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Letter to the Editor

GIOTTO, an Artificial Asteroid Probing the Coma of Comet P/Halley

Herbert Porsche (retired), Institut für Hochfrequenztechnik of DLR, D-82230 Wessling, Germany
Joachim Kehr (Editor, Journal of Space Operations and Communicator, http://opsjournal.org)

Foreword

More than 28 years ago the European spacecraft GIOTTO had passed through the innermost regions of the coma of comet P/Halley. A group of scientists: the Giotto Radio Science Experiment (GRE) group, had joined to investigate the radio signals traveling from the spacecraft to the ground stations. The influence of the cometary atmosphere on the spacecraft, especially possible disturbances or density variations would show up in the received signal as Doppler frequency changes or variations in the received signal power. Therefore the detailed monitoring of the radio signals would give valuable insights in the whole dynamics of the cometary atmosphere. In several publications (*Pätzold et.al.,* [3 to 7]) the GRE group published their results of the data evaluation. *Porsche* had analyzed the data of the experiment in a different way. Because of a number of obstacles these results have never been published.

It is the merit of the editor of this journal, *Joachim Kehr,* to encourage *Porsche* to present this late publication of his results and interpretations, quite different to those of his colleagues.

Abstract

Numerous earlier publications Pätzold et al [3 to 7] provided interpretations of the Giotto Radio Science Experiment (GRE) measurements as recorded during the flyby period. From the frequency changes as received at the ground station (NASA Station in Australia) the Doppler residuals were deduced. Every Doppler shift was interpreted as a velocity change of the onboard transmitter, and consequently as that of the spacecraft. The reason for such accelerations or decelerations were related to particle impacts of suitable magnitude and impact place. No attention was given to possible influences of the gaseous atmosphere. As presented in this up to now not published assessment, the physical analysis of the GRE data, respecting available temperature measurements during the flyby is yielding a comprehensive interpretation of the interaction of the spacecraft with the atmosphere of the comet Halley and is analyzing the possible structure of the innermost coma of the comet. The analyzed data are only referring to the Giotto flyby as close as 598 km distance from the nucleus of comet P/Halley.

1. Introduction

On March 13 to 14, 1986 the European spacecraft GIOTTO penetrated the coma of comet P/Halley. By interaction between the atmosphere of the comet and the spacecraft its velocity and attitude was influenced. A resulting shift in the down link frequency was observed by NASA's ground stations (primarily Canberra, Australia). As proposed by the GRE experimenters the one-way Doppler residuals collected by the stations had to be analyzed in order to gain insights into the structure of the atmosphere of the comet and the actual deceleration of the spacecraft.
These data were supported by two-way Doppler registrations before and after the flyby of the comet. In Figure 1 the obtained one-way Doppler residuals supported by signal level registrations are plotted.

General mission properties of Giotto including a detailed description of the spinning spacecraft (the spin rate was 15 rpm) is summarized in the following.
The most important details affecting the GRE analysis were:

- the properties of the telecommunication system and an
- aluminum protection shield (1 mm thick, 1.92 m in diameter, 2.88 m^2 total surface) protecting against

impacting gas and dust particles and the

- 80 cm wide cylindrical solar generator wrapped around the spacecraft's body.

The telecommunication system consisted of two transmitters for X-band transmission at 8,429 GHz resp. for S-band transmission at 2,299 GHz. The de-spun parabolic antenna reflector was always pointing towards Earth as long as it worked properly. Two-way Doppler registrations were taken at the ground stations via an on-board transponder.
During the flyby in front of the comet, the spacecraft axis pointed in the direction of the relative velocity spacecraft-comet (see also Fig. 3).

