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Similarities between in situ measurements of local dust light scattering and dust flux impact data within the coma of 1P/Halley

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Abstract. In situ measurements of the light locally scattered by cometary dust, as well as the local dust spatial density are only available for one comet, 1P/Halley. These data, returned from the Optical Probe Experiment (OPE) and the Dust Impact Detection System (DIDSY) aboard the European Space Agency spacecraft Giotto, are re-assessed in light of the recent improvements in the analysis and calibration of the OPE data after the encounter of the spacecraft with the comet 26P/Grigg-Skjellerup. We find that the local brightness and dust flux are remarkably consistent (even though the DIDSY data samples a limited range of particle mass) for distances from the nucleus in the 10^3 to 10^5 km range, and broadly speaking both data sets exhibit a -2 radial gradient (albeit with localised features). An interesting deviation from the -2 radial gradient is seen for the local brightness as Giotto approaches within 2000 km of the nucleus (which corresponds to Giotto crossing from the anti-sunward side of the terminator plane to the sunward side). These two in situ data sets, and their similarities and correlation, now offer an excellent diagnostic test of the effectiveness and validity of cometary coma models.

Key words: comets: general – comets: individual: 1P/Halley

1. Introduction

Comet 1P/Halley is the only comet for which in situ measurements of both the light locally scattered by dust, and the local dust spatial density are available (Levasseur-Regourd et al., 1986; McDonnell et al., 1986; McDonnell et al., 1993). The Halley data then, offer an excellent opportunity to provide unique diagnostic information to test cometary models, and thus derive realistic constraints on the physical properties of the cometary dust. This new investigation was undertaken by the authors in the form of a working team at the International Space Science Institute, Switzerland, and represented the experimenters for the Optical Probe Experiment (OPE) and the Dust Impact Detection System (DIDSY). The project was conceived to take advantage of the new assessment of the OPE data at the time of the encounter of Giotto with comet 26P/Grigg-Skjellerup, which has allowed us to obtain a much more satisfactory signal to noise ratio in the outer coma where the level of light scattered by cometary dust is low.

In this paper we present the data used in this comparative study, gathered along the trajectory of the Giotto spacecraft, from the outer edge of coma at approximately 10^5 km from the nucleus to around 10^3 km. We then compare the trends in the data, and discuss some possible local changes inside the cometary coma.

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2. The in situ measurements

The data presented here were obtained inside the coma of comet Halley during its March 1986 Giotto flyby (Reinhard, 1986). The comet was 0.90 AU from the Sun. The Giotto spacecraft passed through the coma with a relative velocity of 68.4 km s^{-1}, the angle between the spacecraft velocity vector in the comet frame of reference and the Sun–comet line being 107°. The spacecraft approached the comet from the antisolar side, entering the sunlit hemisphere at a nucleus distance of about 2030 km. It passed the nucleus at a closest distance of around 600 km.

2.1. Data on the light scattered by dust (OPE)

The Optical Probe Experiment (OPE) was designed to monitor the light scattered by dust inside the cometary coma (Levasseur-Regourd et al., 1984, 1986). The instrument was a small polarimeter with a 2.6° field of view. To ensure reliability, the instrument had no moving parts. The polarisation was thus determined by the rotation of the analyser with the spacecraft. During a spin period (of 4 s), eight consecutive measurements of the polarised intensities were performed in clock sectors at 45° from one another, allowing the brightness to be retrieved from the sum of two components at 90° from one another. To avoid damaging impacts, the optical probe was positioned on the rear of the spacecraft. The resulting phase angle (i.e. the angle between the Sun and the spacecraft as seen from a scattering particle) was thus 73°.

The positioning of OPE at the rear of Giotto had two negative consequences. Firstly, the stray light level due to reflections from the spacecraft structure (antenna and tripod) was high for five out of the eight clock sectors. The brightness was thus retrieved only once per rotation. Secondly, the data after the closest approach were degraded, due to the high level of scattered light from the nucleus region, and also because the field of view, and hence the scattered light intensity, was varying periodically due to a significant nutation of the spacecraft caused by a large dust impact near closest approach.

