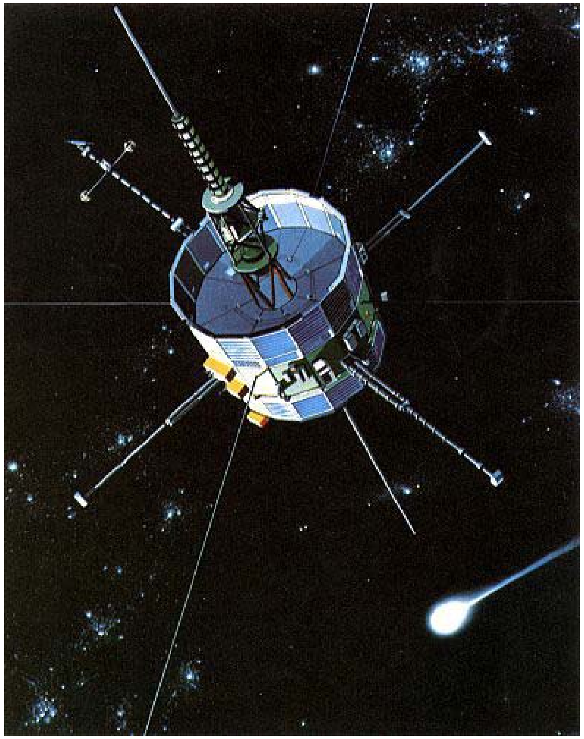
In situ studies of comets (1)

Studies carried out in vicinity of comets with help of spacecraft play an extremely important role in cometary physics.

The main advance of such studies is that the number of assumptions on cometary particles is substantially reduced in comparison with ground based observations.

So far, only six comets have been visited by spacecrafts:

21P/Giacobini-Zinner	1985	International Cometary Explorer (ICE);
1P/Halley	1986	VeGa-1, 2; Giotto; ICE; Suisei; Sakigake;
26P/Grigg-Skjellerup	1992	Giotto
19P/Borrelly	2001	Deep Space 1
81P/Wild	2004	Stardust
9P/Tempel 1	2005	Deep Impact



(1) International Cometary Explorer (ICE)

Spacecraft was originally operated as International Sun/Earth Explorer 3.

In 1982, the spacecraft was repurposed to study the comet 21P/Giacobini-Zinner.

ICE was designed for study magnetic fields.

Aim of ICE flyby near the comet was to observe the magnetic fields induced by the interaction of comet with the solar wind.

The spacecraft approached to the nucleus as close as 7800 km, passing through the ion tail.

Later, ICE flew through tail of comet 1P/Halley at 28 millions km.

(2) VeGa-1 and 2.

Spacecrafts for complex study of planet Venus and comet 1P/Halley.

VeGa-1,2 flew near the nucleus (at 8890 and 8030 km) with velocities of 79.2 and 76.8 km/s.

The closest approaches have happened on March 6 and 9, 1986.

On these days, heliocentric distances of the comet were 0.79 and 0.83 AU.

The spacecrafts were equipped with devices as follows.

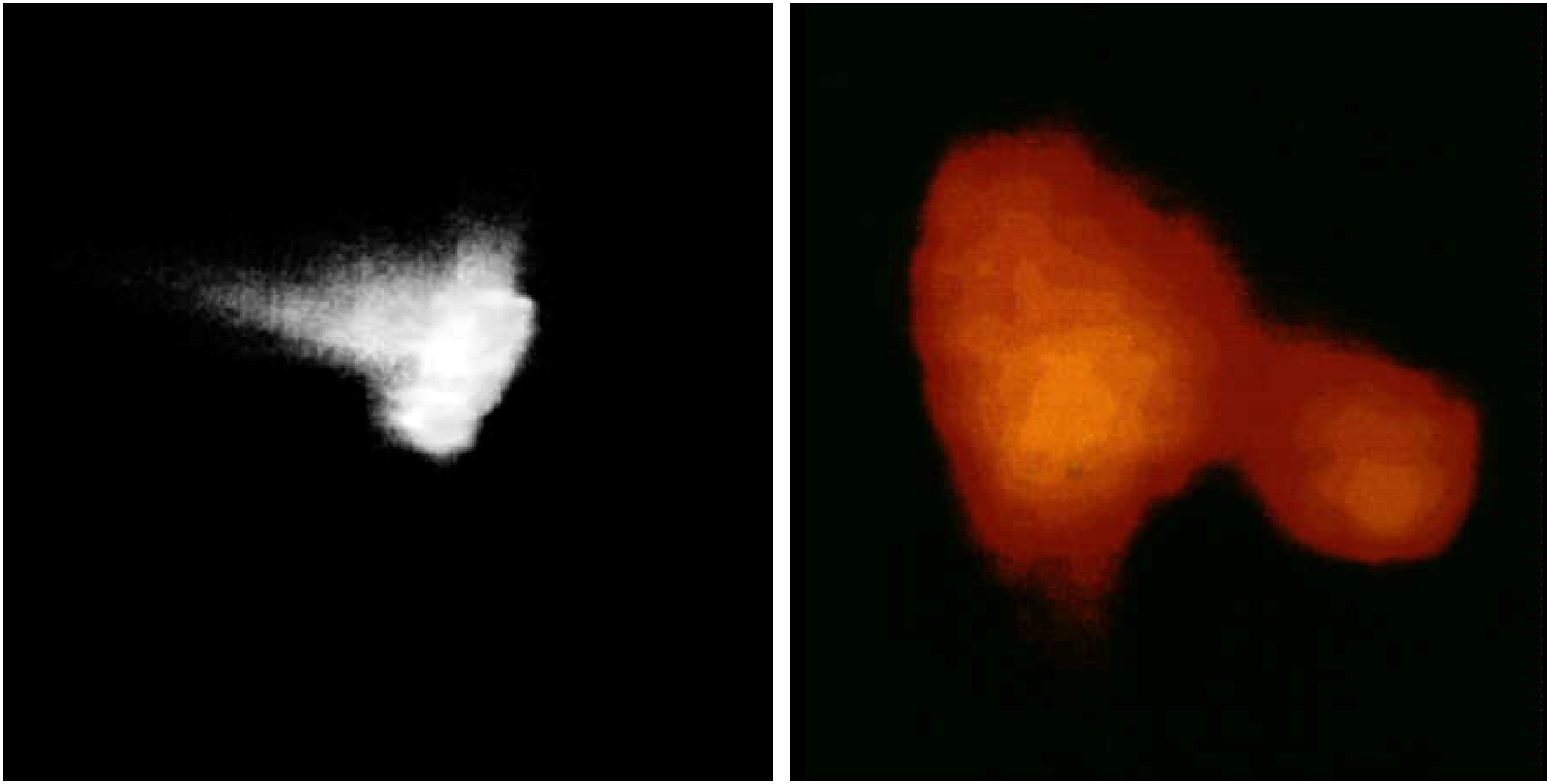
Table Scientific payload of the Vega spacecraft

