The statistical and astronomical view of the decennium of the NASA Cosmic Dust Program

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Received: March 12, 1992

Abstract. A statistical analysis of catalogued samples of cosmic dust and different stratospheric contaminants was made on the basis of the first twelve volumes of the Cosmic Dust Catalog, published in the NASA Johnson Space Center since 1981. All particles catalogued during 10 years to date amount to 1663 samples. Their analysis shows that the percentage of the dust of true cosmic origin is roughly 30%. The percentage of various kinds of contamination (natural, artificial, etc.) is specified, moreover with respect to the shape of each examined particle. Some astronomical aspects and perspectives of the research in this field in Czechoslovakia are also discussed.

1. Introduction

The Cosmic Dust Preliminary Examination Team (CDPET) have compiled and already published twelve volumes of the Cosmic Dust Catalog (CDC) (Clanton et al., 1982 a; 1982 b; 1982 c; 1982 d; 1982 e; 1983 a; 1983 b; 1984; McKay et al., 1985; Zolensky et al., 1985; 1986; 1987; 1989; 1990; 1991).

The CDC is a unique and the first presentation of information resulting from the NASA Johnson Space Center (JSC) Cosmic Dust Program. As part of this program a special type of aircraft has been used since May, 1981 to collect cosmic dust particles directly ("in situ") from Earth's stratosphere at an altitude of about 18 *km*. The total number in the statistical set as a whole, i.e., the number of collected, examined and catalogued particles presented in the first twelve volumes of the Cosmic Dust Catalog, is 1663.

A basic statistical analysis of the whole statistical set (1663 particles) is made and some astronomical aspects are discussed in this paper. Some useful technical details and necessary additional information on the processing and examination of particles, made at the Lyndon B. Johnson Space Center in Houston, were also

Contrib. Astron. Obs. Skalnaté Pleso **22**, (1992), 215– 226.

compiled in nine special issues of Cosmic Dust Courier (1982 a; 1982 b; 1983; 1984 a; 1984b; 1985; 1986; 1989; 1991).

Several papers based on the NASA Cosmic Dust Catalog data or samples have already been published, but their topics are not identical with ours (e.g. Mackinnon and McKay, 1986; Mackinnon et al., 1987; Walker and Zinner, 1988; Jates et al., 1988; Reitmeijer, 1989; Schramm et al., 1989; Flynn, 1989).

2. Technical equipment used in the NASA-JSC Cosmic Dust Program

Flat plate "flags" were used as the basic unit of the collectors. Flags with $\sim 30\ cm^2$ surface area were used all flights up to fall 1989 (CDC - Volume 1-10). CDC volume 11 was the first to be produced from the new Large Area Cosmic Dust Collectors (LAC_s). These collectors have a surface area approximately one order of magnitude larger ($\sim 300\ cm^2$) than the conventional collectors used for CDC 1-10. The recorded particles in the last catalog volume (No. 12) are also from LAC_s.

Each surface area was coated with silicone oil (dimethyl siloxane) and then flown aboard the NASA aircrafts during many series of flights across different regions of the U.S. The flags were installed in specially constructed wing pylons which ensured that the necessary level of cleanliness was maintained between periods of active sampling. During successive periods of high-altitude cruising ($\sim$ 18 km), the flags were exposed to the stratosphere by pilot command and then retracted into sealed storage containers prior to descent. In this manner a total of eight hundred hours of stratospheric exposure were accumulated. It should be emphasized that the cumulative exposure time mentioned above represents summa of some flags only flown and exposed during a series of flights. For instance, flag marked W7017 was one of the eight flags flown aboard a NASA WB 57F aircraft during a series of flights across the western United States from July 7, 1981, to September 15, 1981. Only 104 particles were retrieved for further analysis from W7017 collection surface after 45 hours of exposure.

For further analysis of the particles CDPET used spatial particle "mounts", which were designed for the JEOL 100 CX scanning electron microscope (SEM). Each mount consists of a graphite frame (size $\sim 3 \times 6 \times 24\ mm$) to which a spatial filter was attached. Cosmic dust particles were removed individually from the collection flags by means of micromanipulators under a binocular stereomicroscope. Each particle was positioned on an aluminium-free surface of a freon-cleaned, carbon-coated mount filter and then washed with hexane to remove silicone oil.

