18
L2005	15
L2006	5
L2008	11
L2009	4
L2011	1

TABLE III

Composition	Mean	Standard deviation	Range	Number of spheres
Mg,Si ± Fe	10.6	5.2	2 – 30	46
Mg,Si,Ca ± Al	10.5	4.2	3 – 17	26
Al,Si,Ca	11.2	5.3	3 – 20	14
Total	10.7	4.8	3 – 30	86

Table IV

Composition	Mean	Standard deviation	Range	Number of fragments
Mg,Si ± Fe	19.1	12.1	5.0 – 64.0	34
Mg,Si,Ca ± Al	34.1	7.0	28.3 – 44.0	4
Al,Si,Ca	22.8	12.8	8.4 – 52.5	13
Total	21.2	12.5	5.0 – 64.0	51

Table III shows the mean diameter (micrometers), the standard deviation and size range of the "silicate" spheres listed the NASA Cosmic Dust Catalogs that were collected between May 22, 1981 and July 3, 1994. The "silicate" sphere diameters form normal distributions (at a 95% confidence limit) with remarkably similar size ranges. There is only one Mg,Si ± Fe sphere with a 30 μm diameter while all other spheres in this chemical group are <20 μm in diameter. The mean diameters among the chemical groups are identical (Table III). We point out that our statistical fragments collected in the lower stratosphere between May 22, 1981 and July 3, 1994. The rms size is calculated as $(a^2 + b^2)^{1/2}$, whereby a and b are the orthogonal longest and shortest particle dimensions. The size and size range of the fragments (Table IV) are in excellent agreement with the progenitor-sphere size relationships predicted by Love and Brownlee (1991) for primary spheres formed by melting and ablation of larger progenitor particles.

The modeling study by Love and Brownlee (1991) also showed that the ratio comet/(comet + asteroid) spheres < 30 μm in diameter is unity for primary spheres. Thus, the collected Mg,Si ± Fe, Mg,Si,Ca ± Al and Al,Si,Ca "silicate" spheres are the surviving remnants of micrometeoroids that entered the Earth's atmosphere at velocities >20 km s^{-1} (Brownlee *et al.*, 1995), which would include a fraction of asteroidal asteroids (22–25 km s^{-1}) , low-velocity comets (25-36.5 km s^{-1}) and all other comets (Rietmeijer, 2000b). The progenitors occur as individual IDPs (Table IV), as mineral grains (< 5 μm) embedded in aggregate IDPs and as large (>10 and up to ~50 μm) grains among the fragments of cluster IDPs (Rietmeijer, 1998). They are mostly Mg-rich olivines, Ca-poor and low-Ca Mg-rich pyroxenes and Ca,Mg-rich clinopyroxenes (Rietmeijer, 1998, 1999b; Thomas *et al.*, 1995; Zolensky and Barrett, 1994). The major element abundances of these grains classify them among the Mg,Si ± Fe and Mg,Si,Ca ± Al chemical groups of fragments. Plagioclase fragments found in some aggregate IDPs but of much smaller size (Rietmeijer, 1998) could be progenitors of the Al,Si,Ca "silicate" spheres. The collected spheres might also be refractory melt residues of progenitors with a chondritic bulk composition such as meteorite matrix fragments or chondrules (Rietmeijer and Nuth, 2000). Chondrules are probably not present in comet nuclei but "silicate "fragments and fine-grained chondritic materials will be as predicted by a hierarchical dust accretion model of cycles of proto-planet modification and disruption (Rietmeijer, 1998; Rietmeijer and Nuth, 2000). In the earliest stages these processes will lead to the formation of porous cluster IDPs 60 – 100 μm in diameter, or even larger (as yet uncollected) "giant cluster IDPs". Cluster IDPs with "silicate" fragments will brake up during atmospheric entry, or will melt and quench as "silicate" spheres. The "silicate" spheres could represent (1) individual "silicate" meteoroids, (2) large "silicate" fragments of cluster IDPs, (3) quenched melt residues of aggregates that collapsed due

Error bars show the accuracy of sampling (vertical, proportional to the square root of the number of collected spheres), and the period of time over which the collectors were exposed.