Acronym	Instrument	Goal and instrument parameters
Optical experiments		
TVS	TV system	Inner coma and nucleus imaging. Two CCD* cameras (fields of view, $0.43° \times 0.57°$ and $3.5° \times 5.3°$)
TKS	Three-channel spectrometer	Spectral mapping of coma emissions in the range $0.12 < \lambda < 1.9$ μm
IKS	Infrared spectrometer	Detection of infrared emissions of coma and thermal radiation of nucleus ($2, 5 < \lambda < 12$ μm)
ASP-G	Automatic pointing platform	Pointing of TVS, TKS, IKS at nucleus region
In situ dust experiments		
PUMA	Dust mass spectrometer	Dust particle elemental composition
SP-1	Dust particle counter	Dust particle flux and mass spectrum ($m > 10^{-16}$ g)
SP-2	Dust particle counter	Dust particle flux and mass spectrum ($m > 10^{-16}$ g)
DUCMA	Dust particle detector	Dust particle flux and mass spectrum ($m > 1.5 \times 10^{-13}$ g)
FOTON	Dust particle detector	Large dust particle detection (under anti-dust shield)
In situ analysis of neutral gas, plasma and fields		
ING	Neutral gas mass spectrometer	Neutral gas composition
PLASMAG	Cometary plasma spectrometer	Ion flux composition, energy spectra of ions and electrons
TÜNDE-M	Energetic particle analyser	Energy and flux of accelerated cometary ions
MISCHA	Magnetometer	Magnetic field
APV-N	Wave and plasma analyser	Plasma waves, 0.01–1,000 Hz, plasma ion flux fluctuations
APV-V	Wave and plasma analyser	Plasma waves, 0–300 kHz, plasma density and temperature

Principal findings made by VeGa-1,2 are as follows.

1. The nucleus is an elongated body with long axis measuring 14±1 km and short axis of 7.5±1 km; whereas, rotation period is of 53±3 hours.
2. Though images of the nucleus obtained by VeGa-1 and 2 have appeared in rather poor quality, one can determine that main emission of the material happens from sunlit side of the nucleus through five-six jets.
3. Geometric albedo is about 4±2%. Since this value goes fairly along with the ground-based estimation (5%), there was deduced the average optical thickness $\tau < 1$ ($\tau = -\ln(I/I_0)$), in vicinity of nucleus.
4. The temperature of the nucleus was found to be about 300–400 K. This finding contradicts with assumption of snow on the surface.

Principal findings made by VeGa-1,2 are as follows.



Images of the nucleus of comet 1P/Halley taken by VeGa-2

Principal findings made by VeGa-1,2 are as follows.

5. Gas production rate was found 1.3×10^{30} molecules/s (VeGa-1, 2); if the gas is H_2O, mass production rate is 4×10^{4} kg/s.
6. Total dust production rate is of 10^{4} kg/s (VeGa-1) and 5×10^{3} kg/s (VeGa-2); at that, the dust production rate in the mass range $m\leq10^{-13}$ kg is of 300 kg/s.
7. Dust-to-gas ratio is varied from 0.1 to 0.25.
8. Using the dust particle counters, the first dust particles were detected at distance of 3.2×10^{5} km from the nucleus. The sharp increase of number density of particles with masses 10^{-19} – 10^{-18} kg was observed at distance of 1.5×10^{5} km. For particles with larger masses (10^{-17} – 10^{-15} kg), the boundary of the dust coma was found at closer distance.