Normally each mount was limited to 16 particles. Under NASA/JSC conditions, all processing and storage of particles were realized in a Class-100 clean room. Before leaving this room each rinsed particle was examined by an electron optical microscope. At a magnification of 500, some physical characteristics of each particle were determined by CDPET and recorded in the Cosmic Dust Catalog. After this process, a JEOL 100 CX instrument, equipped with a PGT 600 solid-stay X-ray analyzer, was used to obtain a secondary electron image and the energy-dispersive X-ray spectrum (EDS) of each particle. Each mount was then stored in a dry nitrogen gas atmosphere in a sealed cabinet.

Table 1 gives the basic information about flags taken into account. The number of mounts in a certain flag, if known, is given in brackets after the official designation of the corresponding flag. For a flag given in Table 1, the data of the flight series, the duration of collection (cumulative exposure time) expressed in hours, approximate collection location and total number of examined particle are also presented.

FLAG (No. of mounts)	Collection DATE	Collection DURATION (hours)	Collection LOCATION	NUMBER of examined particles
W7010	May-July 1981	66	N and Centr Am	4
W7013(8)	May-July 1981	65	W-Centr N Am	124
W7026	Sep-Nov 1981	28	Western US	2
W7028	Sep-Nov 1981	31	Western US	7
W7031	Sep-Nov 1981	28	Western US	6
W7029(10)*	15.9.-2.12.1981	35	Western US	161
W7027(9)*	15.9.-2.12.1981	35	Western US	131
W7017(7)*	7.7.-15.9.1981	45	Western US	104
U2001(5)+	13.3.-8.4.1982	31	E-Centr-W US	89
U2011	March-April 1983	35	Mid-W-US	8
U2015(5)+	22.6.-18.8.1983	39.6	W coast of N Am	111
W7066	November 1983	33	N Am, N Pacific	4
W7069	November 1983	33	N Am, N Pacific	3
W7071	November 1983	33	N Am, N Pacific	4
U2017	Jul 1983-Feb 1984	39	Western US	11
U2018	Jul 1983-Feb 1984	39	Western US	6
U2022(6)	9.4.-26.6.1984	41.8	W-Centr N Am	133
U2034(6)	April-August 1985	33.7	W-Centr N Am	97
W7074(9)	During 1988	32	N Am	147
L2005(19)	During the fall of 1989	40	W-Centr N Am	166
L2005-6(22)	During the fall of 1989	40	W-Centr N Am	345
Total:		803.1		1663

Table 1.

Remarks: * 1 of 8 flags; + 1 of 2 flags

It is needless to explain the abbreviations in the "Collection location" column, in Tab. 1 but it should be mentioned that flag U 2001 was exposed during the eruption of the E1 Chichon vulcano in Mexico in 1982.