However, the rearward positioning of OPE meant that the experiment survived the Halley encounter, allowing new data to be gathered at the 1992 Giotto Extended Mission encounter with comet 26P/Grigg-Skjellerup. At this second encounter, the stray light to the instrument was significantly reduced (due to the different encounter geometry) and the stray light levels were high for only three of the eight clock sectors. In addition, it was discovered at this time that an error had occurred in the data reduction code used at the Halley encounter, resulting in the dark current being overestimated by a factor of 16, so significantly reducing the 'apparent' signal to noise in the outer coma. Correction of this error (and the reduced stray light) allowed an accurate calibration of OPE to be undertaken before and after the Grigg-Skjellerup encounter, which contributed to a successful retrieval of scientific information from Giotto's second encounter (Levasseur-Regourd et al., 1993; McBride et al., 1997). Previously published OPE data for the Halley encounter (e.g. Levasseur-Regourd et al., 1986; Nappo et al., 1989) remain valid. However, crucially, the correction of the signal to noise error now allows us to derive the OPE data in calibrated units, over the whole part of Giotto's inward journey towards closest approach.

Fig. 1 presents the integrated brightness of the scattered light, $Z(\mathbf{r}, \alpha, \lambda)$ (where $\mathbf{r}$ characterises the location of a point within the coma), as a function of the distance, r, of the probe to the nucleus. The data on the right of the figure correspond to the probe entering the outer coma (onset of the dust coma was at $\sim 10^5$ km), while the points on the left correspond to the last data before closest approach. Data are retrieved for a phase angle, α, of 73° in three wavelengths, referred to as blue, green and red respectively. The calibrated measured brightness is extracted every 273 km along the Giotto trajectory, although beyond $r = 5000$ km, the data were binned to improve signal to noise, with bin widths of ∼550 km, increasing to ∼10000 km in the outer coma. To obtain the calibrated integrated brightness from the cometary coma, a background contribution is subtracted. Background values used were obtained at ∼4 10^5 km from the nucleus, before the encounter.

The total brightness received by OPE at a time t (operating at a given phase angle, α, and wavelength λ), is $Z(t, \alpha, \lambda)$. This total is produced by an integration of the *local* brightness contributions $z_l(\mathbf{r}, \alpha, \lambda)$ within the OPE conical field of view. Thus, for a measurement taken at time t, we can write

$$Z(t, \alpha, \lambda) = \int_0^\infty z_l(\mathbf{r}, \alpha, \lambda)\, dx \quad (1)$$

