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The dusty heliosphere

BEGINNINGS

Zodiacal light observations and meteor studies

Dust in space has been recognized for centuries. Three dusty phenomena in space can be observed by the naked eye: comets, meteors and zodiacal light. In the past the sporadic appearance of bright comets received much attention, and not only from astronomers, because it was linked to exceptional events in human history such as victory or defeat in war. The physical nature of comets was illuminated by the second dusty phenomenon: meteors. Although several meteors can be observed every clear night, there are special periods, so called meteor showers or meteor storms, when the rate is greatly enhanced. It was the coincidence between such meteor showers and the simultaneous apparitions of comets that suggested their relationship.

Triangulation already proved two hundred years ago that meteors are the luminous trail of pea-sized meteoroids that enter the Earth's atmosphere at about a height of 100 km. The speed of meteoroids was determined to range from $11\,\mathrm{km\,s^{-1}}$, the escape speed from the Earth, to $72\,\mathrm{km\,s^{-1}}$ which is the maximum collision speed with the Earth that a meteoroid can have on a bound orbit about the Sun. This speed range clearly identified meteoroids as members of the Solar System. The scattering of radio waves by the ionization trail in the atmosphere allows us to observe meteors even during the day. Such radar meteoroids can be as small as 0.1 mm in size. Football-sized and bigger meteoroids may survive the entry into the atmosphere, and some residual material may fall to the ground as meteorites, which can be picked up and examined. Up to now only a handful of meteorite falls have been observed with sufficient accuracy that an orbit could be established. All these cases were ordinary stony meteorites which had orbits with aphelia in the asteroid belt.

Because of their exotic nature, meteorites belong to the best-analysed samples on Earth. While some resemble ordinary stones, others consist of almost pure iron–nickel and a third type consists of a mixture of elements that is believed to be the mean composition (cosmic abundance) of the whole planetary system except for some volatile elements, like hydrogen and helium. The latter meteorites (carbonaceous chondrites) are considered to consist of primitive material that has not been modified by thermal processes like those that occur in the interior of planets. Meteoritic material has been used as a model for the material of which interplanetary dust particles are made.

From measurements of the entry trajectory and models of the upper atmosphere it became clear that meteoroids experience quite variable decelerations. While some slowed within a short time, others kept their speed for much longer times. The concept of loosely bound aggregate particles with large cross-section/mass ratios (i.e. low bulk density) was developed for those that decelerated rapidly; others behaved more like normal compact stones and even iron particles. Meteor physicists like Zdenek Ceplecha (1977) found a correlation between meteoroid densities and their orbits; namely, some meteoroids that have eccentric, comet-like orbits consist of low-density material, while higher-density meteoroids have orbits that just reached the asteroid belt.

The asteroid belt has always been suspected to be a source of meteoroids. At the beginning of the twentieth century, Max Wolf detected from the Sternwarte above Heidelberg such a large number of asteroids that he had a hard time to