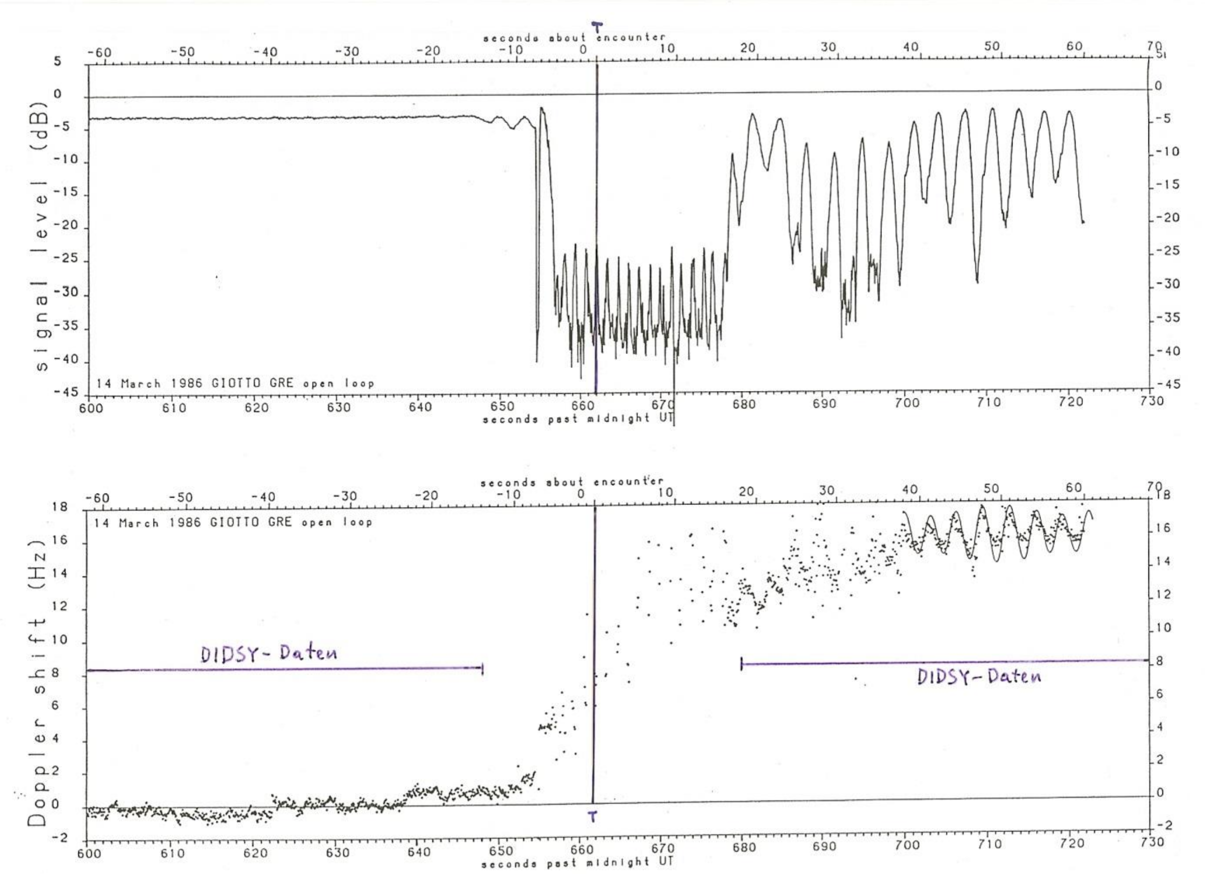


Figure 1: Lower graph: One-way Doppler residuals as determined by the ground stations.
Upper graph: Received signal power, the data transmission was interrupted between T -17 s and T + 20 s (T = encounter time), distance from the nucleus R = 1,307 and 1,492 km. During this interval nothing else than the carrier at 8,429 GHz could be received at very low signal to noise ratio. (Pätzold [1]).
T is marked on top of the two plots.

The angle towards Earth's direction was 44.3 deg (direction of the de-spun antenna). Thus almost all matter surrounding the comet impacted on the aluminum protection shield. The central part of the shield was a half sphere protecting the main rocket motor. The half-sphere could be opened to allow the operation of the motor. The space between the protection shield and the main spacecraft body was 10 cm. The shield was fixed, thermally and electrically isolated from the spacecraft body by 16 Teflon bolts. Only a few additional openings were cut into the shield as windows for experiments and one of the dust experiments was directly mounted on the shield. This experiment had a gold plated surface for thermal protection. The solar generator consisted of solar cells attached to the cylindrical surface like a belt 80 cm in height (see Fig. 2). To prevent the cells from being damaged by energetic particles as well as from high voltage arching, all cells were covered with 0.3mm thick 5%-CeO-doped quartz-layers. The doping reduces the specific resistance of the quartz, thus solar UV irradiation could no longer cause high voltages on the surface of the cells. Figure 3 shows the flyby geometry.

2. Energy and Momentum Conservation

While the spacecraft penetrated the coma of the comet it was bombarded with material surrounding the comet like gas and dust particles. The exchange of energy between the particles from the comet and the spacecraft must follow the energy conservation principle. As long as the impacting particles do not penetrate the protection shield it is:

$$m_0 v_0^2 = M \Delta v^2 + mv^2 + 2(m_0 D_0 + m_0 Q + m D) \qquad (1)$$

m_0= Impacting mass from the comet
M = 573.7 kg = Spacecraft mass
m = Impact-generated debris particles
v_0 = 68,373 m/*s* = velocity of the impacting material
Δv = Spacecraft's velocity decrement
v = Debris' mean velocity
Do = Specific energy necessary to destroy the impacting particles
Q = Specific energy losses (e.g., heating of the target)
D = Specific energy to release (and ionize) debris particles

Note: The relative energy of the material impacting at the protection shield is 24.4 e V/amu. This energy is related to the most abundant molecular types i.e., H_2O, and is equivalent to a temperature of $\vartheta_{H_2O} = \frac{m_{H_2O}\, v_0^2}{3} k \quad = 3.4 \cdot 10^6$ *K. (k = Boltzmann's constant)*

Certainly, $v_0^2 \gg D_0$. Therefore D_0 can be neglected, also Q is zero, since the temperature of the shield is constant. Therefore one can write:

$$\frac{m}{m_0} = \frac{v_0^2}{v^2 + 2D} \qquad (2)$$

In the first instance the evaluation of Eq. (2) shall be restricted to the period before the encounter i.e., as long as all experiments could receive valid data. This is the period up to about T - 17 s (T $=$ encounter time; distance from the nucleus R $=$ 1,307 km). Up to about 5 s prior to t=T, the velocity decrement was below the noise level, although the particle- and gas experiments observed increasing material flux.
The intercepted material impacted on the aluminum protection shield (almost 80% of the shield consisted of aluminum). The energy of the impacting particles was much higher than the sublimation and ionization energy of Al of about 9.6 eV/Al^+. Therefore it is certain that most of the generated debris particles were ions.

The sublimation and ionization energy of the other shielding materials is of the same order of magnitude. It may be appropriate, therefore, to set $D =$ 9.6 eV/ion ~ 3.48 10^7 J/kg. These data allowing to determine an upper limit for:

$$\frac{m}{m_0} < \frac{v_0}{2D} = 68. \qquad (3)$$

To find an appropriate estimate for velocity v, it may be assumed that the whole momentum of the particles is certainly not larger than the total momentum of the impacting particles. This gives:

$$m_0 v_0 = \frac{m}{\mu_{Al}} \cdot e \int \frac{d\Phi}{dr}\, dt - mv \qquad (4)$$

Φ = potential of the Al-target

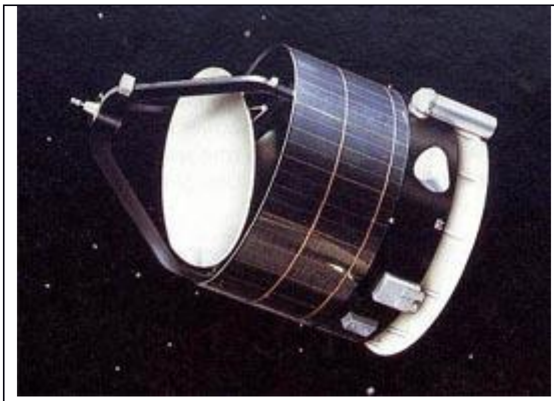


Figure 2: Giotto spacecraft configuration, the protection shield is ▲ on the right hand side.

