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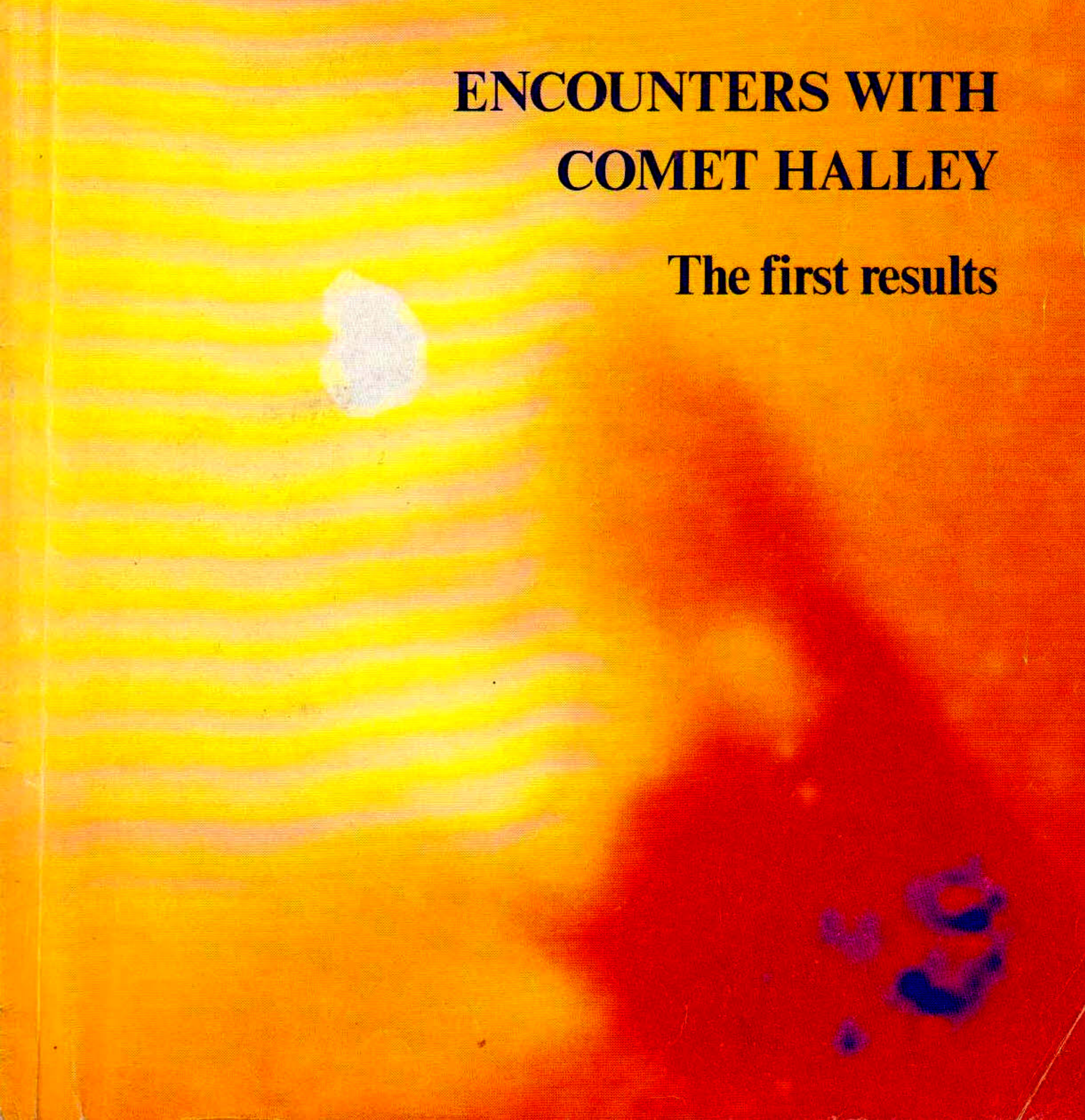