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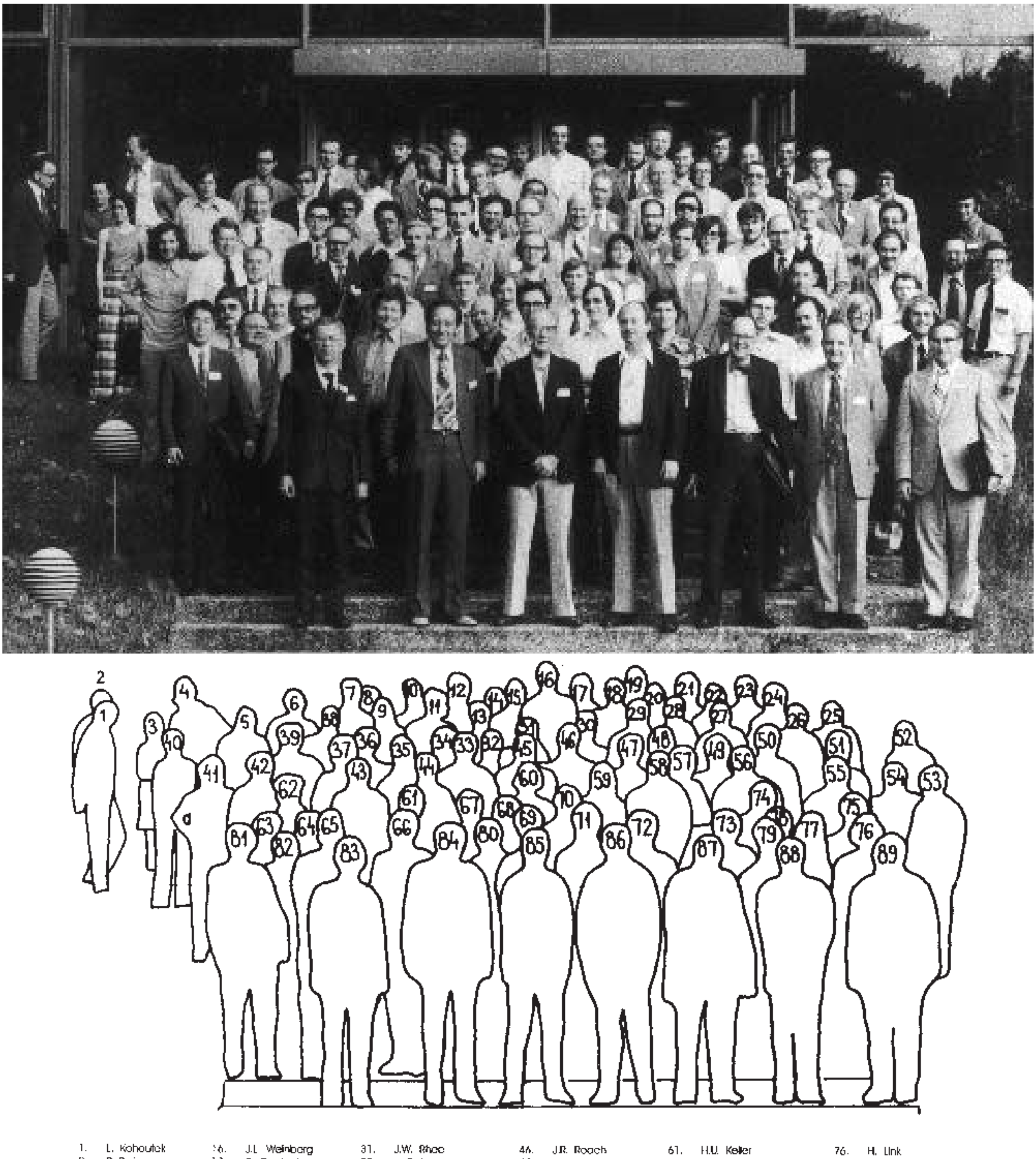
find names for all of them. Since then the number of asteroids for which precise orbits are known has grown to over 20,000. Most asteroids have orbits between Mars and Jupiter. In 1918 Kiyotsugu Hirayama suggested that asteroids with very similar orbits form families that have been generated by the break-up of a larger asteroid in a recent (about 100 million years ago) catastrophic collision. Julius Dohnanyi (1970) developed a collision model of asteroids in which smaller asteroids can break up bigger ones. In each collision a flood of smaller fragments is generated. He showed that the size distribution of observed asteroids is compatible with a population of objects in collisional equilibrium. In these collisions a large amount of dust is generated.

The third dusty phenomenon is the zodiacal light, visible to the naked eye in the morning and evening sky in areas free of light pollution. As early as 1683, Cassini presented the correct explanation of this phenomenon: it is sunlight scattered by dust particles orbiting the Sun. A relation to other "dusty" interplanetary phenomena, like comets, was soon suspected. Comets shed large amounts of dust during their passage through the inner Solar System, which is most visible in their dust tails. The larger of these dust grains stay for extended periods close to the orbit of their parent comet, and are recognized as a meteor shower when they cross the orbit of the Earth. The finer dust gets injected into the zodiacal cloud. Astronomical observations showed that this dust is widely distributed in the planetary system, at least out to the asteroid belt. However, the situation of a zodiacal light observer is similar to that of a person in the midst of a cloud who is trying to determine the extent and the distribution of the cloud. Many particles along the line of sight which are at different distances from the Sun and have different scattering angles (i.e. the angle between Sun and observer) contribute to the zodiacal light brightness. The zodiacal light brightness, therefore, depends both on the dust density and the scattering function, both of which are unknown functions of the distance from the Sun. A way to resolve this problem, at least partially, was developed by René Dumont (1983). He used the fact that an observer (on the Earth or on a spacecraft) who is moving through the dust cloud will observe in the direction of motion different brightnesses at different times. The difference between two brightness values corresponds to the amount of dust along the line between the two observations. Thereby, the observer is able to derive the spatial density along the line of sight.