Principal findings made by VeGa-1,2 are as follows.

9. The mass distribution of dust particles measured with SP-1 detector (ionization) was found to be $n(m) \propto m^{-\alpha}$. For particles with masses $m \leq 10^{-15}$ kg, $\alpha = 1.25 \pm 0.05$; whereas, for $10^{-15} < m < 10^{-13}$ kg, $\alpha = 1.5 \pm 0.05$. In assumption of spherical shape of dust particles, it gives the size distribution $n(r) \propto r^{-a}$. At $m \leq 10^{-15}$ kg, a = 1.75; at $10^{-15} < m < 10^{-13}$ kg, a = 2.5.
10. The mass distribution of dust particles measured with SP-2 detector (acoustic) was found to be $n(m) \propto m^{-\alpha}$. In assumption of spherical shape of dust particles, the size distribution takes a form $n(r) \propto r^{-a}$. At $10^{-19} < m < 10^{-15}$ kg, a = 1.5–2.5; at $10^{-15} < m < 10^{-12}$ kg, a = 2.5–3; at $m > 10^{-12}$ kg, a = 3.4.

(3) Giotto.

Spacecrafts for complex study of comets 1P/Halley and 26P/Grigg-Skjellerup.

Giotto flew near the nucleus (at 600 km) with velocity of 68 km/s.

The closest approach has happened on March 14, 1986 (five days later than VeGa-2).

For this date, heliocentric distances of the comet was 0.9 AU.

The spacecrafts were equipped with devices as follows.