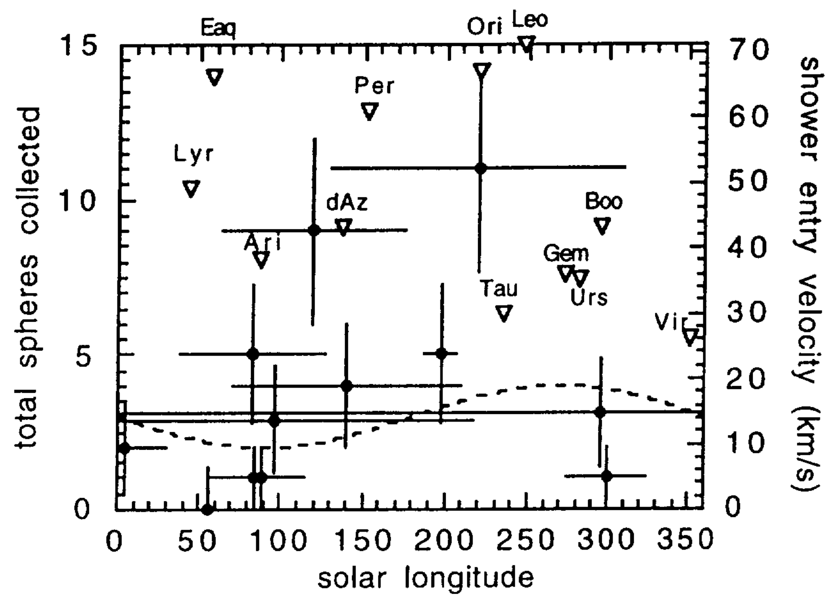

Figure 2. Number of spheres on individual collectors, (shown with error bars; see Table I) and the collection times as solar longitude. The sinuous curve in the lower portion of the diagram represents the possible sporadic background for Northern Hemisphere locations (Jenniskens, 1994). The possible contributing meteor showers (inverted triangles) are shown as a function of solar longitude and entry velocity (shower identifications as in Jenniskens, 1994).

The actual collection dates and times of the NASA Cosmic Dust Program during the period discussed here were somewhat haphazard. Individual collectors have variable lengths of their collection period and the actual times and dates of collection within these periods are randomly distributed. During the period May 1981 to July 1994, collectors flown in different years may have overlapping collection periods but not necessarily also overlapping collection dates (Rietmeijer and Warren, 1994). These, and other factors, make it difficult, but not impossible, to search for annual showers as the sources of the collected

Flags W7027/7029 and U2015 stand out significantly from this sporadic background. If a meteor shower is responsible for such an increase of spheres on a dust collector, then it has to stand out from the sporadic meteor influx in one (or both) of,two possible ways. Possible sources of the primary "silicate" sphere anomalies are shown in Table V. First, it could be a significant anomaly in mass influx. This is expected to occur during a rare meteor storm. The Leonid shower, for example, represents only about 5 hours of sporadic mass influx during a 1-hour storm even if the rate of observable meteors by visual observers (< +6 magnitude) is equivalent to 2000 hours of sporadic activity (Jenniskens *et al.* 1998). The second possibility is that the shower represents an anomaly in the efficiency of sphere production. We can envision three possible reasons. Firstly, large recently ejected Leonid meteoroids were found to fragment more easily than ordinary meteors (Borovicka *et al.* 1999, Murray *et al.* 1999). In that case, also less intense showers can dominate the production of spheres. Secondly, it is possible that sphere formation is efficient mainly for large > 1 cm sized meteoroids, for which fragmentation is often observed in the wake of the meteor. Meteor showers tend to dominate the mass influx of large meteoroids. An intense rain of fireballs was observed during the Leonid outburst of 1998, with much less an increase in the population of smaller meteors. Thirdly, it is possible that sphere formation is a signature of the ablation process itself, which may vary as a function of velocity. Quenching may be more rapid and efficient for the fastest meteors that ablate well above the mesopause. Meteor showers dominate the influx of fast meteors. That could even be annual showers, especially the eta-Aquarids, Perseids, Orionids and Leonids. Also, showers will always lead to relatively high incidences of grazing meteoroids at specific positions on the Earth, a process that may also enhance the efficiency of sphere formation. This process is especially relevant for the most active showers, because the meteor rate is much reduced at grazing incidence. The last mechanism could work for both slow and fast meteors. However, for meteor streams with velocities of 24 – 27 km s^{-1} that could have entered the atmosphere at 60 – 80° (almost skipping) angles, the results obtained by Love and Brownlee (1991) then indicates they could survive without melting.