3. The main characteristics of particles

Our statistical analysis (see Section 4) considers some of the following descriptive data: SIZE (μ m) - was measured using the original SEM image and its known magnification factor. For irregularly shaped particles, the minimum dimension in the field of view was found and determined; then a second (maximum) dimension was measured at right-angles to the first. For a spherical or equidimensional particle, a single size was recorded only.
SHAPE - of the particle may in general be spherical (marked S), equidimensional (E), or irregular (I). Particles with shapes between S and E, or E and I were denoted as S/E or E/I, etc.
TRANSPARENCY - was determined by optical microscopy. The particles were transparent (T), translucent (TL), or opaque (O).
COLOR - was also determined by optical microscopy. The color was determined under oblique (fiber optic, quartz halogen) illumination supplemented with normal reflected (tungsten-lamp) illumination. The distinction of dark (Dk) from light (Lt) was unambiguous in spite of the changes of color perception of the observer. The distinction of colorless (CL) from pale-colored conditions is rather uncertainly and sometimes problematic.
LUSTER - was determined by optical microscopy using a combination of different illuminations. Commonly applied descriptions, adopted from mineralogical usage, include dull (D), metallic (M), submetallic (SM), vitreous (V), subvitreous (SV) and resinous (R) particles. Lusters transitional between these categories (or difficult to identify with certainty) have been designated D/SM, SV/V, etc.
TYPE - was the main characteristic of the particle on which our study was concentrated. In the first-order identification of the particle the type indicates a provisional conclusion derived from the particles' morphology (according the SEM image), elemental composition (from EDS), and optical properties. It must be emphasized that, for the purposes the CDC, types were defined for their descriptive and curatorial utility, not as a scientific classification. Thus, in the volumes of the Cosmic Dust Catalog quoted, different "types" were specificed only to aid the users of this Catalog in distinguishing cosmic dust particles from other particles which were invariably collected during cosmic dust sampling. Categorizations are only tentative and reflect judgements based mainly on the collective experience of the CDPET, and should not be construed to be firm identification. In this sense some types of particles have hitherto been defined in the Cosmic Dust Catalog as follows:

"C" - Cosmic dust (variety unspecified) or other extraterrestrial material. In the Cosmic Dust Catalog type "C" was used to conveniently group together all particles which were supposed to be of extraterrestrial origin, including "large" particles that had apparently experienced strong ablation heating or melting and consequently had many special attributes. Naturally, type "C" also includes micron and submicron particles, which are called micrometeoroids or micrometeorities, and which refer only to the particles physical state which did not change during their passage from interplanetary space through the atmosphere to the Earth's surface.

"TCA" - Terrestrial contamination of artificial or man-made origin. This category probably includes particles produced by or derived from aircraft operation or collector hardware, or possible spacecraft debris. Their physical features and EDS spectra made it possible to distinguish this category from others.

"TCN" - Terrestrial contamination of natural origin. According to morphologies and EDS spectra of most "TCN" particles, they very probably represent the principal components of stratospheric volcanic ash. This category also includes mineral, rock, or soil from the Earth, or various biological contaminants such as spores, insect parts, etc.

"AOS" - Aluminum oxide sphere. With high probablity AOS (almost ideal spherical particles) represent products of solid-fuel rocket exhausts. In its EDS spectrum "Al" displayed a distinctively dominant peak, sometimes the only one. Nonspherical particles with high "Al" abundance were of enigmatic origin and were provisionally called "Al particles".

"?" - Identification uncertain. This category includes particles which do not unequivocally resemble those grouped together as AOS, C, TCA or TCN. Careful examination will thus be required before they can be reliably identified. Also symbols "AOS?", "C?", "TCA?" and "TCN?" indicate that the classification was not very reliable. The questionable determination of other particle characteristics such as shape (e.g. "E?"), luster (e.g. "SV?"), etc., was indicated similarly.

4. Results of the statistical analysis of all available data

Classification of the particle types presented above was made by CDPET according to the examination of each particle by both electron microscope and obtained EDS spectrum. This classification represents only a first-order attempt to distinguish particles which are probably of extraterrestrial origin from those that are probably contaminants. On the basis of this classification, after statistical processing of whole set of data, we can gain some specific astronomical results. In the first step we concentrated on the question of the percentage of the different types in the set as a whole, even with respect to the shape of particles. Table 2 gives the main results of this analysis.

Part. TYPE	NUMBER of part.	Corresp. PERCENTAGE	NUMBER of different particle SHAPES in the individual types					
			I	I?	S	S?	E	E?
C	453	27.2	394	10	32	3	10	4
C?	212	12.8	136	7	50	6	7	6
TCA	258	15.5	208	5	29	2	13	1
TCA?	112	6.7	76	1	17	3	8	7
TCN	232	14.0	200	3	19	2	7	1
TCN?	73	4.4	57	4	4	2	4	2
AOS	166	10.0	6	1	151	4	1	3
AOS?	5	0.3	0	0	2	1	1	1
?	152	9.1	96	8	38	1	4	5
Total:	1663	100	1173	39	342	24	55	30

Table 2.

