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A fragmentation model of dust grains in the inner coma of Halley. A possible explanation of the color effect

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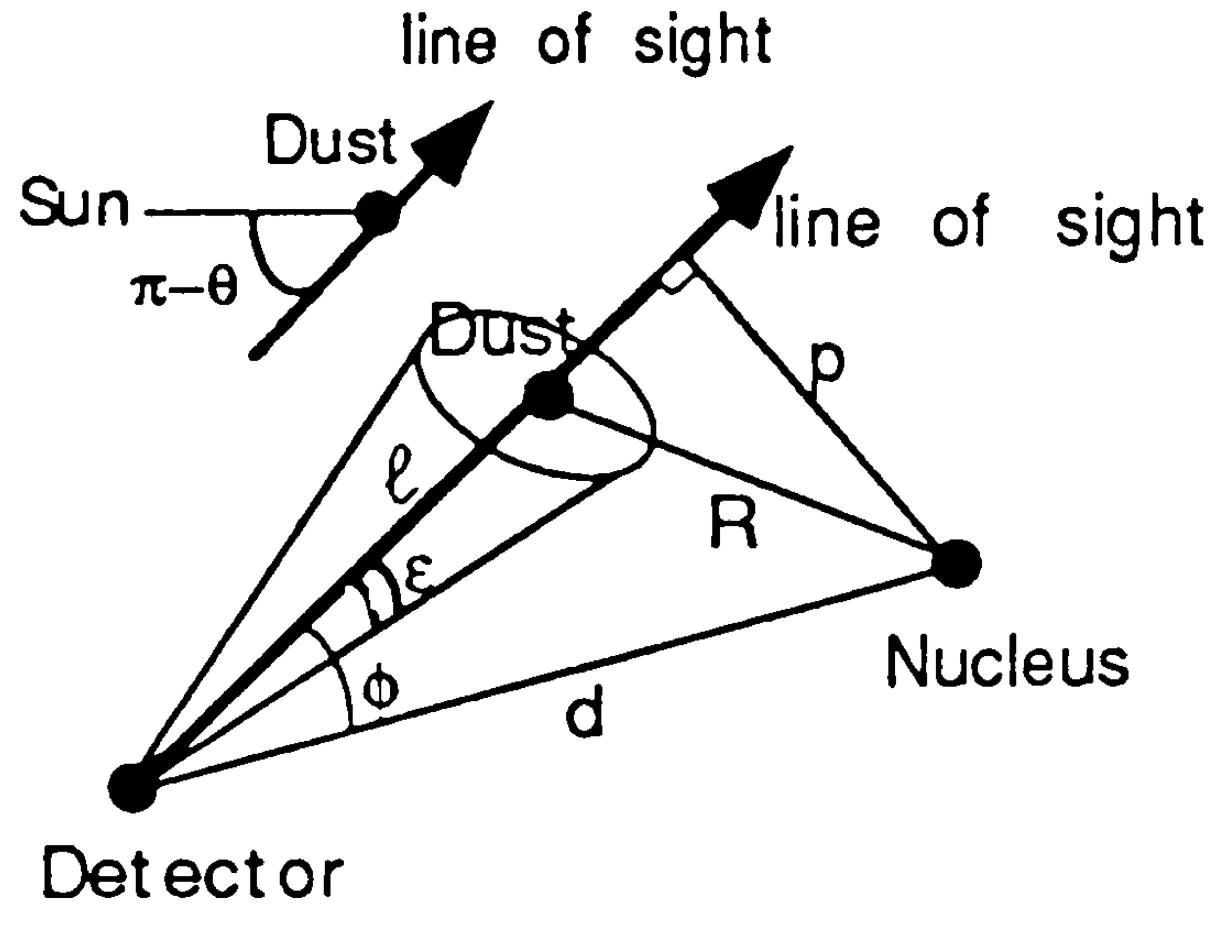
Abstract. A model to describe the intensity of dust scattered light observed by the spectrometer TKS during the Vega/Halley encounter is presented. Good agreement is obtained when using a particle radius dependent mass density. The color effect is reproduced if the refractive index of tholin is adopted.