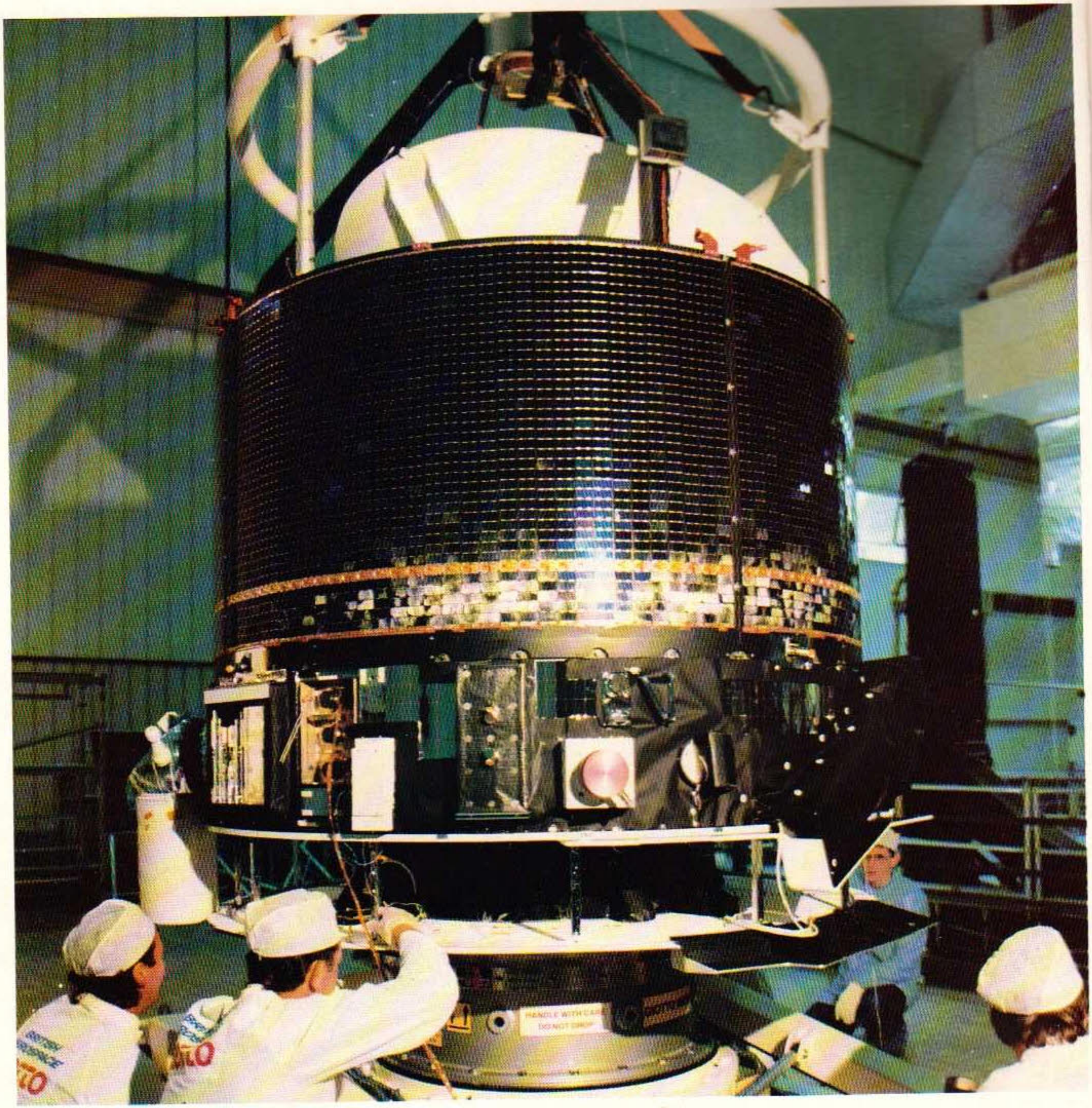
ENCOUNTERS WITH COMET HALLEY