5. The main conclusions drawn from the statistics

From both the analysis of the peaks in EDS spectra of each particle and our statistical analysis summarized in Table 2 it is possible to draw the following basic conclusions:

5A - The reliability of type and shape determinations of particles by CDPET (follows simply from Table 2):

- For 66.7 % (i.e. for 1109 particles) of the whole statistical set (1663 particles) the type was determined with high reliability. Other determinations were questionable (i.e. C?, TCA?, TCN?, AOS?) or were not made at all (?).
- The shape of 94.4 % (i.e. 1570) particles was classified with high reliability.

5B - The percentage and characteristics of the individual types of particles in the whole set:

- The percentage of type "C" particles (true cosmic origin) is 27.2 % (453 particles). If we would also consider type "C?" (212 particles), the percentage of the corresponding type (C + C?) would increase to 40 % (665 particles). Category "C" included obviously irregular to spherical, opaque, dark-colored particles, composed mostly of Fe with small amounts of S and Ni. Sometimes they are translucent to opaque, dark-colored containing Mg, Si, and Fe with traces of S and/or Ni. We can also say that the dull to metallic luster of the "C" particles distinguishes them from terrestrial minerals. Their EDS spectra are very reminiscent of those exhibited by meteoritic Fe - NiS minerals, or combinations of Fe - Ni - S phases with olivine and/or pyroxene.

- The percentage of "TCA" particles in the same statistical set is 15.5 % (258 particles) and of "TCA?" particles 6.7 % (112 particles). More than 80 % of the particles included in the "TCA" category is commonly irregular in shape. Their EDS spectra often show Fe, Al or Si as the principal peaks together with a variety of minor peaks including those of Cd, V, Ti, Cr, Mn, Ni, Cu, or Zn.
- "TCN" particles represent 14.0 % (232 particles) of the statistical set and the questionable type "TCN?" only 4.4 %. This type of particle may exhibit a variety of colors, but they are commonly irregular in shape (roughly more than 85 %). The EDS spectra indicate that they are distinctively rich in Si and Al with minor abundances of Na, K, Ca, or Fe.
- 10 % (166 particles) of all examined particles represent type "AOS". Only 5 particles (0.3 %) are included in the questionable category "AOS?". More than 90 % of the AOS particles have a nearly perfect spherical shape. The Al peak distincly dominates in the relevant EDS spectrum.
- For 9.1 % (152 particles) of all examined samples the origin cannot be specified at all (type "?").

5C - Type-shape relation of the particles:

- The percentage of irregularly shaped particles (category "I") decreases from roughly 87.0 % for "C" type particles to 86.2 % for "TCN", 80.6 % for "TCA", 63.2 % for "?" and 3.6 % for "AOS" type particles.
- In the highest percentage (91 %) of spherically shaped particles ("S") are evidently present among the "AOS" type particles. The respective percentages for types "?", "TCA", "TCN" and "C" are 25 %, 11.2 %, 8.2 %, and 7.1 %.
- The percentage of equidimensionally shaped particles ("E") in te individual types is very low: 5.0 %, 3.0 %, 2.6 %, 2.2 % and 0.6 % for particles type "TCA", "TCN", "?", "C" and "AOS", respectively.

All presented results and conclusions are in good agreement with those published by CDPET. The statistical analysis of the data also enables the relative contamination of collection surface during different periods to be determined. Figure 1 presents the level of contamination (all particles which are not included in category "C" or "C?") expressed in percentage. The histogram only applies to the collection experiments for which the number of examined particles was roughly 100 and more, and the collection duration exceeded $\sim$ 30 hours. Thus the ten separate columns in Figure 1 represent the percentages of contamination for the following ten flags (see Table 1):