The dust community – astronomers and space physicists

In the early days of space research, the space agencies, mainly in the USA, organized conferences and workshops to present and discuss results from space measurements of dust, laboratory simulations and theoretical studies. International exchange of latest results in dust research took place at COSPAR (Committee on Space Research) conferences. It was Curt Hemenway, from the Dudley Observatory in Albany, USA, who founded the Cosmic Dust Panel within COSPAR. At the annual (and, later, biannual) meetings, researchers from around the world met and exchanged their results and ideas on dust in space. Initially, astronomers met in parallel at meetings of the International Astronomical Union (IAU). Soon it was recognized that it was mutually advantageous to bring together these partially overlapping communities of scientists. In 1967 Jerry Weinberg organized the first international dust meeting at the University of Hawaii in Honolulu, USA, that produced a significant proceedings volume (Weinberg 1967). After that, specialized international dust meetings took place every four to five years under the sponsorship of IAU and COSPAR. The first of these meetings, IAU Colloquium No. 13, was organized in 1971 by Curt Hemenway, Peter Millman and Alan Cook (Hemenway *et al*. 1973) in Albany, USA. It was followed in 1975 by IAU Colloquium No. 31 at the Max-Planck-Institut für Kernphysik in Heidelberg, Germany (Elsässer and Fechtig 1976; the attendees of this meeting are shown in Figure 1), in 1979 by IAU Symposium No. 90 at the Herzberg Institute of Astrophysics in Ottawa, Canada (Halliday and McIntosh 1980), by IAU Colloquium No. 85 in 1984 at the Laboratoire d'Astronomie Spatiale in Marseille, France (Giese and Lamy 1985), IAU Colloquium No. 126 in 1990 at the Kyoto University in Kyoto, Japan (Levasseur-Regourd and Hasegawa 1991), IAU Colloquium No. 150 in 1995 at the University of Florida in Gainesville, USA (Gustafson and Hanner 1996), and IAU Colloquium No. 181 organized in 2000 by Ian Williams and Tony McDonnell at the University of Kent in Canterbury, England. Proceedings of these meetings are a good record of the knowledge and an indicator of the advancements in the field.

Besides these international specialist dust meetings, there are many national meetings or meetings on broader topics in which dust research plays some role. Among the regular meetings are meetings of the Meteoritical Society at which analyses of meteoritic and other extraterrestrial material are discussed; the Lunar and Planetary Science Conferences in Houston, which focus on the study of the lunar, Martian and Venusian samples and related topics; AGU (American Geophysical Union) and EGS (European Geophysical Society) meetings at which a broad range of topics in geophysics and space plasma physics are discussed; DPS (Division of Planetary Science of the American Astronomical Society) meetings at which discussions on a wide range of planetary topics take place, from observations of planetary phenomena to theories of planetary formation; and the Asteroid, Comets, Meteors (ACM) meetings, which were founded in 1983 by Hans Rickman and Karl Lagerkvist in Upsala, Sweden, and later held at



1. L. Kohoutek
2. P. Proisy
3 Mrs. Proisy
4. K.W. Michel
5. D.E. Brownlee
6. A. Mujica
7. A. Llebaria
8. W. Kokott
9. Mrs. Gehrels
10. C. Leinert
11. T. Gehrens
12. J.G. Dalcourt
13. S. Temesvary
14. R. Bloch
15. N. Pailer
16. J.L. Weinberg
17. Z. Ceplecha
18. J.G. Sparrow
19. W. Kempe
20. G. Eichhorn
21. E. Grün
22. B. Donn
23. D.A. Morrison
24. B. Marsden
25. B.K. Dalmann
26. W. Gentner
27. H.J. Völk
28. M.S. Hanner
29. F. Link
30. P. Robley
31. J.W. Rhee
32. J. Trulsen
33. Z. Sekanina
34. H.J. Staude
35. J.M. Alvarez
36. E. Pitz
37. T. Nishimura
38. S. Drapatz
39. H. Elsässer
40. P. Szkody
41. J.A.M. McDonnell
42. E. Schneider
43. V. Vanysek
44. J. Rahe
45. F.E. Roach
46. J.R. Roach
47. D.A. Tomandl
48. S. Röser
49. V. Stöhle
50. O.E. Berg
51. J. Kissel
52. R. Soberman
53. J. Hartung
54. H. Wolf
55. J.C. Mandeville
56. R. Dumont
57. B. König
58. J.E. Blamont
59. A. Levasseur
60. G.B. Burnett
61. H.U. Keller
62. J. Rosinski
63. ?
64. D.S. Hallgren
65. L.W. Bandermann
66. D.W. Hughes
67. C.F. Lillie
68. H. Lee
69. R.A. Howard
70. R.D. Wolstencroft
71. G. Morfill
72. R.H. Munro
73. G. Schwehm
74. S. Hayakawa
75. K.D. Schmidt
76. H. Link
77. M. Kröger
78 R.H. Giese
79. G. Braun
80. P.W. Blum
81. H. Tanabe
82. M. Alexander
83. A.H. Delsemme
84. H. Fechtig
85. F.L. Whipple
86. J.S. Dohnanyi
87. C.L. Hemenway
88. P.M. Millman
89. R. Wlochowicz

Figure 1 Participants of the 1975 Dust Meeting in Heidelberg (Elsässer and Fechtig 1976).

different places around the world. There are one or more meetings each year to which an active researcher in the dust field could go in order not to lose contact with the latest developments in the field.