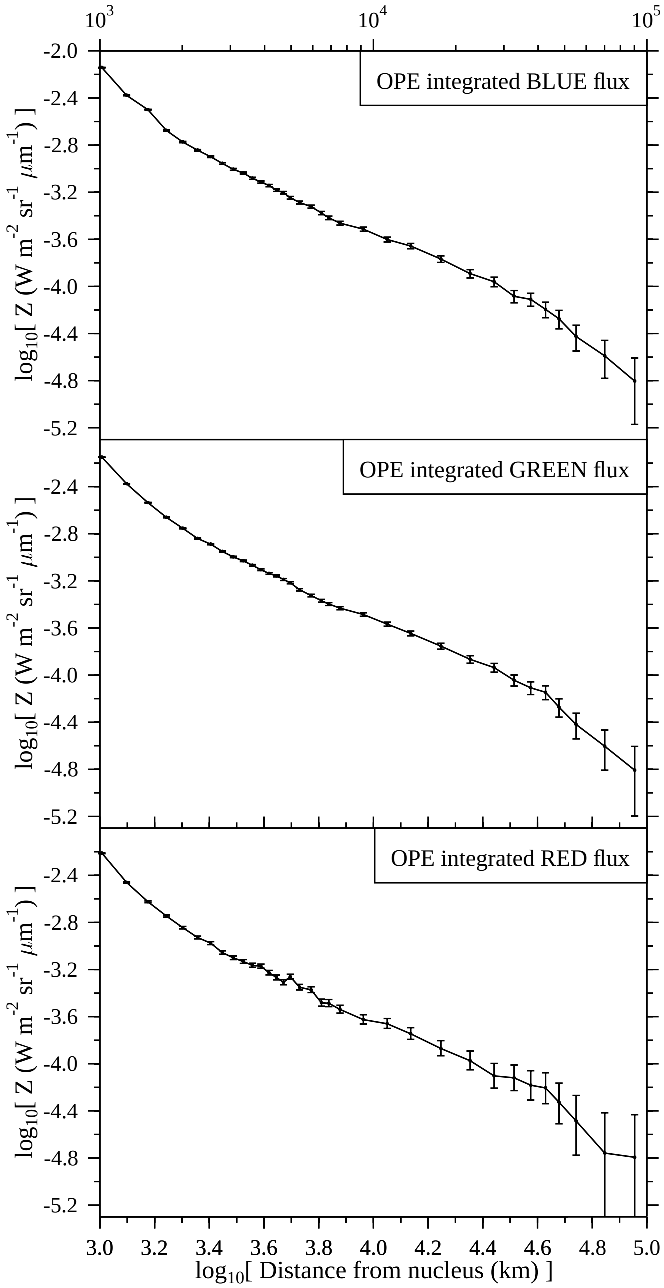

Fig. 1. The OPE integrated brightness as a function of the distance, r, of the probe to the nucleus. We present data for pre closest approach, and for filter wavelengths of 442 nm (blue), 576 nm (green) and 718 nm (red). The integrated brightness is extracted every 273 km along the Giotto trajectory, although beyond $r = 5000$ km, the data were binned to improve signal to noise. Background subtraction is performed using brightness values obtained at $r \sim 4\ 10^5$ km.

where x is the distance from the spacecraft measured along the line of sight, and thus $z_l(\mathbf{r}, \alpha, \lambda)$ represents the contribution of a 'slice' of the conical field of view perpendicular to this line of sight, at distance x. The scattering contribution depends on the solar irradiance at the Sun–comet distance R (given by $S_\circ(\lambda)/R^2$ where $S_\circ(\lambda)$ is the solar irradiance at 1 AU), the spatial density of the scattering particles, and the scattering properties of the particles such that

$$Z(t, \alpha, \lambda) = \int_0^\infty \frac{S_\circ(\lambda)}{R^2\, x^2}\, n(\mathbf{r})\, x^2\, \sigma(\mathbf{r}, \alpha, \lambda)\, dx \qquad (2)$$

where $n(\mathbf{r})$ is the spatial density of particles, which have some scattering function $\sigma(\mathbf{r}, \alpha, \lambda)$.

One of the most useful quantities that the optical probing technique returns, is the local brightness. Between two consecutive measurements taken at time t_1 and t_2, the spacecraft has travelled distance L, (equal to $v_G(t_2 - t_1)$ where v_G is the relative velocity of Giotto). It is seen that for a steady state coma, where the spatial density of particles is increasing as the spacecraft travels along its trajectory towards the nucleus region, then the local brightness contribution is approximately given by the simple subtraction of two consecutive brightness measurements (Dumont, 1972; Levasseur-Regourd, 1996) such that

$$z_l(\mathbf{r}, \alpha, \lambda) \;\approx\; \left[Z(t_2, \alpha, \lambda) - Z(t_1, \alpha, \lambda)\right]/L \qquad (3)$$

where $\mathbf{r}$ is the mean position corresponding to the mid time between measurements at t_1 and t_2. Because the local brightness is effectively a measurement of the scattering contribution of particles *near* the spacecraft, then it allows a direct comparison with local particle spatial density measurements returned by dust impact data.