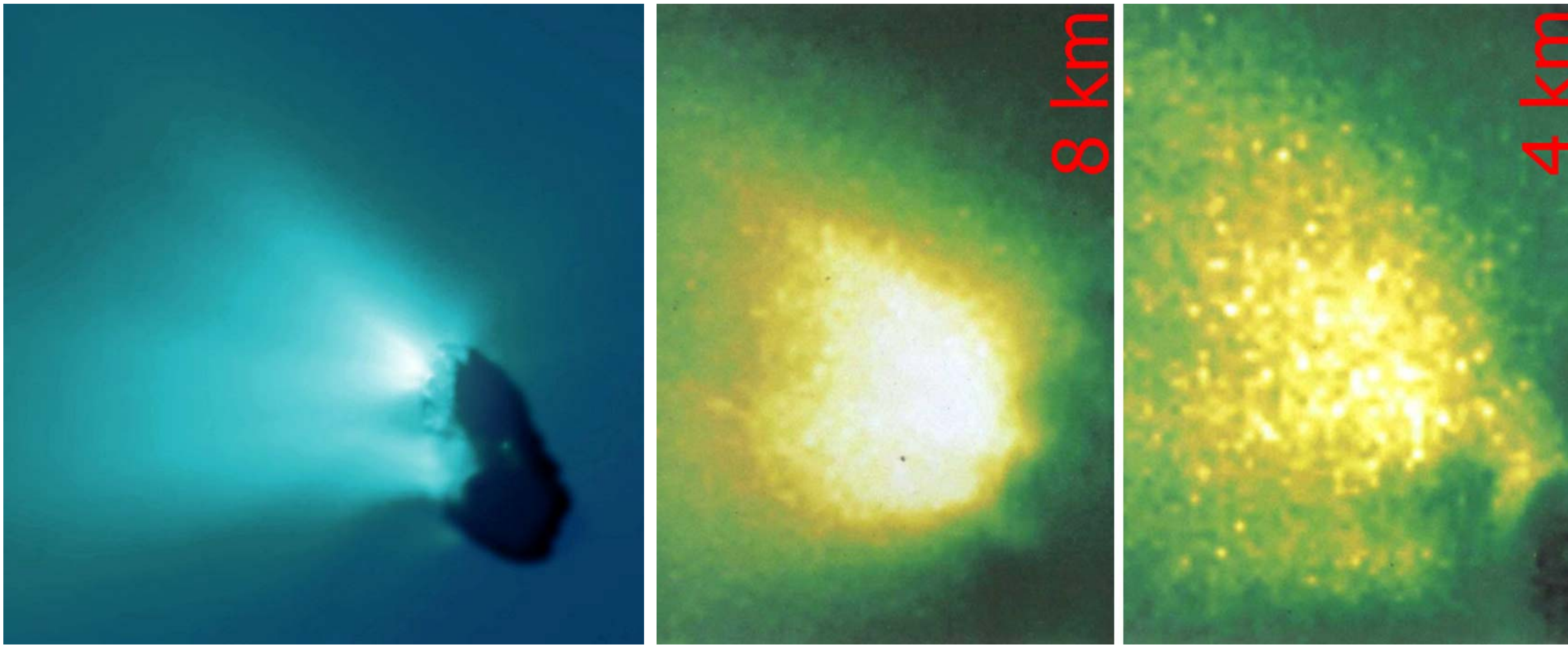
Table Giotto scientific payload

Experiment (acronym)	Mass (kg)	Data rate (bits s^{-1}) F1*	F2†	F3‡	Goal and instrument parameters
Camera (HMC)	13.51	20,058	20,058	723	Inner coma and nucleus imaging, CCD§ narrow-angle camera, 11-m resolution from 500 km
Neutral mass spectrometer (NMS) M-analyser E-analyser	12.70	4,156	4,156		Neutral gas composition M-analyser: 1–36 AMU E-analyser: 1–57, 9–89 AMU
Ion mass spectrometer (IMS) High-energy-range spectrometer (HERS) High-intensity-range spectrometer (HIS)	9.00	3,253	3,253	1,084	Ion composition HERS: 1–35 AMU/q HIS: 12–57 AMU/q
Dust mass spectrometer (PIA)	9.89	2,891	5,782		Dust particle flux and composition, 1–110 AMU, 3×10^{-16}–5×10^{-11} g
Dust impact detection system (DID) Meteoroid shield momentum sensor (MSM/RSM) Impact plasma and momentum sensor (IPM) Capacitor impact sensor (CIS)	2.26	361	903		Dust particle flux and mass distribution IPM: 6×10^{-17}–6×10^{-11} g CIS: $>10^{-10}$ g MSM/RSM: 10^{-10}–10^{-1} g
Plasma analysis 1 (JPA) Fast ion sensor (FIS) Implanted ion sensor (IIS)	4.70	3,975	1,265	1,355	FIS: 3-dimensional ion velocity distributions, 10 eV–20 keV IIS: ion flux, mass and velocity distributions, 90 eV–90 keV, 1–45 AMU/q
Plasma analysis 2 (RPA) Electron electrostatic analyser (EESA) Positive-ion cluster composition analyser (PICCA)	3.21	2,530	1,807	904	EESA: 3-dimensional electron velocity distributions, 10 eV–30 keV PICCA: composition of cold ions, 10–50 AMU, 50–203 AMU
Energetic particle analyser (EPA)	0.95	181	181	181	Energy and flux of electrons and accelerated ions, ⩾20 keV
Magnetometer (MAG)	1.36	1,265	1,265	407	Magnetic field, 0.004–65,536 nT, up to 25.4 vectors s^{-1}
Optical probe experiment (OPE)	1.32	723	723		Coma brightness in 4 continuum bands (dust), 4 discrete emissions (OH, CN, CO^+, C_2)
Radio-science experiment (GRE)					Dust and gas column densities in the coma
Total	58.90	39,393	39,393	4,654	

Principal findings made by Giotto are as follows.

1. The nucleus is an elongated body like a potato. The major axis is ~15 km and the minor axis is of 7 – 10 km.
2. Images of the nucleus obtained by Giotto appeared in quite good quality, one can determine that main emission of the material happens from sunlit side of the nucleus through two major and five faint jets.
3. Geometric albedo is about 2-4%. The average optical thickness was found to be $\tau < 1$ in assumption of quite low geometric albedo (3%) of single particles forming jets.
4. Two bright jets are originated from areas with diameter of ~3 km. One of these area reveals highly discrete structure.
5. Gas production rate was found to be of 6.9×10^{29} molecules/s with an uncertainty of 50%; whereas, 5.5×10^{29} molecules/s are caused by water vaporization (~10^4 kg/s).

Principal findings made by Giotto are as follows.



Images of the nucleus of comet 1P/Halley taken by Giotto

Principal findings made by Giotto are as follows.