In 1978 Tony McDonnell took up the task to assemble a comprehensive review of the "cosmic dust" field (Mc Donnell 1978). With contributions from Fred Whipple, Jerry Weinberg, David Hughes, Mayo Greenberg, Don Brownlee, D.G. Ashworth, Julius Dohnanyi and Hugo Fechtig as lead authors, a wide range of topics was covered: from zodiacal light over lunar craters to dust particles collected in the atmosphere; from dust dynamics to laboratory simulations.

It was more than 20 years before a new version of a comprehensive review of the field was published. The author, Bo Gustafson, Stan Dermott and Hugo Fechtig (Grün *et al*. 2001), edited reviews of topics ranging from near-Earth dust to circumplanetary to cometary and interstellar dust, from instrumentation over properties of interplanetary dust to orbital evolution of dust.

Table 1 lists major research centres and schools at which space dust was or is being studied. Key persons, relevant methods and space missions are given. Many early and recent dust researchers who made an impact on the field can be identified in the photograph (Figure 1), taken in 1975 at the IAU Colloquium No. 31. Since then some key figures have moved to other institutions, changed to different fields or terminated their dust research. Long-term involvement in the field and several researchers at one location have been used as criteria for inclusion in the table; however, the selection is subjective and is not complete in neighbouring fields, like comets, zodiacal light, theory, meteoritics, meteors, laboratory work, and others.

THE EARLY YEARS: FROM TOO MUCH DUST TO VERY LITTLE

Space dust: Dangerous, dirty and difficult

The danger from meteoroids to crewed and uncrewed activities was obvious. Centimetre-sized meteoroids entering the Earth's atmosphere at several tens of kilometres per second will certainly damage any spacecraft they strike. Smaller particles could also be dangerous to not-well-shielded satellites and to crewed extravehicular activity. Therefore, all space agencies considered it necessary to understand the hazard that comes from meteoroids. There were two aspects to consider: (1) the flux of meteoroids, which was a question of observations and measurements in space; and (2) the effect of hypervelocity impacts on space systems, which was best studied in the laboratory. Therefore, as one of the first space activities, vigorous research programmes were instigated to characterize the meteoroid hazard in space.

In everyday terms, "dust" is often a synonym "dirt" – something to be avoided. This is true as well for interplanetary dust. Astronomers who want to observe extra-Solar System objects have to contend with foreground obscuration by the zodiacal light. In the extremely empty space environment a few specks of dust, like paint flakes, cause significant problems to highly sensitive measurements; for example, infrared observers have to struggle with debris particles floating around their telescope. Physicist who want to study plasma effects in space have to modify their "clean" theories if dust is around. Dust is not easily controlled: it follows its own dynamics and disperses rapidly from its source, like smoke from a fire. This aspect, however, has a positive side: dust conveys messages from remote processes and objects by which it was generated.

Dust has many aspects and is thus difficult to quantify. An observer who determines one aspect of a dust particle in space, like its size, will find it difficult to determine other parameters. Dust particles come in many sizes, compositions and shapes. In all cases there is no single size, composition or shape that represents a certain space-dust environment. Therefore, many different parameters have to be measured in order to comprehensively characterize dust grains. Even if a dust particle is predominantly made of a single material, minute surface contamination changes its optical appearance so that it can no longer be easily recognized. If one wants to know the properties of an ensemble of dust particles, distributions in all relevant parameters have to be determined. Theoreticians modelling interplanetary dust have the difficulty of representing these particles by simplified models, for example a spherical particle of uniform composition and having the optical properties of a pure material. The description of the dynamics of dust involves many disciplines: Keplerian dynamics, interactions with the radiation field, and the plasma and magnetic environment. Some of the dust theories involve detailed assumptions about particle properties and the space environment that cannot be derived from first principles or that are not discernible from direct observations, and hence cause unease in theoreticians who are trained mostly in, for example, "pure" celestial mechanics. Interplanetary dust particles are difficult to characterize and to quantify, and only a small number of scientists, both experimenters and theoreticians, have dealt with them. However, it is the belief of the author that recent observational and theoretical methods are mature enough for us now to consider dust as an important and exciting subject of astrophysical research. Progress in the field is made by taking a multidisciplinary approach involving *in situ* space measurements, astronomical observations, theoretical studies and modelling, and laboratory investigations of basic processes. Close cooperation between astronomers, cosmochemists, dynamicists and experimental physicists has, in fact, been beneficial in solving dusty problems.

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