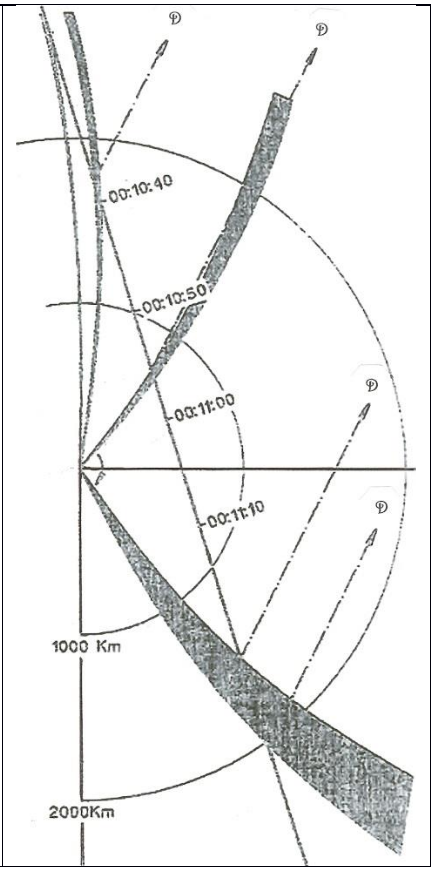


Figure 3: Flyby geometry; the curved shaded cones indicate plasma jet streams. The diagonal straight line indicates the flight pass of Giotto (with encounter time ticks), 𝕻 indicates the direction of the Earth line of sight). ►

With the solution:

$$|v| \leq \approx 2200 \text{ m/s} \;; \quad \frac{m}{m_0} \approx 61 \tag{5}$$

This results in the density relation

$$\frac{\varrho}{\varrho_0} = \frac{\dot{m} v_0}{\dot{m}_0 v} \approx 1900 \tag{6}$$

and in the number density water /aluminum

$$\frac{N}{N_0} \cdot \frac{\mu_0}{\mu} \approx 1270 \tag{7}$$

3. Aerodynamic-Plasma Shock Wave.

Krankowski *et al.* [9] (1986) have measured the gas density of the impacting water vapor, CO_2, etc., Figure 4. All particles streaming against the spacecraft must penetrate the cloud of debris ions before they arrive at the protection shield. The gas and dust particle density follows roughly a R^{-2} law (Krankowski *et al.* [9], 1986; McDonnell *et al.* [10], 1987). As the density of the secondary particles is proportional to the density of the matter surrounding the comet, the number of collisions must follow a R^{-4} law (Porsche & Hoell, [11], 1991). The mean free path length can be estimated as:

$$\Lambda \approx \frac{1}{\sigma N} \tag{8}$$

Λ = Mean free path length
σ = Collision cross section: primary particle - Al-ion (Coulomb collisions)
N = Number density of the debris plasma

A good estimate of the collision cross section of a H_2O-dipole and an Al^+-ion may be: $\sigma \approx 10^{-18} m^2$.

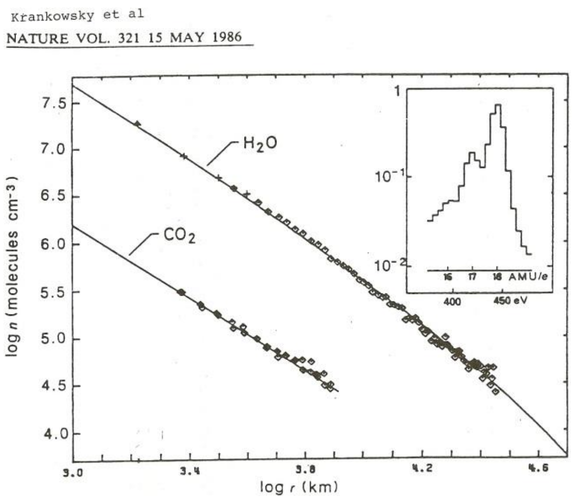


Figure 4: Gas Densitiy Measurements (Krankowski)

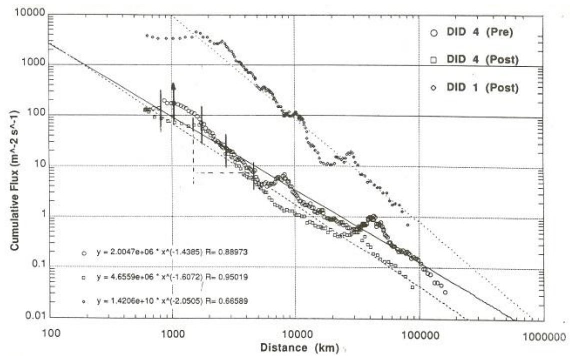


Figure 5: Results of Dust Count Experiment (DIDSI)

From the results of the dust count experiment DIDSY (McDonnell *et al*, [10]) (Figure 5) and the gas analyzer experiment (Krankowski *et al*. [9], 1986) (Figure 4) the number density N can be estimated. Immediately before the data transmission was interrupted, i.e., before the dust experiment stopped, the number density of H_2O from the comet at a nuclear distance of 1,660 km was determined to be $N_{H_2O,1660km} \approx 2 \cdot 10^{13}\ m^{-3}$.

The generated debris ion density was then $N_{Al,1660km} = 6 \cdot 10^{16}\ m^{-3}$.

Assuming an inverse square law, this would increase to $N_{Al,600km}$, $\approx 4.6\ 10^{17}\ m^{-3}$ at closest approach.

Here the mean free path length of the impacting water molecules would be not more than about $\Lambda \approx 2m$.

Impacting dust particles and the gas molecules other than H_2O add substantially to the debris ion density, the mean free path length was certainly considerably shorter.

The relative velocity between the particles from the comet and the debris ions is supersonic. As soon as the mean free path length is comparable to the typical dimensions of the target body, which is about 2 m, an aerodynamic-plasmatic shock must have built up.

The indication of such a shock is the event at T - 15 ($\pm$ 2) s (R = 1,187 ± 110 km), the spacecraft signal began to show varying values and got very noisy (Figure 1, upper panel). At the same time the data transmission was interrupted, i.e., no on-board data could be received any longer. While during the last 5 to 7 seconds earlier no variations in velocity exceeding the noise could be observed, a blue-shift of the carrier frequency started to build up right at that time. The signal level was reduced by 25 to almost 40 dB. The intensity at this very low level was modulated by a 1.33 s oscillation.

Bird *et al* [8], 1988 and Pätzold *et al* [3-7], 1991 interpreted this oscillation as an electrical/mechanical disturbance of the antenna pointing system. They believe the spacecraft had received an unknown sudden electrical impulse which caused antenna misdirection. A well-defined reason for such an impulse could not be offered.