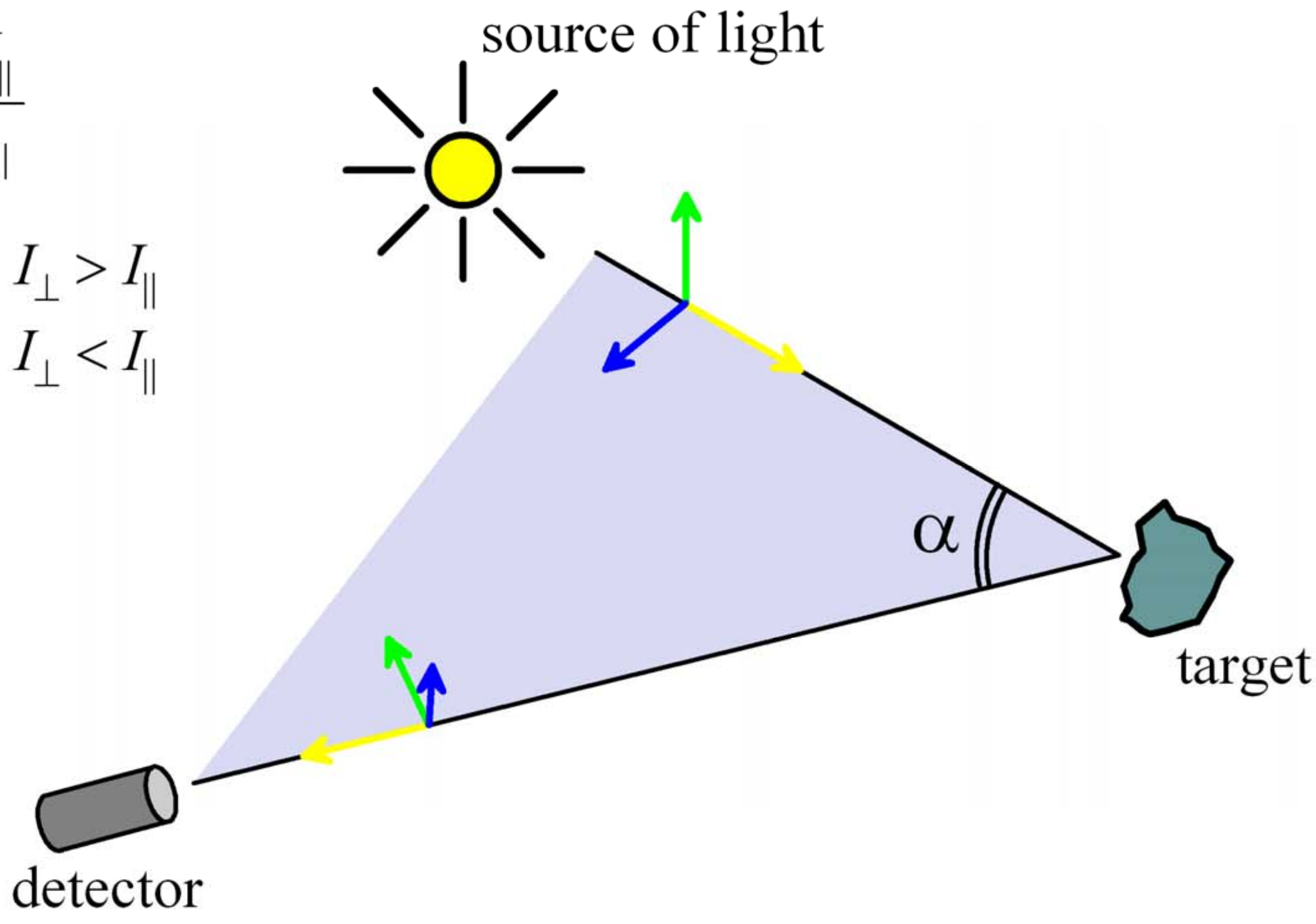
6. Total dust production rate is of 3.1×10^3 kg/s.
7. The first dust particles were detected at distance of 2.9×10^5 km from the nucleus.
8. The observed dust size spectrum at 2200 km from the nucleus can be approximated by a power law $n(r) \propto r^{-a}$ with index a = 2.98±0.15.
9. Within Optical probe experiment, there were obtained profiles of intensity and degree of linear polarization of the scattered light through the inner coma of 1P/Halley. These parameters play a key role in cometary physics since they are only available parameters in ground-based observations.

Definition of the degree of linear polarization.

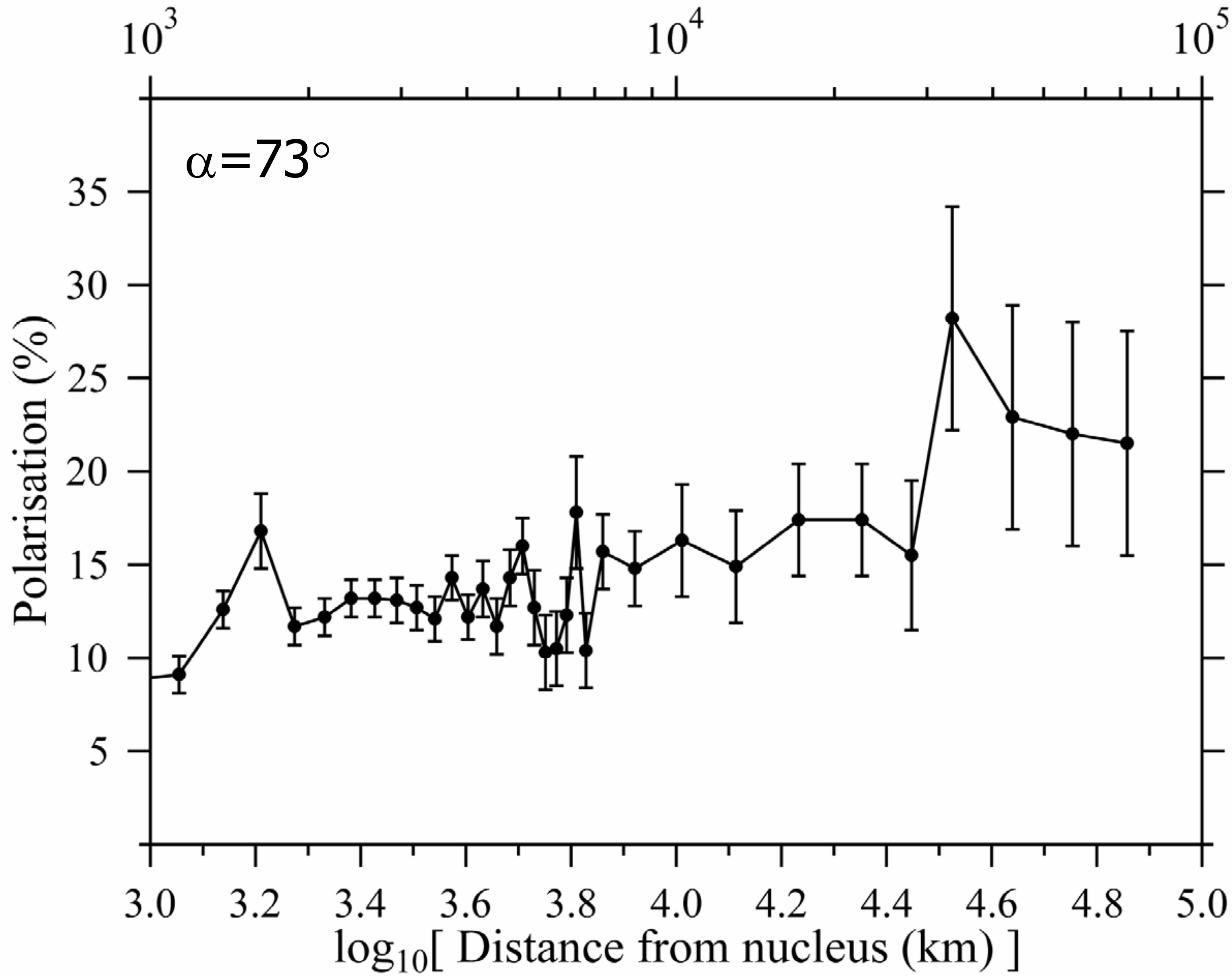
$$P = \frac{I_\perp - I_\parallel}{I_\perp + I_\parallel}$$