1. Introduction

The irradiance of Halley's coma due to solar radiation scattered by dust particles and measured by the spectrometer TKS on board Vega 2 decreases as p^{-s} where p is the distance between the nucleus and the line of sight (Figure 1). We found $s = 1$ in most parts of the coma except in a region between $p = 3000$ km and $p = 7000$ km where s is higher than 1 (Goidet-Devel et al., 1994). In this paper we present a model to reproduce the irradiance curves, showing that the color index of dust which may be defined as the absolute irradiance ratio at two wavelengths λ could be explained by the fragmentation of dust grains in the inner coma of comets.



d: distance Detector -Nucleus
R: distance Dust-Nucleus
p: perpendicular distance Nucleus-line of sight
ℓ. Detector-Dust, variable of integration along the line of sight

θ: scattering angle
ε: aperture half-angle of the instrument field of view
ϕ: angle between the line of sight and the Detector-Nucleus line

Figure 1. Geometrical parameters

2. The brightness model and its results

In order to be able to model the irradiance $I(p, \lambda)$, we first had to choose a particle size distribution. For that purpose, it was decided to use the absolute values of the flux distribution measured at different locations in the coma of Halley by the SP-2 in-situ experiment (Mazets et al., 1987): the experimental mass distribution given by SP-2 was converted into an hypothetical size distribution, assuming that the grains are spherical. As it was necessary to extrapolate the data to distances smaller than 8030 km (closest approach distance of the spacecraft), we fit the fluxes with a $C(m)/R^2$ law for the ten decades of mass given by SP-2. The integral appearing in the expression of the irradiance can then be separated in three different contributions (Goidet, 1994): $I(p,\lambda) = KA(p)B(\lambda)$ where:

$$K = -\frac{1}{V_r}F_o(\lambda)\pi\left(\frac{3}{4\pi\rho}\right)^{2/3}\pi tan^2\epsilon$$

$$A(p) = \left[\frac{\arctan\frac{l-R\cos\phi}{R\sin\phi}}{R\sin\phi}\right]_{l=0}^{l=l_{max}(p)}$$

$$B(\lambda) = \int_m m^{2/3}Q_{sca}(m,\lambda,n_r)S(\theta,\lambda,m)\frac{dC(m)}{dm}dm$$

The parameter K gathers the geometrical constants (like ϵ, cf. Figure 1), the relative velocity V_r, the solar flux $F_o(\lambda)$ and the density of the grains ρ. We have tested the model with $\rho = 0.3\ g.cm^{-3}$, $1.0\ g.cm^{-3}$ and, following Lamy et al. (1987), $\rho = 2.2 - 1.4a/(a+1)\ g.cm^{-3}$, where a is the particle radius.
The function $A(p)$ is the result of the geometrical integration of the $1/R^2$ law along the line of sight. In the integral, the limitation of the coma by the fountain effect is taken into account through the p dependence of the integration limit l_{max} (Figure 1).
Finally, $B(\lambda)$ is the integral of all the dust grain mass-dependent factors, including the phase function $S(\theta,\lambda,m)$, and the scattering efficiency $Q_{sca}(m,\lambda,n_r)$. These two quantities are calculated by using Mie theory. Radial profile of the logarithm of the irradiance can then be calculated and plotted for three wavelengths for which molecular emission is negligeable (377 nm, 482 nm and 607 nm), and in a region of the coma where there is no gas and dust jet. In order to reproduce the inflexion point and the slope ($s = 1.6$) near 6000 km, i.e. in the region where we have extrapolated the mass distribution, we had introduced a fragmentation process in the inner coma. This mechanism creates a larger number of small micrometer-sized particles that efficiently scatter the solar radiation.
To model this, we have supposed that among the distribution of the grains the mass decades after fragmentation can be linearly connected with the same quantities before fragmentation. This gives a 10x10 fragmentation matrix for the 10 decades of mass taken into account (10^{-16} to $10^{-6}g$). As an example, if we only consider 3 mass decades, the fragmentation matrix is written under the following form:

$$\begin{pmatrix} 1-k & 10k & 0 \\ 0 & 1-k & 10k \\ 0 & 0 & 1-k \end{pmatrix}$$

This matrix is bidiagonal because i) the grains cannot fragment in a decade of higher mass, and ii) the particles resulting from the fragmentation of a grain are supposed to have a similar size. The coefficients are deduced from the assumption that the total mass is conserved. As the fragmentation process is probably