The polarisation is another important diagnostic measurement of the physical properties of the scattering dust particles (albedo, size distribution, porosity), although it is still difficult to deconvolve the influence of these different factors (see for example Levasseur-Regourd et al. 1996). The polarisation is retrieved from the ratio of the difference over the sum of two polarised components of the brightness at 90° from one another. At the Halley encounter, because of the stray light constraints, the polarisation was retrieved once per rotation by using appropriate combinations of the three available clock sectors.

2.2. Data on the dust spatial distribution (DIDSY)

The Dust Impact Detection System (DIDSY) was designed to measure the flux of impacting dust particles in the mass range 10^{-19} kg to $> 10^{-6}$ kg, and comprised several sensors (McDonnell 1986; McDonnell 1987). Unlike OPE, DIDSY could potentially return comparable data before and after closest approach to the nucleus.

Three piezoelectric sensors (DID 2, DID 3 and DID 4) were mounted on the front shield. DID 2 and DID 3 could operate independently or measure in coincidence, and cycled between these modes automatically, although before closest approach the behaviour became erratic for a few seconds and then settled in a non-preferred mode, making comparison of pre-encounter and post-encounter fluxes difficult. Similarly, the data from the Capacitor Impact Sensor (CIS) and the Impact Plasma and Momentum sensor (IPM) do not allow easy comparison between pre and post-encounter fluxes. However the front shield DID 4 piezoelectric sensor operated independently and nominally throughout the encounter, and thus returned directly comparable fluxes before and after the closest approach. As this post-encounter data will no doubt be of use in subsequent modelling (even though no OPE data is available for this period) we will concentrate exclusively on the data returned from the DID 4 front shield piezoelectric sensor (hereafter referred to as the DID data).

Near closest approach telemetry was lost due to a nutation of the spacecraft associated with a large impact event. Thus the actual data leads to two separate reliable 'partial fluences' obtained while the probe was further than 2900 km from the nucleus, A 'total fluence' was nevertheless reconstructed by attempting to account for the missing telemetry (McDonnell et al. 1991).

The DID system gave the number of dust impacts per data gathering interval (which was 1.133 s), which when combined with the effective sensing area, produces dust flux rates which are a direct measure of the local spatial dust density in the coma. The sensor had a detection mass threshold, although signals from impacts could also be 'binned' according to their signal strength, such that 3 separate *effective* mass thresholds could be identified. Bin 1, 2 and 3 had effective mass thresholds of $7.7\,10^{-12}$ kg, $1.3\,10^{-10}$ kg and $7.7\,10^{-10}$ kg respectively. Fig. 2 shows the flux of particles returned from 3 sensitivity bins, from both before (top graph) and after (lower graph) closest approach.

3. Comparison of the data

A preliminary comparison had been done by Nappo et al. (1989) for distances to the nucleus of less than 7000 km. They had noticed that the radial gradients for both data sets were comparable, with power law indices approximately equal to -2.9. On the much wider distance range now available, it is indeed clear that the slopes may be steeper below 7000 km, whereas when considering the whole sampled coma (up to 10^5 km) the overall regression leads approximately to a r^{-2} law. We now compare the data in detail.

Fig. 3a presents the OPE local brightness, deduced by subtraction between consecutive measurements of the integrated OPE data. We have taken a mean of the blue and green channels as the local data follow virtually identical trends. Beyond $r = 5000$ km (nucleus distance) the data are binned to improve signal to noise. Fig. 3b presents DID data (bin 1) before closest approach, which will be used for direct comparison with the OPE local brightness (Fig. 3a). The DID data have been smoothed to allow easier comparison with large scale trends in the data.