$$P > 0 \text{ if } I_\perp > I_\parallel$$

$$P < 0 \text{ if } I_\perp < I_\parallel$$



Principal findings made by Giotto are as follows.



Summary of dust mass spectrometry carried out by VeGa-1, 2 (PUMA-1, 2) and Giotto (PIA).

1. Cometary dust consists mainly of H, C, N, O, Si, Mg, and Fe.
2. Dust particles are intimate mixtures of two components, dubbed CHON (rich in elements H, C, N, and O) and Rock (rich in Si, Mg, Fe), respectively.
3. The CHON component is refractory organic material.
4. The Rock component includes Mg-rich Fe-poor silicates, metals, oxides, sulfides, and others.
5. Dust grains can be classified into three groups: CHON-rich particles (mass of carbon exceeds mass of any rock-forming component for more than 10 times), Rock-rich particles (mass of carbon is less than mass of any rock-forming component for 10 times), and Mixed particles (all the intermediate cases). 25% of the studied particles are CHON-rich, 25% – Rock-rich, and 50% – Mixed particles.

Summary of dust mass spectrometry carried out by VeGa-1, 2 (PUMA-1, 2) and Giotto (PIA).

6. Iron-rich particles present in cometary dust in amount of 6.5%. More than half of them appear as metal particles (1.1%), iron sulfides (1.9%), and Fe-rich silicates (0.8%).
7. In a particle composed of almost pure carbon, isotopic ratio $^{12}C/^{13}C$ is as high as 5000. It links cometary matter to circumstellar graphite grains.
8. Particles masses and densities were estimated to range from 10^{-19} to 10^{-14} kg (approximate diameter range 0.02 to 2 μm) with densities from 300 to 3000 kg/m^3.
9. An overall dust-to-gas ratio is of 2.
10. An overall mass ratio of silicates to organics in comet 1P/Halley dust is between 2 and 1.
11. Particles containing some amounts of organics (CHON and Mixed) are relatively more abundant closer to the nucleus.

(4) Study of comet 26P/Grigg-Skjellerup with Giotto.

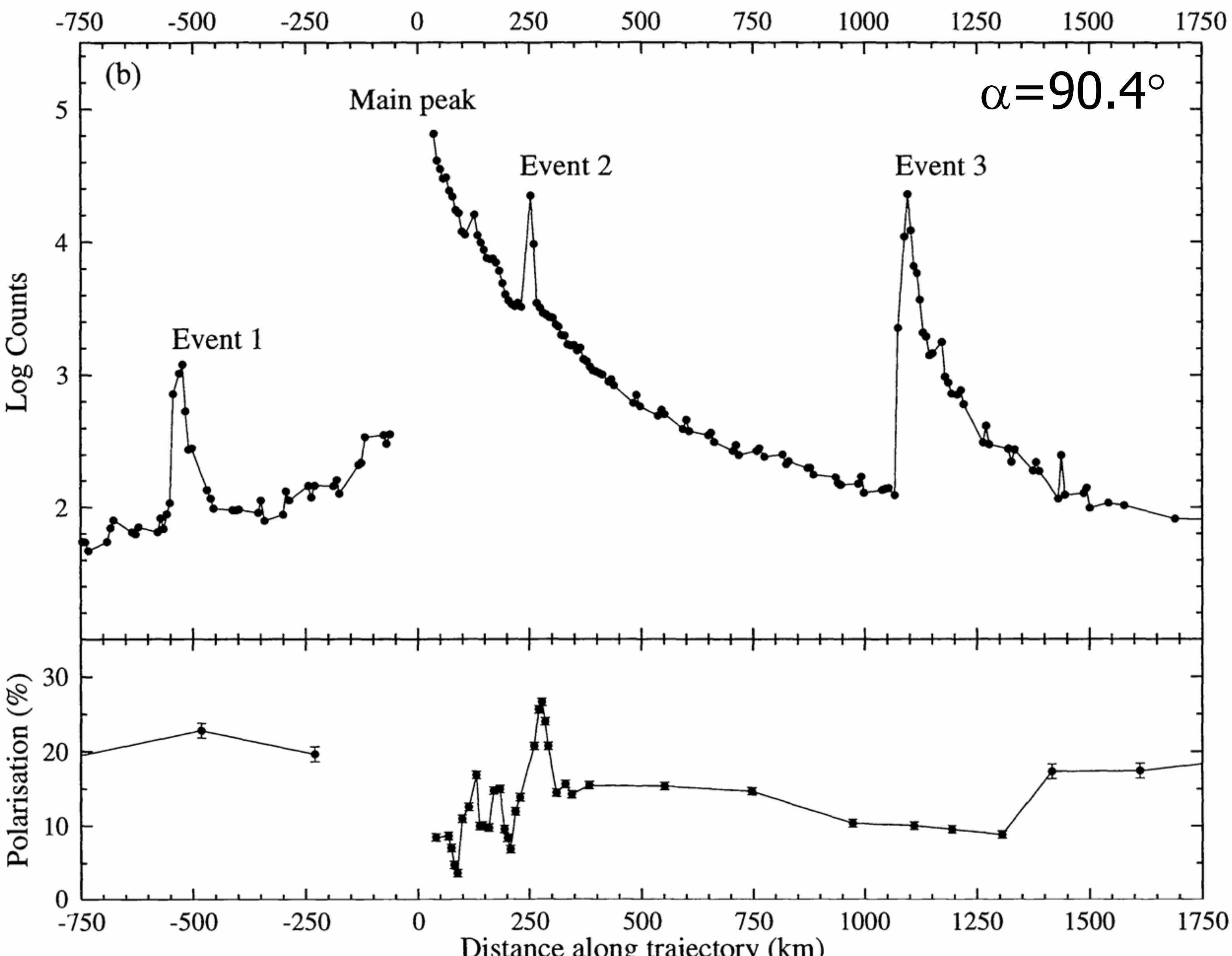
Giotto flew near the nucleus (at 100 – 300 km) with velocity of 14 km/s.