The first results





GIOTTO – an outstanding success

The GIOTTO spacecraft was built under contract to the European Space Agency by British Aerospace leading the STAR Consortium. GIOTTO intercepted Halley's Comet on 13th March 1986. The mission was accomplished beyond all expectations so making a unique contribution to the scientific study of comets.

GIOTTO survived the barrage of cometary particles with some experiments still working. It has now been put into an orbit which will bring it within 12,500 miles of Earth in 1990.

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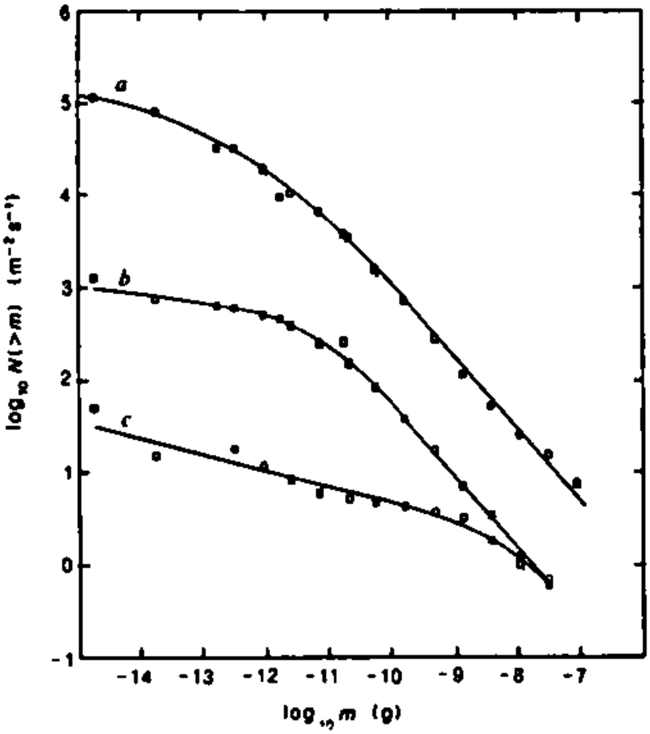

Fig. 4 Dust particle mass distributions $N(>m)$ for three regions of the Vega 2 trajectory. *a*, $t = 58$ s, accumulation time 4 s; *b*, $t = -11$ min, accumulation time 100 s; *c*, $t = -(48-28)$ min, accumulation time 20 min. Curves are preliminary best-fit lines to the experimental points.

for $10^{-12} < m < 10^{-9}$ g, $u \simeq 2.5$-3; and for $m > 10^{-9}$ g, $u \simeq 3.4$.

Note that because u is always less than 4, integration of the distribution $M \propto \int a^{-u+3}\,da$ yields a divergent result for the total dust mass. However, it is natural to expect the distribution to have a cutoff corresponding to particles of mass ~1 g which are too massive to be carried by the gas flow away from the nucleus. If we take for the dust particle velocity $v_d = 10^3\,(\rho a)^{-0.5}$ cm s^{-1} (ref. 2), we find that the total dust production rate of the comet $\dot{M}_d$ is related by a simple expression to the total mass ΔM of the dust particle flux in the size interval a_0 to a_{max} detected by the instrument sensors during the encounter:

$$\dot{M}_d = \frac{2\times 10^3}{\sqrt{\rho}} R_0 \frac{(4-u)}{(3.5-u)} \frac{a_{max}^{3.5-u} - a_0^{3.5-u}}{a_{max}^{4-u} - a_0^{4-u}} \Delta M$$

where $R_0 = 8\times 10^6$ cm is the distance of closest approach to the nucleus and ρ is the dust particle density. For the range $1 > m > 10^{-9}$ g, $a_{max} = 1$ cm, $a_0 = 10^{-3}$ cm, which provides the major contribution to the total dust mass, our data suggest that $\Delta M = 1.5\times 10^{-6}$ g cm^{-2}. This leads to an estimate $\dot{M}_d = (5-10)\times 10^6$ g s^{-1}, which agrees fairly well with the predictions of cometary dust models. By comparing this result with the gas production rate estimated from gas flux measurements[6], $Q = 1.3\times 10^{30}$ molecules s^{-1}, we conclude that comet Halley is indeed characterized by a high dust-to-gas production rate ratio, $\mu = \dot{M}_d/\dot{M}_g = 0.1-0.25$. The fact that the dust paraboloid does not have a sharp boundary can be accounted for by a large velocity dispersion of particles of comparable size, and by their nonsphericity and different lifetimes. Although the first particles to be detected were in the lowest detectable mass range, it is clear that in the periphery of the dust coma large particles are relatively more abundant than in the central regions (Figs 3, 4). This is most probably due to the resonant enhancement of the light-scattering cross-section for particles of size comparable with the wavelength[7].

Within the dust coma the particle spatial distribution exhibits a complex structure. It is remarkable that the locations of the intense peaks in the time profiles obtained from Vega 1 and Vega 2 (Figs 1, 2) agree closely, while the peak intensities differ strongly. Indeed, the first and second peaks in Fig. 1 correspond to the second and third (most intense) peaks in Fig. 2. The third peak of Vega 1 was found by Vega 2 to have diminished markedly in intensity. This pattern is undoubtedly associated with the dust jet which had been expected to exist in comet Halley. Indeed, in a photograph taken in 1910, Larson and Sekanina[8] identified three long-lived jets with a periodicity of ~20 h. Further analysis of our data should permit a reliable determination of the temporal behaviour of the observed dust jets.