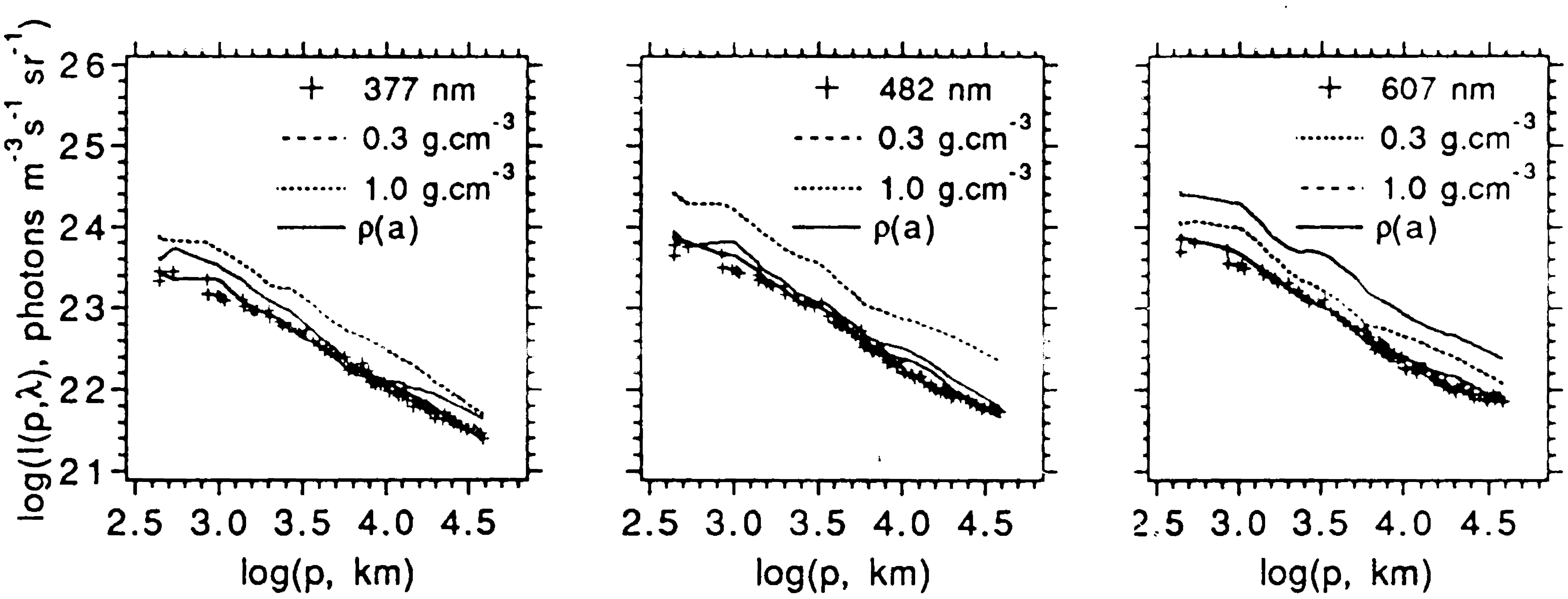


Figure 2. Comparison between experimental data and the model for 377nm (left), 482nm (center) and 607nm (right) for $n_r = 1.7 - 0.02i$

more efficient closer to the nucleus than at larger distances, we have supposed that the fragmentation parameter k varies with the distance R: $k(R) = 0.87$ for $R < 1000$ km and $k(R) = 1050/R - 0.175$ for $1000km < R < 6000$ km.

The comparison between the model including fragmentation and the experimental data shows a good agreement if the refractive index is $n_r = 1.4 - 0.03i$ (calculated by Mukai et al. (1987) for an hypothetic cometary material) and a radius dependent mass density as given by Lamy et al. (1987). The agreement measured with this set of parameters by the rms of the difference between the model and the data, is equal to 0.22 for 377nm, 0.11 for 482 nm and 0.28 for 607 nm. However, the same $\rho(a)$ and the refractive index of tholin obtained from Khare et al., (1984) give better results with lower rms values: 0.07 for 377nm, 0.10 for 482nm and 0.08 for 607nm (Figure 2).

Let us stress here that all the curves for the different wavelengths were obtained with the same parameters, that the brightness measurement was absolute and that the principal contribution to the brightness came from the dust grains with masses of the order of $10^{-12} - 10^{-11}g$. This decade was indeed greatly enhanced by the fragmentation process. This stresses the importance of fragmentation for a detailed description of the distribution of the particles in the coma.

3. The color effect

The color index of dust-scattered radiation is even more sensitive than its intensity to the parameters defining the density and the complex index. This is due to the cancellation of various factors affecting the absolute value of the brightness, for example the purely geometrical effect. Figure 3 shows the results of the model with the same set of mass densities as before for the brightness and with the refractive index of tholin (Khare et al., 1984).