Right at the time when the shock started to build up at T-15sec (R $=$ 1190 km) the spacecraft began to nutate with a period of 3 sec.

Pätzold et al assume an impact of a heavy grain as the reason for this event. They disregard that such an impact would generate instant oscillations while an increased oscillation was observed (Figure 8).

Moreover, for larger particles heavy enough to transfer a strong momentum to the spacecraft, the mean free pass length within the AL^+ atmosphere would be much shorter than the pass length of water molecules (Porsche and

Hoell [11]) for μm particles the mean pass length would not exceed 10^{-4} mm. However, a well defined reason for such an impulse could not be offered.
Consequently it is not possible that impacts of heavy particles could be the reason for the nutation as Pätzold *et al* argue.
There is still other evidence supporting the interpretation of the measured data during this time period as the result of the build-up of a shock wave.
For normal operations the neutral gas mass spectrometer had to be supplied with high voltage. Therefore the experiment is endangered of malfunction in case of corona discharges. During the probe's comet encounter penetration of Al+-plasma through the openings (provided for the experiment sensors) was unavoidable. Consequently the experiment stopped its operation while the shock piled up.
The camera electronics switched off during the shock built-up as well. Housekeeping data reported an under-voltage condition.
High currents introduced by the shock-compressed ("shocked") plasma must be expected thus causing the decrease in voltage.
Moreover, when the spacecraft had recovered from the shock generated stress the camera worked normal again but could not detect any light source. Even the strongest sources like that of planet Jupiter triggered no signal. Most likely the baffle had bent due to the high shock temperature. It shadowed the optical receiver completely. This interpretation is further supported by a measured change of the camera baffle system's moment of inertia.
The pressure of the shock compressed plasma on the spacecraft is proportional to the observed deceleration of the spacecraft after the shock had piled up. From Figure 1 the average deceleration of the spacecraft caused by the pressure of the shocked plasma can only be roughly estimated. It is equivalent to a pressure on the protection shield of $p \approx 2.4$ Pa.
It is difficult to estimate the temperature of the shocked plasma, since the collisions between the impacting molecules (H_2O, CO_2, CO etc.) and dust particles with the Al^+-ions may cause not only destruction, fragmentation etc., of the impacting particles but also chemical reactions like the generation of AlOH etc. Without doubt however, the temperature of the shocked plasma could be expected to be very high. This correlates with a steep temperature increase of the protection shield starting at moment of the shock building-up (Figure 6).
After passing through the closest approach, the density of the medium surrounding the comet decreased. Therefore the breakdown of the shock was to be expected. Also, after the shock had broken down no deceleration should be measurable as was the case before the shock had piled up.
This is from T +10 (± 2) s (R = 908 ± 110 km) onwards. Most probably the deep spike at T=671 s (Figure 1 upper panel) indicates the breakdown of the shock.
Assuming the dust and gas mass distribution around the comet follows an inverse square law of the distance from the nucleus, it is possible to estimate a lower limit of the total mass impacting the spacecraft. It is not possible to estimate the flux exactly, because although the pressure of the shocked plasma is caused by the impacting matter, only part of the pressure building up the shock wave is transferred into the pressure of the shocked plasma. This plasma mass drained off through the gap between the shock front and the spacecraft's rim.
For the deceleration of the spacecraft passing through the shock wave phase one can write:

$$\dot{m}_0 v_0 \geq M\dot{v} \qquad (9)$$

For an estimate of the total impacted mass, the inverse square law is applied

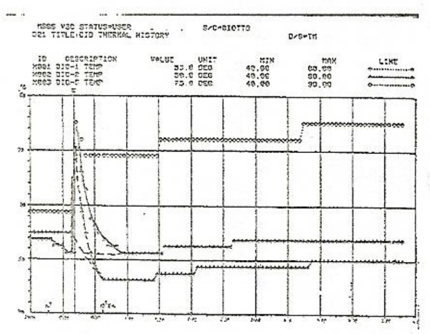
$$\dot{m}_1 \left(p^2 + v_o^2\, t_1^2\right) \approx \dot{m}_2 \left(p^2 + v_o^2\, t_2^2\right) \qquad (10)$$

p = 598 km; encounter distance from the nucleus,
t_1, t_2 = time before or after the encounter.

$$m_0 = \int \dot{m}_0\, dt \geq \frac{M\ p^2}{\mathrm{v}_0} \int_0^\infty \frac{\Delta\dot{\mathrm{v}}}{p^2 + \mathrm{v}_0^2 t^2}\, dt \qquad (11)$$

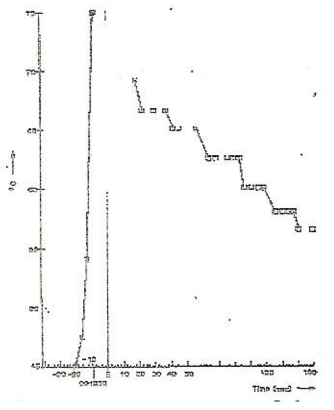
`The total impacting mass is the integral of the mass rates

resulting in $m_0 \geq \pi \frac{Mp\Delta\dot{v}}{v_0^2} = 2.8gr.$ (12)



◄ **Figure 6**: Temperature data of 4 measurement channels. At the time of the built-up of the shock,the temperature of the protection shield increased by 3 K/s.

Figure 7: Temperature of a selected protection shield channel around the closest approach. ►



4. Temperature Measurements

Figure 6 gives the temperature measurements of four temperature detectors (measurement channels), two of which were mounted at the back side of the protection shield. Figure 7 is an enhanced plot of the selected, most interesting temperature measurement. First of all, despite the increasing dust and gas flux the temperature did not increase during the inbound phase of the flyby before the shock began to pile up at about T - 15 s (R = 1,187 km). Even a slight decrease of the temperature cannot be excluded. As already mentioned in chapter 3, the pile up of the shock was accompanied by a steep increase of the protection shield temperature of about $\Delta\vartheta \approx 3$ K/s. This temperature increase is due to heat transfer of about 21 kW to the protection shield or approximately 7.25 kW/m^2. Of course, the heat source is the shocked plasma in front of the protection shield.
To estimate the temperature of the shocked plasma, it is assumed again, like in chapter 3 that the potential of the protection shield did not change considerably compared with the conditions before the shock had piled up. This assumption might not be appropriate for exact calculations. However, for the sake of discussion, only rough estimates are possible after all.