We thank the many people whose dedicated work has made the Vega project, including the SP-2 experiment, possible.

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Dust counter and mass analyser (DUCMA) measurements of comet Halley's coma from Vega spacecraft

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The Vega encounters with comet Halley allowed the first direct measurements of the spatial and temporal distributions of the masses and fluxes of dust particles originating from the comet nucleus. These data are fundamental for establishing the physical processes of dust emission from the nucleus, their propagation to form a coma, and the behaviour of dust jets. The measurements reported here were made with instruments employing a new principle of dust detection[1,2], which have a high time-resolution (~4 μs) over a large range of dust fluxes and masses. The dust coma, whether quiescent (as seen by Vega 2) or containing a major jet structure (as seen by Vega 1), displays large, short-term variations throughout, which are at times quasi-periodic. The integral mass spectra increase in intensity to the lowest masses measured (contrary to some theoretical models), and the flux levels lie approximately in the ranges estimated previously from ground-based observations[6]. The coma is highly dynamical on all spatial and temporal scales, suggesting a complex structure of localized regions of dust emission from the nucleus.

The overall character of our dust measurements from the two encounters is shown in Fig. 1, in which 2-s averages of dust count rates are plotted against the time from closest approach to the nucleus by Vega 1 (*a*) and Vega 2 (*b*). These graphs display the integral count rates of all dust particles of mass $\geq 1.5\times 10^{-13}$ g. Until the onset of the large flux shown in Fig. 1*a*, which we believe to be due to a dust jet emanating from the active side of the nucleus[3] (S. Larson, personal communication),

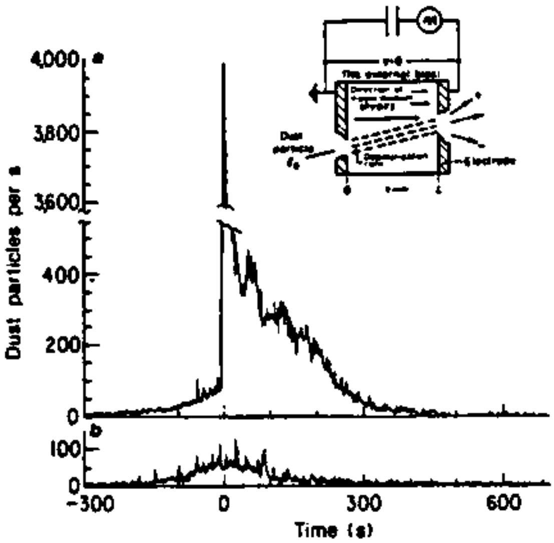

Fig. 1 Count rate of dust particles of mass $\geq 1.5\times10^{-13}$ g detected at Vega 1 (*a*) and Vega 2 (*b*), averaged over 2-s intervals and plotted against time from closest approach for each spacecraft (8,890 ± 45 and 8,030 ± 45 km, respectively). The ordinate in *a* is interrupted to allow the peak intensity to be shown. Inset, schematic diagram illustrating the PVDF detection principle[1,2].