The closest approach has happened on July 10, 1992. For this date, heliocentric distances of the comet was 1 AU.

After the approach to comet 1P/Halley and the six-years flight, the devices aboard Giotto were definitely not in good shape; almost nothing was working properly, maybe, only Optical probe experiment (OPE).

Also, there were registered only 3 impacts into Dust impact detector (DID). However, it did not come as a surprise because the dust production of comet 26P/Grigg-Skjellerup is for 200 (!) times less than that of 1P/Halley.

Optical probe experiment for comet 26P/Grigg-Skjellerup



(5) Deep Space 1.

Spacecrafts was dedicated for testing advanced but high risk technologies (e.g., artificial intelligence control system to control a spacecraft without human supervision and ion propulsion engine).

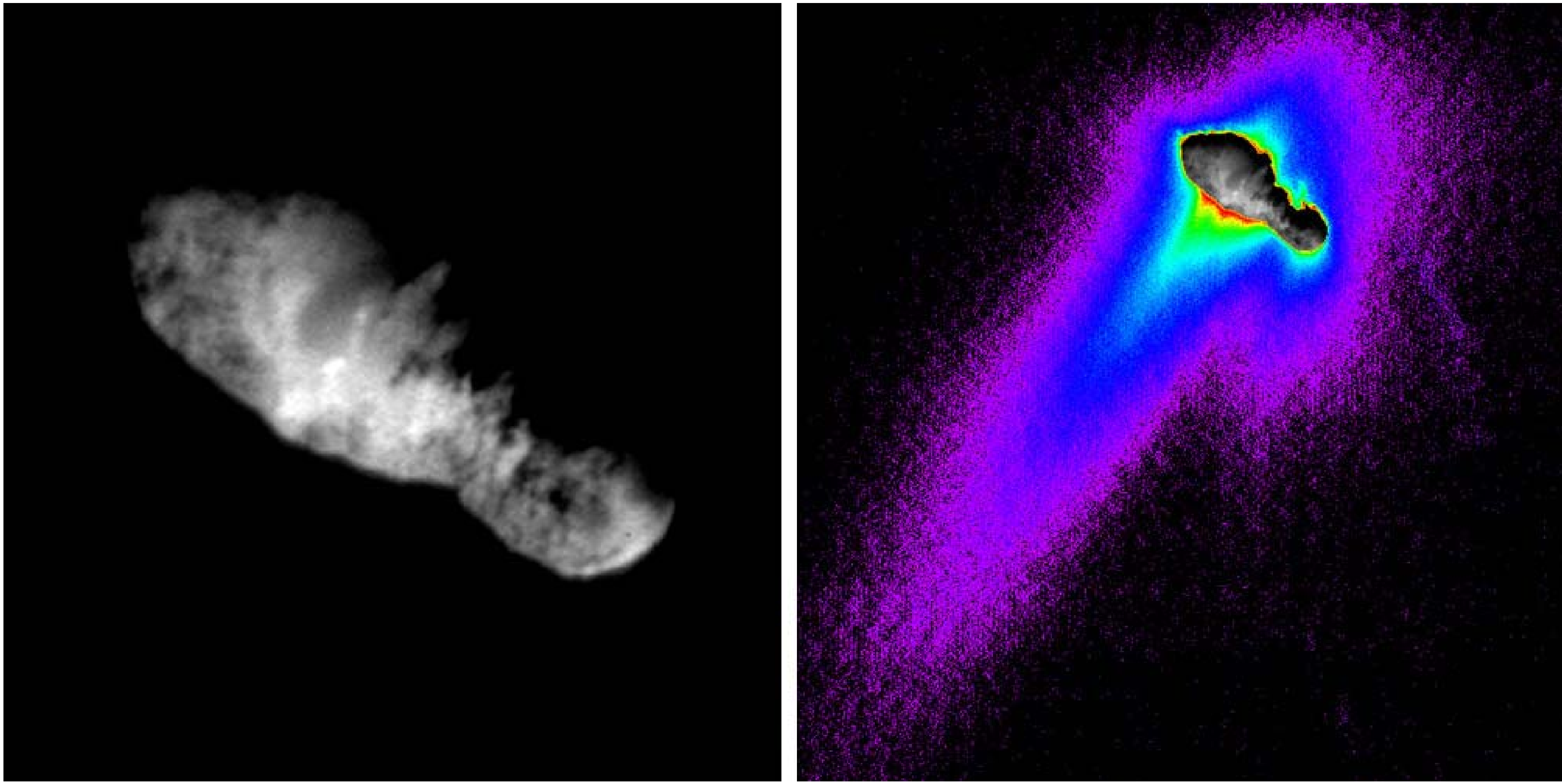
One of secondary goals was comet 19P/Borrelly.