The heat transfer may be described by:

$$\frac{1}{2}\dot{m}_s v_s^2 \;=\; c\varrho F\delta\dot{\vartheta} \qquad (13)$$

c = specific heat of the protection shield material (mainly Al) = 896 J/kg·K
ϱ= specific mass of the protection shield material ($\varrho_{\,Al}$ = 2700 kg/m^3)
ϑ = temperature of' the protection shield
This results in a mean velocity component of:

$$v_s \;=\; 6380\, ms^{-1} \qquad (14)$$

This velocity allows to estimate the shock cone ς. It is

$$\varsigma \;=\; arctan\,\frac{v_s}{v_0} \;\approx\; 5degr \qquad (15)$$

From around T + 20 s (R = 1,492 km) onwards data reception could be re-acquired from those experiments having survived the flyby as well as associated temperature data could (Figure 6 and 7) be transmitted again.

After the heating of the protection shield the temperature decreased by about - 0.15 K/s. One might guess that this temperature decrease is primarily caused by heat radiating off the protection shield. However, this is not the case, as can be demonstrated by a brief assessment:

$$AB_{Al}\cdot S\;\cdot cos\psi \;=\; Em_{Al}\;\cdot\sigma\cdot\vartheta^4\;+\varrho_{Al}\;\cdot c_{Al}\;\cdot\delta\;\cdot\dot{\vartheta} \qquad (16)$$

AB_{Al} = Absorption of aluminum
Em_{Al} = Emission of aluminum,
S ≈ 1,700 W/m^2 = Solar constant at the current location of the Giotto spacecraft,
ψ= 72.8 deg = angle of incidence on the protection shield,

ϱ_{AL}= 2,700 kg/m^3 = specific mass of aluminum,
c_{Al} =896 J/kg·K = specific heat of aluminum,
∂ = 10^{-3} m = thickness of the aluminum protection shield,
σ = 5,662 10^{-8} W/m^2K^4.

The left side of Eq. (16) describes the radiation absorbed by the protection shield. The first term of the right side is the radiation emitted by the hot shield and the second term gives the heat loss of the shield.

For $\vartheta \approx 340\,K \;\; Em_{Al} \approx 1.44$ (17)

a realistic value would be *Em < 0.1*. Thus the temperature decrease of the protection shield after the flyby cannot be explained by a radiation effect of the aluminum material. The most probable reason causing the temperature decrease is cooling by sublimation and ionization.

If this would be the case, essentially it must be possible to estimate the amount of debris respectively the mass of the impacting material. Conservation of energy of course must be true also. Supplementing Eq. (1) or Eq. (2) yields

$$\dot{v_0^2} = 2\rho_{Al}c_{Al}\delta F\dot{\vartheta} + \frac{m}{m_0}\dot{m}_0(v^2 + 2D) \tag{18}$$

As the temperature is decreasing $m/m_0 > 61$ and

$$\dot{m}_0 > \frac{2\rho_{Al}\, c_{Al}\delta\, F\, \dot{\vartheta}}{61(v^2 + 2D) - v_0^2} \approx 3.85 \cdot 10^{-5}\, kgs^{-1} \tag{19}$$

Again, let the total impacting mass follow an inverse square law, Eq. (10), then for t_{20} = T + 20 s, this mass would be:

$$m_0 > \pi m_{0,20}\, \frac{p^2 + v_0^2\, t_{,20}^2}{p\, v_0\, t_{20}} \approx 6.6\, gr \text{ or } 3\, gm^{-2} \tag{20}$$

5. Potential Around the Solar Generator

A thorough analysis of Giotto's nutation during its flight through the coma of comet P/Halley has been provided by Bird *et al* [8].

However, these authors as well as Pätzold *et al* [3-7] assumed that the nutation of the spacecraft was stimulated by one or more impacts of heavy dust particles on the protection shield. As the stimulation of nutation started simultaneously with the built-up of the shock wave (Fig. 8), this assumption is unlikely. Those grains had to penetrate through the dense Al^+-atmosphere of debris ions before they could arrive at the shield. That means, they had to overcome many millions of collisions with ions, each of which could transfer about 670 eV. It is by far more realistic to assume the plasma shock wave was the source of the observed nutation.

A candidate for stimulating the nutation is the interaction of ions draining off from the shock region through the narrow gap between the spacecraft's cylindrical surface of charged quartz layers on top of the solar cells and the shock wave. These quartz sheets, doped with CeO, shielded the solar cells from being damaged by high energetic particles as well as by high voltage arching generated by solar UV light. Nonetheless the specific resistance was still sufficiently high to allow the built up of a potential. The potential was high enough to generate Coulomb forces with the ions drifting away.

As the spacecraft is rotating, the solar UV will build up a high potential at the sunlit side, while decreasing at the dark side. The process is described by the differential equation:

$$C\,\Phi\,\dot{\Phi} + \frac{\Phi^2}{R} = J\,cos\varphi \tag{21}$$

C = capacity of the quartz sheets,
Φ = potential,
R = resistance of the quartz sheets,
J = ionizing solar irradiation,
φ= angle of incidence: ω = the angular velocity of the spacecraft.

Eq. (21) can be transformed into:

$$\Phi \frac{d\Phi}{d\varphi} + \frac{\Phi^2}{\tau\omega} = \frac{J\varrho\delta}{\tau\omega} \, cos\varphi \qquad (22)$$

$\tau = R \cdot C$ = the time constant of the quartz sheets,
ρ = specific resistance of the sheets: $R = \rho\vartheta/A$; A = projected area,
$C = \varepsilon \cdot \varepsilon_0 A/\vartheta$.
The solution of Eq. (22) is for the dark side:

$$\Phi^2 = \Phi_{\frac{1}{2}}{}^2 exp\left[\frac{2}{\tau\omega}\left(\frac{\pi}{2} - \varphi\right)\right] =: X(\varphi) \qquad (23)$$

For the sunlit side:

$$\Phi^2 = X(\varphi) + \frac{J\Delta\delta}{\frac{\tau\omega}{2} + \frac{2}{\tau\omega}}\left(-exp\left[\frac{2}{\tau\omega}\left(\frac{\pi}{2} - \varphi\right)\right] + sin\varphi + \frac{2}{\tau\omega}\cos(\varphi)\right) \qquad (24)$$

Typical estimated values are:
$10^{10} < \rho < 10^{12}$ Ωm;
$\vartheta = 3 \cdot 10^{-4}$ m;
$J \approx 1.7\, Wm^{-2}$ (estimated 1% of the whole solar constant being ionizing UV with an ionizing efficiency of about 10%).
$\varepsilon = 4$;
$0.35 < \tau < 35$ s.