Figure 2 shows the time in the year (and the entry velocity) of a number of meteor showers that stand out above the sporadic background (Cook 1973; Jenniskens 1994). We adopted a 12-day settling time, and all times of the meteor showers were shifted accordingly. Annual streams is > 150 μm in size, which is considerably larger than the fragments and spheres considered here, and larger than the typical sporadic meteoroid (150 μm).

Here we reached an interesting junction in the arguments. We used the predicted relationships between the diameters of the "silicate" progenitor fragments and the "silicate" spheres to claim that they are primary spheres of cometary origin. Using the information on the size distributions in cometary meteor streams and comet dust trials we find that the collected "silicate" progenitors are seemingly too small. In other words, the mechanism of sphere formation must not be the ablation of these individual progenitors, but result from the fragmentation of much larger meteoroids, or 'giant" cluster IDPs containing fragments > 50 μm in size. In that case, future-sampling efforts during meteor showers that are known to be rich in bright fireballs may reveal considerable numbers of spheres. This work predicts that some fraction of these spheres will be 10 μm-sized Mg,Si,Ca ± Al, Mg,Si ± Fe and Al, Si,Ca "silicate" spheres but their relative abundance in these showers is at this time unknown.

TABLE VI

Composition	All spheres	Flag U2015	Flags W7027/7029
Mg,Si ± Fe	54	67	27
Mg,Si,Ca ± Al	30	22	55
Al, Si,Ca	16	11	18

4.4. WERE DIFFERENT COMETS SAMPLED?

If we accept that flags W7027/7029 may have sampled dust from comets 1P/Halley and 55P/Tempel-Tuttle, while collector U2015 may have sampled dust from comet P/Swift-Tuttle, we can examine possible differences between the dust from different high-velocities (>61 km/s) cometary sources. Table VI lists the relative proportions (%) of the three chemical groups of "silicate" spheres on flag U2015 and the simultaneously flown flags W7027 and W7029. These proportion on flag U2015 resemble these proportions found on all collected spheres (Table VI). The flags W7027/W7029 contain a higher than average proportion of Mg,Si,Ca ± Al spheres and a less than average amount of Mg,Si ± Fe meteor showers. The collected primary "silicate" spheres < 30 μm in diameter and their progenitor fragments show the predicted size ratios for cometary debris entering the Earth's atmosphere. The compositions of the spheres and fragments each define three qualitatively similar chemical groups. The "silicate", sphere abundances on most collectors indicate an annual background of 2–4 "silicate" spheres < 30 μm in diameter per collector normalized to a 30 cm^2-area and an average 35-hours collection time. This background is composed of contributions from sporadic meteor activity and many weak annual meteor showers. During two collection periods, from 06/22 until 08/18, 1983 (U2015), and from 09/15-12/15, 1981 (W7027/7029), higher numbers of "silicate" spheres were collected with a smaller average diameter then during the times of the year represented by the other collectors listed in Table I. This study combined the times of "silicate" dust collection and peak shower activity, and constraints on dust properties of individual meteor showers. For the first time we identified specific showers, and thus cometary sources, for collected "silicate" IDPs. The majority of spheres on flag U2015 may originate from comet P/Swift-Tuttle, while the majority of spheres on flag W7027/7029 are from either comet 1P/Halley or comet 55P/Tempel-Tuttle. We have to admit that our statistical analyses alone does not, and can not, prove these associations of these stratospheric IDPs and high-velocity comets conclusively. This work stresses a need for targeted cosmic dust collections such as following the November 1999 peak in the Leonid storm activity. If we can sure that this dust are quenched-melt Leonid meteors this would be the first experimental verification that it is possible to link collected dust in the lower stratospheres to periodic events. Improvement in the frequency of targeted dust collections will offer great opportunities to explore differences and similarities among IDP-producing sources.

Acknowledgments

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Appendix

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