Deep Space 1 flew near the nucleus (at 2170 km) with velocity of 16.5 km/s.
The closest approach has happened on September 22, 2001.
For this date, heliocentric distances of the comet was 1.36 AU.

Principal findings made by Deep Space 1 are as follows.

1. The nucleus is an elongated body. Visible side has sizes 8×4 km. There is no evidence for impact craters with diameters larger than 200-m. It is not typical for surface of asteroids.
2. The entire nucleus is extremely dark with geometric albedo ranging from 0.7% to 3.5%.
3. Surface is quite hot (≤345 K).
4. Extensive release of the dust is observed in quite few places (90% of the surface is inactive). There is only one prominent jet. At high resolution, this jet is resolved into at least three smaller collimated jets nearly parallel to each other in the sunward hemisphere. Diameter of small jets is about 0.5 km.
5. In addition to the collimated jet-activity, there is a non-collimated activity. However, such activity is also originated in limited number places.

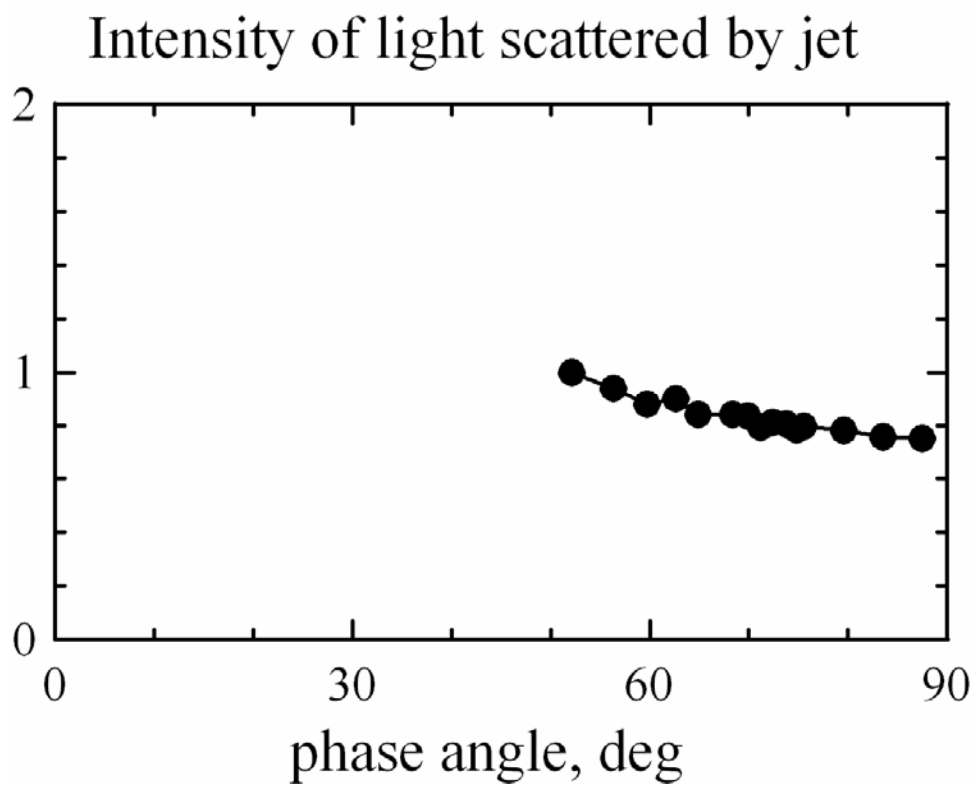
Principal findings made by Deep Space 1 are as follows.



Images of nucleus (left) and jets (right) of comet 19P/Borrelly

Principal findings made by Deep Space 1 are as follows.

5. Asymmetry in the dust from dayside to nightside is pronounced (ratio is about 2:1).
6. The obtained images span phase angles from 88° to 52°. It allows to retrieve the angular profiles for intensity of light scattered by jets.



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