The range of potential differences in the possible range of time constants is given in Figure 9.
Apparently the difference in the potential of the sunlit side versus the dark side is almost in resonance with the rotation period of the spacecraft. Therefore this difference is at or near its maximum. The Coulomb forces between the Al^+-shock ions drifting away along the flanks of the spacecraft and the charged quartz sheets covering the solar cells transfer a torque on the spacecraft which indeed can be the source of the observed nutation.

The potential distribution for Φmax ≈ 37 V (Φ_{max} - Φ_{min}~28 V) is plotted in Figure 9.

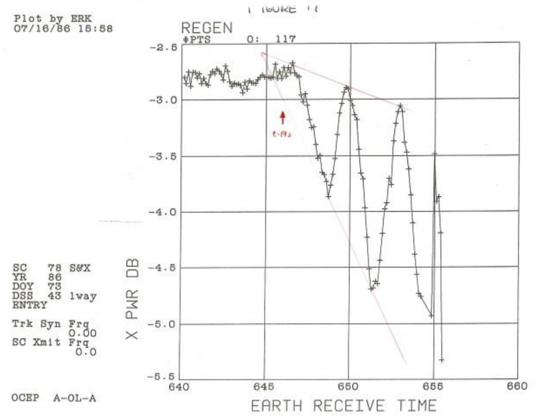


Figure 8: Begin of the nutation simultaneously with the built up of the shock wave.

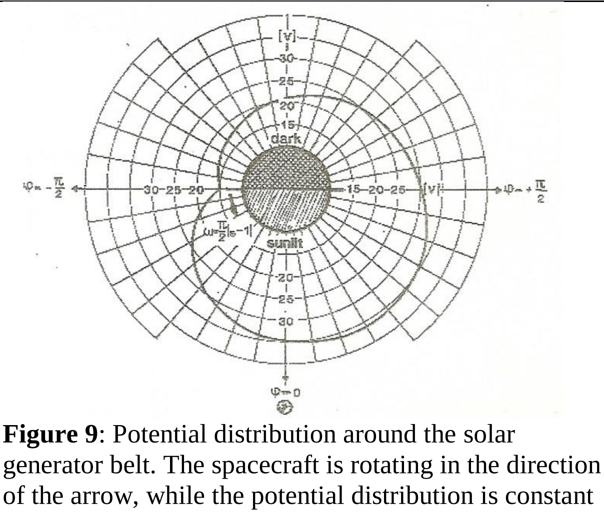


Figure 9: Potential distribution around the solar generator belt. The spacecraft is rotating in the direction of the arrow, while the potential distribution is constant with respect to the solar direction,

6. Stimulation of Nutation

Following the analysis of the nutation of Bird et al ([8], ESA-J. 12, 1988) the angular momentum is:

$\underline{L}_T = \Phi \cdot \omega$= 7,804kgm^2 s^{-1} (25)
Φ = moment of inertia
ω = angular velocity

Fig.9 is a plot of the potential distribution around the solar generator. The shocked ions drifting off must pass by the quartz covers of the solar generator.

For a rough estimate one may set:

$$m_{Al}\,\frac{d\underline{v}}{dr} \approx e\frac{d\Phi}{dr} \rightarrow m_{Al}\Delta\,\underline{v}\frac{\Delta r}{\Delta t} \approx e\Delta\Phi \rightarrow \Delta\underline{v}^2 \approx \frac{e}{m_{Al}}\Delta\Phi \tag{26}$$

e = elementary charge

The total momentum transferred to the spacecraft is the difference of the momenta sunlit side vs. dark side:

$$\Delta\Phi \quad \leq 35V \rightarrow \Delta\underline{v} \leq 12.6\,km\,s^{-1}\,;\, \Delta\Phi \geq 15\,V \rightarrow \Delta\,\underline{v} \geq 7.9\,km\,s^{-1} \tag{27}$$

This gives a resultant of $\delta\Delta\underline{v} \leq 4.7\,km\,s^{-1}$
causing an angular momentum:

$$|\underline{L_T}| \approx n m_{Al}\delta\Delta\underline{vr} \tag{28}$$

The average lever arm is estimated $\underline{r} \approx 0.6\,m$. Therefore, to generate the necessary torque $n \geq 6 \cdot 10^{22}\,Al^{+}$ ions are needed.

In chapter 4 the total amount of Al-ions was estimated to be 6.6 gr, which is equivalent to $2 \cdot 10^{24}$ ions, well in agreement with the amount necessary to generate the observed nutation. Of course, the force between the shocked plasma and the potential on the solar generator may not only generate nutation motions by one of its components. It may also shift the spacecraft sideways and additionally influence the spin of the spacecraft. A more precise treatment regarding all these influences would need a more sophisticated analysis which is not a topic of this paper.

7. Dust-Plasma generated X-band Absorption

From T + 23 s onwards the received intensity is showing a reduction by up to about 5 dB (Figure 1). Pätzold et al assume this reduction in intensity to be due to a deviation of the spacecraft antenna by a few degrees caused by the impact of a large dust particle.

The self-adjusting antenna system would have recovered such a deviation and returned to nominal operations after approximately 20 s. Therefore this interpretation of the minimum of the received intensity is not convincing.

An impact of a heavy particle would have caused an instantaneous, large deviation of the antenna, while the data show a slow decrease of intensity followed by a slow recovery to its former original value. Besides the fact that even at T + 23 s a particle impact would still be not probable due to the atmosphere of secondary emissions in front of the protection shield. In case of such an impact-generated deviation of the antenna the reduction of intensity would have happened instantaneously, not slowly.

In chapter 4 the case of an ionized dust cloud was discussed. Dust ion atmospheres are known to be absorbing electromagnetic waves in case of suitable dust densities. The flyby geometry shows that the radio waves must penetrate the plasma jet streams on their way from the spacecraft to earth (Figure 3). It is indeed possible that such a dust filled jet-plasma might absorb even X-band radio waves when travelling through such dense jet-plasma.