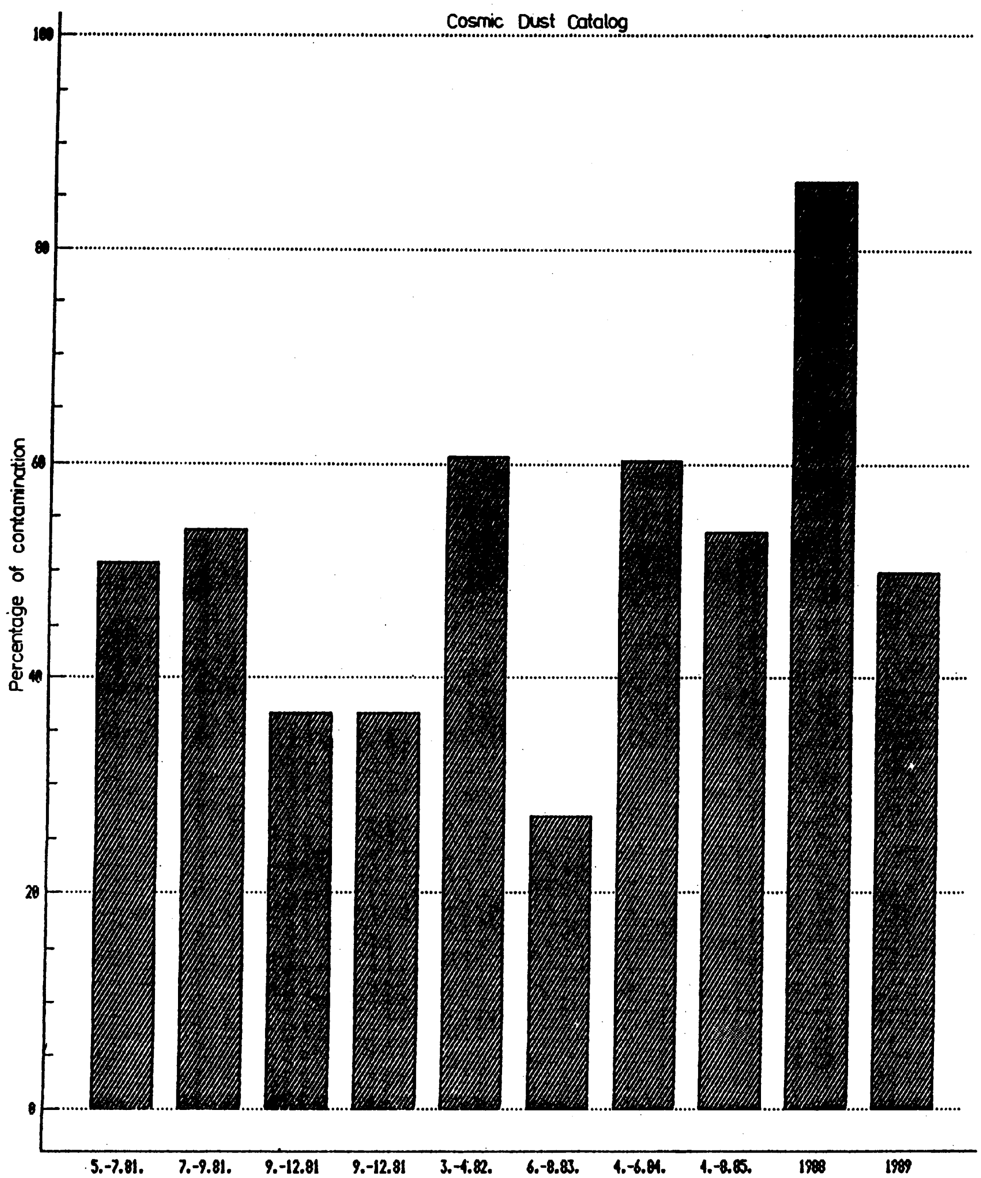
Cosmic Dust Catalog
Percentage of contamination
100
80
60
40
20
0
5.-7.81.
7.-9.81.
9.-12.81
9.-12.81
3.-4.82.
6.-8.83.
4.-6.84.
4.-8.85.
1988
1989

Figure 1.

W7013 (May-July 1981; 124 particles)
W7017 (July-September 1981; 104 particles)
W7029 (September-December 1981; 161 particles)
W7027 (September-December 1981; 131 particles)
U2001 (March-April 1982; 89 particles)
U2015 (June-August 1983; 111 particles)
U2022 (April-June 1984; 133 particles)
U2034 (April-August 1985; 97 particles)
U7074 (During 1988; 147 particles)
and L2005 and L2006 together (During 1989; 166 and 345 particles).