Fig. 4a shows both the OPE local brightness and the DID flux, with an arbitrary shift applied to the DID flux to allow the data to overlay for comparison. Note that in the 8000–30000 km region, the data are relatively featureless and the slopes agree well. Fig. 4b shows the plot again, but the flux is replaced with the flux multiplied by r^2 which accentuates the variation in the two data sets. A horizontal line in this plot would be indicative of a simple r^{-2} dependence. We have indicated when Giotto

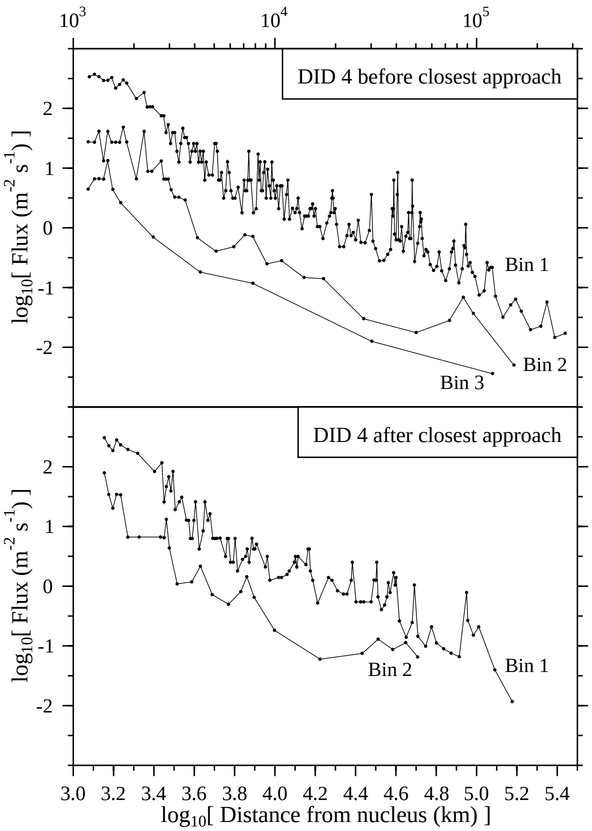

Fig. 2. The dust flux obtained from the DID 4 sensor. Signals from impacts were binned according to their signal strength, such that 3 separate statistically valid effective mass thresholds could be identified. Bins 1, 2 and 3 had effective mass thresholds of $7.7\,10^{-12}$ kg, $1.3\,10^{-10}$ kg and $7.7\,10^{-10}$ kg respectively. The bins are cumulative, and so an impact registered in Bin 3 would also be counted in Bin 1 and 2. Bin 3 post closest approach registered only one impact, and is not shown.