Following the general theory of wave propagation the absorption is described by

$$ln\frac{I}{I_0} = -4\pi\,\frac{f}{c}\int_s \kappa(s)ds \tag{29}$$

$$f = 8.429\,GHz$$

c = velocity of light
s = way of wave propagation
κ= absorption coefficient
I, I_0= received intensities

The absorption coefficient is given by

$$\kappa(s) = \frac{1}{12}\pi^3\,N_e(s)\frac{e^2}{\varepsilon_0 m_e f^2}\,\frac{\nu(s)}{f} \tag{30}$$

m_e= electron mass
$\nu(s)$= number of Coulomb collisions between electrons and charged dust particles
$N_e(s)$= number of electrons per m²
$\nu(s)$, the mean collision frequency, is a function of the plasma density N(s) and of the mean collision cross section *S*.

$$\nu(s) = N(s)S\,u \qquad (31)$$

where *u* is the mean relative electron velocity (~ square root of the electron temperature).
Within the magnetic cavity of the comet i.e., in the innermost regions of the coma the temperature is of the order of a few hundred K. Therefore predominantly single ionized particles can be expected: $N(s) = N_e(s)$.
The absorption must follow the rules of quantum physics. Therefore by collisions only the energy equivalent to the temperature can be exchanged between the X-band wave and an absorbing particle, where :

$$hf = \frac{\bar{m}}{2}\,(u^2 - u'^2) \approx \bar{m}u\delta;\ \delta = u - u' \ll u;\ \bar{m} = \frac{m_i\,m_e}{m_i + m_e} \qquad (32)$$

That means, the transferred energy does not depend on the relative particle velocity (its temperature) alone, but on the product $u\delta = const$ of the energy.
Following the deduction of *Burgers* [12] (Eq. 23.11) one gets:

$$S = \frac{e^4 ln\Lambda}{16\pi\varepsilon_0^2(hf)^2} \qquad (33)$$

as only the energy *hf* can be exchanged, *Burgers* ([12], Eq 23.10) defines $\Lambda =: 3k\Theta_{ie}\frac{3\pi\dot{\varepsilon}_0 R_D}{e^2}$ (34)
with $\Theta_{ie} = \frac{m_i\Theta_e + m_e\Theta_i}{m_i + m_e}$ (35)
R_D = Debye length
The cross section as defined by (32) is the virtual equivalent (Coulomb) cross section to transfer quantum energy *hf* by collisions. In the innermost regions of the coma, i.e., the collision dominated region of the atmosphere, Θ_e can not deviate too much from Θ_i. Therefore $\Theta_{ie} \approx \Theta$.
The Debye length is given by:

$$\frac{1}{R_D} = e \cdot \sqrt{2\frac{N}{\varepsilon_0 k\Theta}} \qquad (36)$$

This gives:

$$\Lambda = \frac{12\pi}{e^3} \cdot \sqrt{\frac{(k\Theta\varepsilon_0)^3}{2N}} \qquad (37)$$

In conclusion: The definition for the mean particle velocity $u = \sqrt{\frac{3k\Theta}{m_e}}$ and an inverse square law for the density distribution in the jet $N = N_0 \cdot \frac{R_0^2}{R^2}$, $R_{0,R}$= distances from the cometary nucleus, reveal with the phase angle φ, $R = 7.5\ km$, and $f = 8.429\ GHz$

$$ln\frac{I}{I_0} = -\frac{e^6 u}{48\pi^3\varepsilon_0^3 m_e h^2 f^4} \cdot \frac{R_0^4 N_0^2}{cos\varphi} \cdot \int ln\left(\Lambda\frac{R}{R_0}\right) \cdot \frac{dR}{R^4} \qquad (38)$$

$$ln\frac{I}{I_0} \approx 1.92\ 10^{-16}\left\{\frac{\sqrt{\Theta}N_0^2}{cos\varphi} \cdot \frac{7.74 + ln\frac{\Theta^3 R}{2}N_0}{R^3}\right\}_{R1}^{R2} \qquad (39)$$

No = const. can be set, because the logarithm has not been considered for the integration, since it is almost constant in each integration interval.
Eq. 39 can be solved for N_0. From Fig. 3 one can estimate:
$\varphi = 106\ deg$; and from Fig. 6: $\Theta \approx 350\ K$.

The results of the maxima of the oscillation amplitudes (Fig. 1, upper panel), which are considered to be usable points to determine the ratio $\frac{I}{I_0}$, are given in Table 1:

time s	$-ln\frac{I}{I_0}$	$R_1\ km$	$R_2\ km$	$N_0\ m^{-3}$	$N\ m^{-3}$
20.0	0	1495	1495	0	0
23.0	0.07	1685	1644	$3.6 \cdot 10^{16}$	$0.73 \cdot 10^{12}$
26.2	0.44	1891	1803	7.3	1.2
29.5	0.59	2106	1967	8.57	1.16
32.7	0.40	2316	2126	7.11	0.81
36.0	0.44	2535	2290	7.73	0.75
39.2	0.15	2748	2449	4.67	0.39

Table 1: N_0 values for T=20 sec to T= 39 sec

The $N_0 -$ column gives the density near the nucleus provided the density is following an inverse square law. Its mean value, disregarding the values at the rim of the jet (T + 23 s and T + 39 s), gives;

$N_0 = (7.7 \pm 0.9)\ 10^{16}\ m^{-3}$. (40)

$n = N\, v_0\, A\, \Delta t \approx 3 \cdot 10^{18}$ (41)

as the average number of jet particle impacts at the shield while GIOTTO traversed this jet.

The predominant deceleration of the spacecraft was not caused by mechanical momentum transfer, but by Coulomb forces between arriving ions and the potential of the shield.
As *n* charged dust grains have impacted on the shield, the Coulomb forces offer another means to determine the potential of the shield.