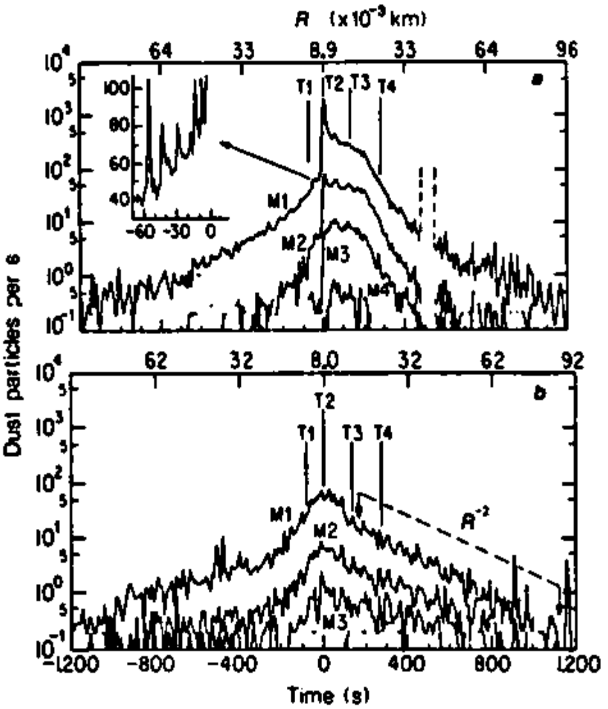

Fig. 2 Dust count rates for Vega 1 (*a*) and Vega 2 (*b*), averaged over 10-s intervals, for the four mass thresholds listed in Table 1. There was one telemetry dropout, marked by dashed lines in *a*. T1–T4 are times at which the mass spectra in Table 2 were derived. Also shown in *b* is an interval where an R^{-2} flux dependence holds for particles of mass $\geq 1.5\times10^{-13}$ g. On the scale of this figure the M4 event rates in *b* fall close to the 10^{-1} line, with only occasional values appearing above this line. Inset, detail of a portion of the M1 spectrum (time scale in seconds), showing characteristic quasi-periodic fluctuations.

the intensities and mass distributions are remarkably similar for the two pre-closest-approach periods. Because of its rotation period of ~52 h (ref. 8), the nucleus was presenting a relatively inactive side towards the Sun during the Vega 2 encounter.

The DUCMA detector of area 75 cm² was within 10° of perpendicular to the velocity vector of the spacecraft relative to the dust. Fortunately, the detector is mounted so that it cannot 'see' possible ejecta from massive dust particles striking the solar arrays or other spacecraft structures, except for a small portion of the guard cone[2], used to retain the surrounding thermal blanket. A dust particle generates an electrical pulse when it enters the detector foil, composed of the polymer polyvinylidene fluoride (PVDF), the molecules of which are polarized, as shown in Fig. 1 inset. The rapid depolarization in the volume destroyed by the dust particle induces a fast (nanosecond-range) pulse with amplitude proportional to $m^a v^b$, where m and v are the mass and relative velocity of the particle, respectively. Since v is the known spacecraft velocity (77–79 km s⁻¹), the mass of the particle can be determined. The pre-launch calibrations, responses and other details of the instrument have been published[1,2]. (All count rates designated here as M1, M2, M3 and M4 correspond in the published instrument description[2] to M1NV, M2NV, and so on.) Because there was no laboratory dust accelerator available which could calibrate our instruments up to the spacecraft velocities, we have extrapolated our calibrations into the spacecraft velocity range. The instruments on both spacecraft performed perfectly.

Figure 2 shows in greater detail the intensity-time plots for the four mass thresholds specified in Table 1. These plots illustrate the remarkable quasi-periodic fluctuations (such as those shown in Fig. 2*a* inset) which are present over a wide range of flux levels. These small-scale intensity variations which correspond to spatial structures of 200–300 km are not believed to be due to any artefacts of the missions. These flux enhancements may be present over substantial periods of time, in which case they represent fast dust streams, or microjets, along a spiral that would map back to the nucleus over a rotation angle of 30–35°. The fact that, at 8,000–9,000 km from the nucleus, some of these enhancements are only 200–300 km wide suggests that the source regions on the nucleus are small and discrete. A less likely cause of the flux enhancements might be sequences of dust bursts from the nucleus. Further study of the measurements should decide this question.

By relating time of measurement to spacecraft–nucleus distance, R, we have found, for 10^{-13} g particles, that dust fluxes within extensive regions of the coma follow an R^{-2} dependence

Table 1 Peak flux (F) and number density (N) measured by DUCMA instruments

Mass threshold		M1 ($m \geq 1.5\times10^{-13}$ g)		M2 ($m \geq 9\times10^{-13}$ g)		M3 ($m \geq 9\times10^{-12}$ g)		M4 ($m \geq 9\times10^{-11}$ g)	
Averaging interval		2 s	10 s	2 s	10 s	2 s	10 s	2 s	10 s
Vega 1	F	53	25	1.7	0.9	0.1	7×10^{-2}	7×10^{-3}	1×10^{-3}
	N	7×10^{-6}	3×10^{-6}	2×10^{-7}	1×10^{-7}	2×10^{-8}	8×10^{-9}	8×10^{-10}	2×10^{-10}
Vega 2	F	—	1	—	0.1	—	3×10^{-2}	—	—
	N	—	1×10^{-7}	—	1×10^{-8}	—	4×10^{-9}	—	—

F is measured in cm⁻² s⁻¹, N in cm⁻³.