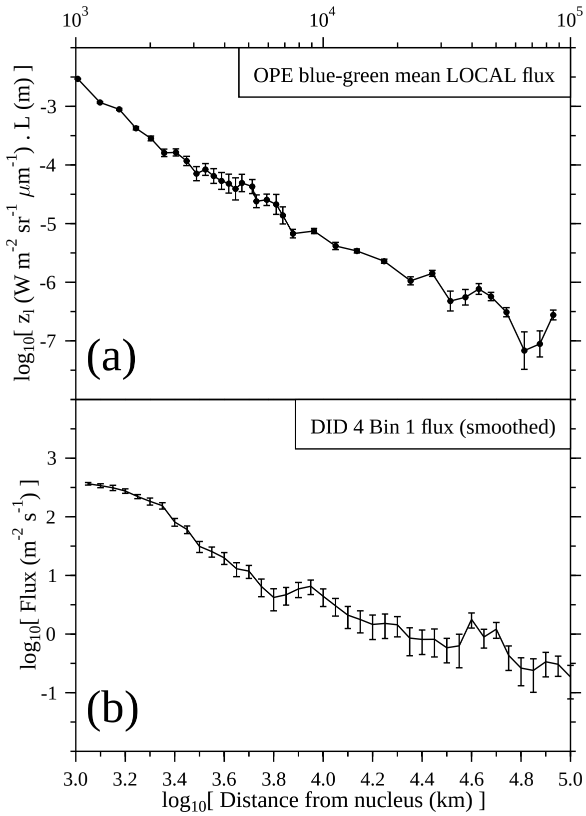

Fig. 3. a The OPE local brightness. This is deduced by subtraction between consecutive measurements of the integrated OPE brightness along the trajectory, and represents the contribution from the volume of space (near the spacecraft) of length $L = 273$ km. We have taken a mean of the blue and green channels as the local data follow virtually identical trends. Beyond $r = 5000$ km (nucleus distance) the data are binned to improve signal to noise. Note that as background subtraction is not needed (i.e. it is implicit in the consecutive subtraction), errors are smaller than with the integrated brightness. **b** The DID flux data, before closest approach. The data have been smoothed to allow easier comparison with large scale trends in the data.

passed the shadow terminator plane (i.e. when Giotto passed to the sunward hemisphere with respect to the nucleus).

It is seen in Fig. 4 that below 2000 km, a steep increase, already noticed in the raw data (Levasseur-Regourd et al., 1986), is displayed in the local OPE brightness. Note that this increase in brightness appears correlated with the crossing of the terminator plane, i.e. at this time Giotto was passing into the sunward hemisphere with respect to the nucleus (with angle between the trajectory and the terminator plane being 17°). This brightening may be due to several mechanisms: a sharp increase in the spatial density of very small, or very large cometary particles i.e. those particles not registered by the DID sensors; a change in the dust optical properties, such as increasing albedo caused by some icy particles near the nucleus; a change in the illumination characteristics of the region, caused by the sunlit side of the nucleus adding to the scattered contribution. These points will be discussed further.

Beyond 2000 km, the mean radial gradient in the OPE data is approximately -2 as might be expected. Relative to the OPE data, the DID data shows a 'dip' in the 3000 to 8000 km region. In this dip, the DID flux follows a gradient of around -3 between 3000 and 6000 km, and then rises sharply between 6000 and 8000 km. This dip in the DID flux is unexpected, especially when uncorrelated with the OPE local brightness. In the 8000 km to 30000 km region, the agreement between the two data sets is remarkable.

In the outer region (beyond 35000 km) the two data sets do not appear to follow a simple power law. Although the signal to noise in this region is relatively poor, it is hard to ignore the apparent correlation in the trends between the two data sets. The data behave similarly with a steep increase in the 30000 km to 50000 km region, followed by a decrease, and another increase, causing a rather striking feature followed by both experiments.

The trends observed in the OPE and DID data from the 2000 km (crossing of the terminator) to the 10^5 km (outer coma) region are fairly consistent, although mechanisms for the OPE brightening below 2000 km, the DID flux 'dip' between 3000 and 8000 km, and the variation in the outer coma, need to be identified.