Once again, this clearly shows that the combination of i) a radius dependent mass density, ii) an index close to those of tholin and iii) a fragmentation effect describes the data quite well.

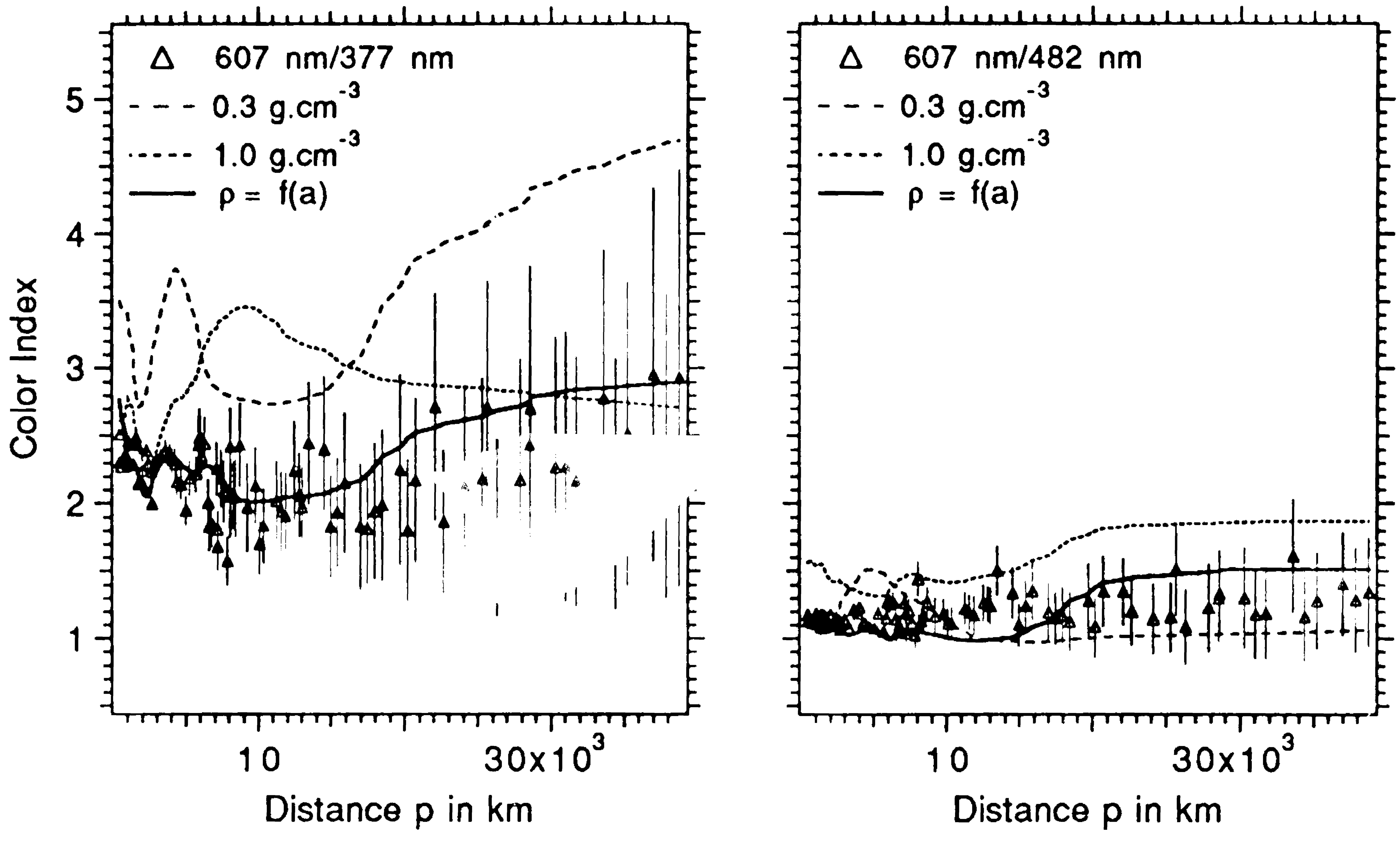


Figure 3. Color index vs distance p. Comparison between the model (lines) for $n = 1.7 - 0.02i$, and experimental color indices (triangles) with error bars.

New data concerning observations of comet Borrelly were obtained at Observatoire de Haute Provence on Dec. 4, 1994. Images were taken with narrow-band filters at 527 and 682 nm. The images ratios show that the color of dust is not uniform in the coma. They confirm the experimental results for Halley, i.e. the color effect also could be due to the fountain effect and fragmentation process.

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