6. Discussion of results and our own research

Reliable type determination of the stratospheric dust particles collected in NASA JSC is a very important task if we consider the fact that, generally speaking, the reliable identification and scientific classification of cosmic dust are two of the many important tasks in the wide field of cosmic dust research. The study and our statistical data analysis clearly show that much more work must be carried out to achieve a more reliable determination of particle origin in the future. Unfortunately the precise laboratory classification of each collected particle is often beyond the scope, intent and also possibilities of NASA CDPET and so far also beyond the scope and possibilities (mainly due to the lack of instrumental and sampling equipment) of the author of this paper. As we mention below the situation has now changed.

The statistical data processing and the presented results have several snags which do not allow them to be interpreted in full. For instance, the percentage of the individual types of particles in the whole set must be viewed as relative, because the "whole set" does not represent all particles collected during a particular flight (or on a particular flag). For example a total of 5560 particles larger than 12 microns on the entire collection surface was collected on FLAG L2005. As we see in Tab 1 of this number only a small portion was catalogized and analyzed. They represent only a random choice of samples and it is, therefore, questionable, e.g. whether the percentages of true cosmic dust or contaminants should be extrapolated to all stratospheric or cosmic dust in general.

Other problematic issues arise mainly in the categorization of the individual particles. For example, the "TCN" category may include distinctive particles with apparently nonrandom shapes which are rich in low atomic number elements. This is indicated by their EDS spectra with high levels of continuum X radiation and relatively small peaks for characteristic X-rays. And these particles are thus distinguished from the "TCA" category only by their unusual, organized morphologies, and the CDPET's collective mineralogical experience leads to the conclusion that they probably represent biological contaminants.

Sometimes it was a problem to distinguish reliably "AOS" particles from other types ("AOS?", "?", or "TCA?"), mainly if the transparent Al-rich particles were of irregular shape. The interpretation of TCA particle spectra also presented some difficulties. In some cases, a high intensity (relative to the intensities of the characteristic X-ray peaks) of continuum radiation occured in the EDS spectrum, suggesting that low atomic number elements, not detectable by the EDS (e.g. H, C, N, O), were abundant in the particle. Such "TCA" particles are tacitly inferred to be synthetic-carbon-based materials. According to te opinion of CDPET this category probably included particles produced by or derived from aircraft operation or collector hardware, or possible spacecraft debris. Some of these particles are available for additional research and re-analysis because there is a suspision that they may represent a true extraterrestrial "low z" material.

In spite of these difficulties we tried to carry out an independent research at our institute in order to avoid them and also to re-analyze, and to improve the classification made by NASA JSC, for the purpose of applying it to theoretical research mainly in the area of micrometeoroid dynamics.

After successfully initiating cooperation with the Institute of Materials and Machine Mechanics we have at our disposal a laboratory fully equipped for this research. After a rigorous proceeding in the case of our sample request for allocation of stratospheric dust particles from NASA JSC, we have received a set of several particles of different types. Our own research of stratospheric samples is thus just beginning and we hope that the first results will already be available this year. If the re-analyses are successful, if the difficulties mentioned above are avoided, the quality of SEM images and EDS spectra improved, and flight trajectories specified in more detail, etc., we should be able to draw some preliminary conclusions about some of the astronomical problems such as

- the influx of cosmic dust on Earth and its possible seasonal variations;
- the density of the cosmic dust envelope around the Earth;
- the level, and local and time variations of natural and artificial contamination in the stratospheric layer;
- the sedimentation rate of volcanic ash on the Earth's surface due to such events as the eruption of the El Chichon vulcano in Mexico in 1982; etc.

Acknowledgements. My thanks are due to my wife Zdena, Mr. Alexander Nagy and Ing. Miloš Koska for storing thousands of data from all volumes of CDC, their processing, statistical calculations and for preparing this paper technically.

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