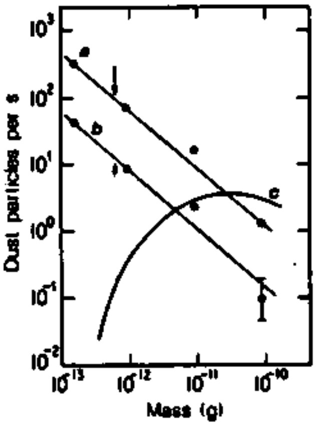

Fig. 3 Integral mass spectra derived from 2-min averages at time T3, assuming a power-law dependence, $F \propto m^{-\alpha}$. Experimental errors not shown are less than the dot diameter. The two straight lines are fits to the Vega 1 (*a*) and Vega 2 (*b*) data, with spectral index $\alpha = 0.9$. The curve *c* is the differential spectrum predicted by Carey and McDonnell[5] for direct particles at 500 km, and the arrows indicate the spectral peak predicted by Divine *et al.*[6].

(see Fig. 2*b*) out to distances of ~100,000 km; that is, beyond the distances predicted by some models[4,6].

The integral mass spectra sampled at four times by Vega 1 and Vega 2 (T1–T4, Fig. 2) have been obtained by assuming that the integral spectra in the DUCMA mass range can be represented by a power law in mass, so that the flux $F(m)$ is proportional to $m^{-\alpha}$. Values of α for each sampling time are listed in Table 2, which shows that there is a significant, progressive reduction in α at increasing (outbound) radial distances.

Table 2 Integral mass spectral index, α

Time	T1	T2	T3	T4
Vega 1	1.6	2.0	1.0	0.9
Vega 2	1.4	1.3	1.0	1.0

All values are uncertain to ±0.1.

Note that the mass spectra from the two encounters are similar, in spite of the presence or absence of a jet, and, as shown in Fig. 3, there is no experimental evidence for a significant flattening of the mass spectrum down to the lowest mass measured, contrary to the predictions of various models[5,6] that the differential spectrum should peak, as indicated in Fig. 3. Indeed, the first particles encountered at the 'fringes' of the coma (637,000 km inbound for Vega 1; 255,000 km inbound for Vega 2) had the lowest masses measured, instead of the higher masses predicted by the 'fountain' model first introduced by Eddington[7] and later widely developed to predict the mass distribution of cometary dust[5,6].

These observations, together with our observed mass spectrum, suggest that the solar radiation pressure acting on the lightest coma dust particles is smaller than suggested in the literature[6]. Alternatively, if some dust particles are comprised of much smaller particles held together by a substance which sublimes, these very small secondary particles could appear at great distances from the nucleus.

The instrumentation was designed, built and tested in the Laboratory for Astrophysics and Space Research of the Enrico Fermi Institute, University of Chicago. It was included in the Vega missions at the invitation of R.Z.S. We thank the many individuals who helped make this US-USSR space collaboration possible, notably, R. Reinhard, A. Richter, E. Grün, L. Eagleburger and G. Briggs. Support for this experiment was provided by the USSR Space Research Institute, NASA contract NAS-W-3959, and the Arthur H. Compton Fund.

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Composition of comet Halley dust particles from Vega observations

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The dust impact mass analyser (PUMA) carried by the spacecraft Vega 1 and Vega 2 has provided the first direct measurements of the physical and chemical properties of cometary dust. Particles of mass $<10^{-14}$ g are much more abundant than was predicted by models[1]. Most of the particles are rich in light elements such as H, C, N and O, lending support to models that describe cometary material as consisting of radiation-processed ices. Three examples of mass spectra for typical particle compositions are shown.

The heart of the PUMA instrument is a time-of-flight mass spectrometer as described, for example, in ref. 2. When a dust particle strikes the target in front of the spectrometer, ions are formed, and those with positive charge are mass-analysed. Onboard electronics and microprocessor-control allow the instrument to adapt to the cometary environment, and provide data compression. The instrument design was as close as possible to that of the corresponding instrument PIA, carried by the Giotto spacecraft. The PUMA and PIA instruments are described in greater detail elsewhere[3,4].

For the design of the instrument several assumptions had to be made; concerning, for example, the number and size distribution of particles that would hit the target, the chemical and physical nature of the cometary dust particles, and the nature of the process which leads to the formation of positive ions upon particle impact. Based on the cometary dust emission model given in ref. 1, a target area of 5 cm² was chosen, assuming a fly-by distance of 10,000 km. This was thought to be sufficiently large to record enough impacts but also not too large, taking into account changes in the comet's activity and the ability to handle up to 100 impacts per second. Our model for cometary dust particles was the 'Brownlee particles'[5] with a fluffy structure