The electrostatic energy transfer is given by:

$$n \cdot e\Phi = \frac{M}{2}\Delta v^2 \qquad (42)$$

From Fig 1, lower panel the velocity decrement can be estimated. While Giotto penetrated through the jet the frequency change was $\delta f \approx 3.8 Hz$. This is equivalent to a velocity decrement of $\Delta v \approx 5\ cms^{-1}$. Therefore the according floating potential during the penetration of the ion-dust jet was:

$$\Phi \approx +1.5V. \qquad (43)$$

It is also possible to estimate the mean momentum loss of a single grain when running against the potential of the shield:

$$\mu\,(v' - v_0) \approx \mu\delta v \approx \int F dt \approx \frac{e\Phi}{\underline{v}} \qquad (44)$$

μ average grain mass
v' relative velocity when arriving at the shield
$\underline{v} \approx v_0$ mean relative velocity of the grain

The result for a single ionzed grain is:

$$\delta\mu v \approx 3.5\ 10^{-27} kgms^{-1} \qquad (45)$$

For the total momentum exchange, however, as far as jet particles are concerned, the momentum component $\frac{e\Phi}{\underline{v}}$ is small and may be neglected. The momentum residual is described by:

$$N\mu v_0 + N\frac{m}{m_0}\mu v < M\Delta v \tag{46}$$

resulting in:

$$\mu < 7 \cdot 10^{-23} kg = 4 \cdot 10^4 amu \tag{47}$$

as an upper limit for the average mass of a single grain.

8. Faint Dust generated at the Cometary Nucleus

The average momentum of a grain arriving at the protection shield is very low. Therefore the mass of a dust grain is also very low. Obviously, there is a mechanism to generate and accelerate such dust-grains.

The nucleus is irradiated by solar radiation. However, as the gas in the innermost sunlit zone is neutral, hard parts of the solar UV are filtered out still outside the cometo-pause. Only the visible light and soft UV can arrive at the bottom of the nucleus. This power might end up at about 0.1 % or 1 to 2 W/m². The generated potential may be strong enough to pull off faint dust particles from the bottom. The topography of the cometary surface is showing peaks and valleys. The electric field above the surface cannot be homogeneous. It must show a component parallel to the surface. Thus the faint particles are accelerated towards the peaks and further into jets.

This radiation may ionize the bottom to a few volts, sufficient to solve light-weight particles off their basis.

The potential of a dust grain of the mean mass μ kg might be U Volt. Then it is:

$$\mu \cdot \left(F_0 + \frac{w^2}{2}\right) = Z\, e\, U \tag{48}$$

Z ionization rate
F_0 relative release function
For this estimate the shape of a grain may be approximated by a sphere. This gives:

$$\mu = \frac{4\pi}{3} r^3 \varrho \text{ and } e = 4\pi\varepsilon_0 r U \tag{49}$$

yielding an estimate of the mean radius r of a grain $r^4 = \frac{3e^2}{16\pi^2\varepsilon_0\left(F_0+\frac{w^2}{2}\right)}$ (50)

For this rough estimate it can be defined:

$$0.2 < \rho < 2.5\, Mg/m^3 ; F_0 \ll \frac{w^2}{2};\ w \approx 400\, m/s. \tag{51}$$

This reveals

$$0.910^{-9} < r < 1.410^{-9} m ; \qquad 2.1 \cdot 10^{-24} < 4.0 \cdot 10^{-24}\ kg, \tag{52}$$

and $1200 < \mu < 2400$ amu (53)

This is well in agreement with the upper limit of the particle mass (47) as derived from the absorption observations when crossing a dust jet.
Such very tiny dust grains, large molecules, have already been observed in the vicinity of the VEGA spacecraft when crossing through outer regions of the coma of comet Halley (Sagdeev et al. [13])

The results fit well with the momentum of $\mu\delta v \approx 3.5 \cdot 10^{-24} kg\, m/s.$

It implies
$\delta v \approx 1\, m/s.$

An average grain is decelerated by 1 m/s when it is running against the potential of the shield.

9. Conclusions

- It was the goal of the GRE experiment of the GIOTTO mission to the comet P/HALLEY to investigate the atmosphere in order to get comprehensive information about density distribution, dynamics and as many as possible other properties of the cometary atmosphere. The main source for the experiment was the precise frequency and power of the telecommunication signals received at the ground stations. The stability of the transmitted frequencies X-band 8,429 GHz or S-band 2,299 GHz was better than needed to distinguish frequency variations as low as generated by mm-variations of GIOTTO's velocity and better than the in-avoidable noise.

- Unexpectedly no velocity variations could be registered in the beginning until about 25 s before the encounter T at 598 km distance from the nucleus. As discussed in chapters 2 and 3, the energy and the impacts of the gas molecules on the protection shield were compensated by generated Al-ions and the negative potential of the shield. Impacts of single larger grains influencing the velocity or attitude of the spacecraft could not be detected.

- Atmospheric particles impacting on the protection shield generated shield ions (Al ions). While the spacecraft approached its encounter, the gas molecules could no longer penetrate through the Al-ion cloud (chapter 4). A plasma-dynamic shock piled up in front of the spacecraft. The high-density and very hot plasma terminated the proper operations of the high-voltage experiments. The pressure increased to about 2.4 Pa. This decelerated the spacecraft. The temperature of the shield, measured on its back side increased steeply. Unfortunately the temperature sensor went out of operation when the temperature approached its maximum . Therefore the temperature as well of the plasma as of the shield could only be estimated. The plasma temperature could well exceed 1000 K, while the temperature of the shield went up to higher than 300 K.

- In chapters 5 and 6 estimates of the total mass of gas and the loss of mass of the shield is calculated from the velocity deceleration of the spacecraft. The integration of all masses of gas yielded the loss of aluminum to be 0.03 mm aluminum of the shield’s thickness.

- The panel of solar cells around the cylindrical body of the spacecraft was covered by a 0.3 mm thick quartz layer, doped with CeO. The reason for the dope was to reduce the resistance of the quartz, thus to prevent the cells of being damaged by high voltage discharges. As a consequence of the lower resistance an electrostatic “lever arm” was built up between the sunlit and the dark side of the cylinder. Between the ions drifting off in an angle of about 5 deg along the generator quartz and the lever. The resulting torque was responsible for the observed nutation.

- When the spacecraft was already leaving the encounter region, (chapter 9) at T + 23 s, the power received by the ground stations decreased by -5 dB. The analysis of this phenomenon showed that a dust cloud of very faint particles had come between transmitter and ground station. The spacecraft reacted with deceleration i.e., GIOTTO had passed through a dust jet of very faint particles. The average particle mass was assessed to be between 1200 and 2500 amu.

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