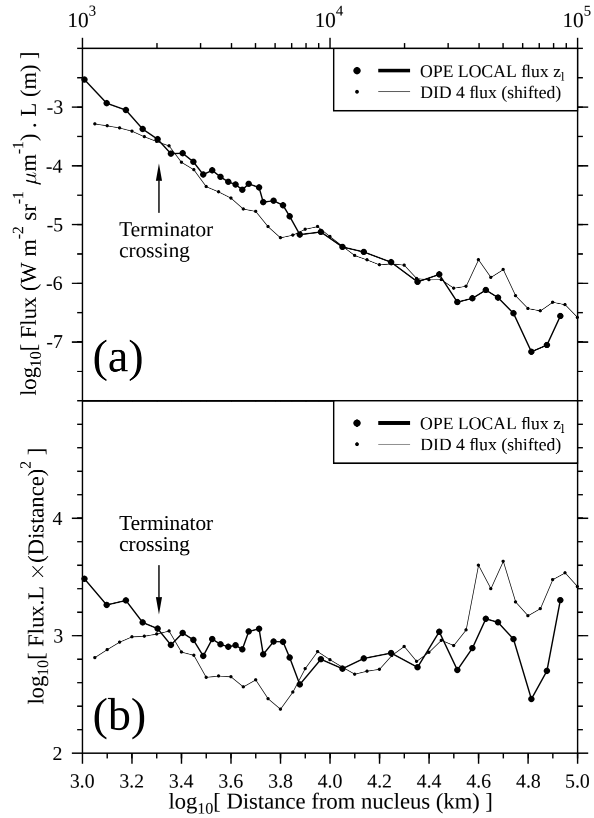

Fig. 4. a The OPE local brightness compared with the DID flux. The DID data have been shifted to overlay the OPE data. For clarity, error bars (given in Fig. 3) are not shown. **b** The same plot, but the flux is replaced with flux multiplied by r^2 which accentuates the variation in the 2 data sets. A horizontal line in this plot would be indicative of a simple r^{-2} dependence.

The OPE experiment also offered the opportunity of obtaining the polarisation along the line of sight. The evolution of the polarisation with distance from the nucleus is shown in Fig. 5 (for a mean of the blue and green channels). In general, the polarisation value slowly increases with increasing distance. Because of the empirically determined inverse relationship between polarisation and albedo (Umov law), this could indicate that the albedo of the particles is decreasing as the distances to the nucleus increases. The significant changes in the polarisation trend which occur at below 2000 km (crossing of the terminator) and above 30000 km probably indicates that the physical properties of the scattering particles are changing drastically over these two regions. The change in polarisation occurring above 30000 km, appears to be correlated with the striking feature noticed in the OPE and DID outer coma data.

It may indeed be suggested that the scattering particles have a higher albedo in the $r < 2000$ km region. This could be consistent with the idea of small, icy particles, which quickly loose their volatiles near to the nucleus (i.e. they suffer a reduction in albedo). However the increase of the OPE brightness compared to the DID trend (in Fig. 4) is almost an order of magnitude, and it seems unlikely that a higher albedo could explain *all* of

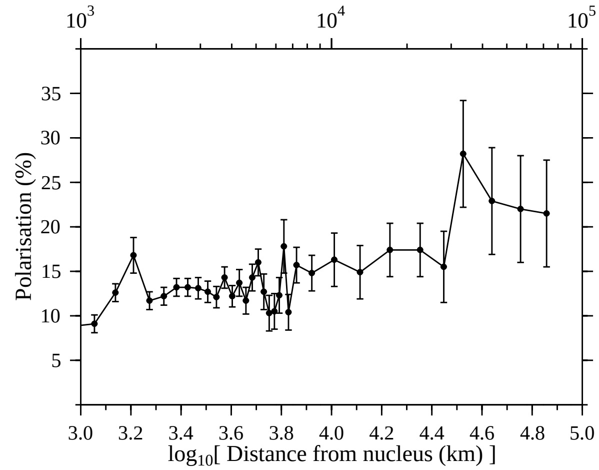

Fig. 5. The OPE polarisation as function of distance from the nucleus. The data set shown is the mean from the blue and green channels (which follow very similar trends).

this enhancement. It could be a result of an additional scattered light contribution coming from the nucleus (which is also consistent with the sharp reduction in polarisation very close to the nucleus) as Giotto crosses sunward of the terminator plane.

4. Conclusions

We have performed a comparative analysis of the characteristics of the dust within the coma of comet Halley, as deduced from unique in situ data obtained during the Giotto spacecraft encounter in 1986. It is found that the Optical Probe Experiment and the Dust Impact Detection System data are remarkably consistent. Possible explanations were identified for the enhancement of the OPE brightness below 2000 km nucleus distance (relative to the local spatial dust density given by the DID data). The difference identified in the data trends in the 3000 and 8000 km region may in part be attributed to the fact that only a fraction of the light detected by OPE will be due to scattering from particles in the mass regime detected by the DID sensors. Striking features followed by both experiments beyond 30000 km nucleus distance still need to be explained. The unique combination of the OPE and DID in situ data, now offer an excellent opportunity for modellers to derive realistic constraints of the physical properties of cometary dust.

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