Circular polarization of light scattered by a non-central region of a comet

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A Monte-Carlo model of radiative transfer in comets has been developed. It calculates the four Stokes parameters of the light scattered by particles in the coma. By applying this model, non-negligible values of the DCP were obtained just by assuming conditions of multiple scattering by spherical optically inactive particles, and considering only light coming from a non-central small region of the coma of the comet. The calculated values are one or two orders of magnitude below the observed, but the mechanism fits all other features of the observations.

INTRODUCTION

A non-zero degree of circular polarization (hereafter DCP), has been observed in light scattered by Comets Halley [1, 2, 3], Hale-Bopp [4, 5], C/1999 S4 (LINEAR) [6] and C/2001 Q4 (NEAT) [7]. The DCP is of the order of 1 % in Halley's observations, and of the order 0.1 % for the others that were observed in the 1990s and 2000s with better precision. Some other remarkable features of the observations are the following:

1. The DCP approaches zero when the aperture of the diaphragm increases in Halley's observations [2, 3].
2. For precise observations (all but Halley's), the DCP approaches zero when looking at the nuclear region of the comet.
3. In all cases, the observed DCP for a certain region of the comet is highly variable in time (day-to-day and even minute-to-minute).
4. In most cases, both positive and negative values of the DCP are obtained, except for two exceptions: observations of Hale-Bopp by Rosenbush et al. [5], where all obtained values were negative, and observations of Comet C/1999 S4 (LINEAR) [6]. For the latter case, all observed values were positive for the largest scattering angle (119.1°). Then both positive and negative values appeared at intermediate values of θ, becoming finally mostly negative at $\theta = 57.9°$.

Several mechanisms that may give rise to circular polarization in astrophysical environments have been historically proposed: *Alignment of non-spherical particles* [8], *Asymmetrical particles in random orientation* [9], *Optical activity* [6, 7] and *Multiple scattering* [2, 6]. As previous attempts to reproduce the observations of DCP by all mechanisms listed above were unsuccessful, we tried another one: local observation of a non-central region of the comet.

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FEASIBILITY OF THE MECHANISM

From now on, let us make two assumptions: the coma of the comet is spherical, and the source emits natural light (as solar light when considering wavelength bands as wide as those used in the observations [11]).

To be valid, the mechanism should explain all features of the observations listed above:

1. Opening the diaphragm means taking into account photons coming from other parts of the comet, with values of the Stokes parameter V, that may partially compensate those of the photons coming from the original region. Then, the DCP tends to zero.
2. By looking at the nuclear region of the comet, the scattering system becomes azimuthally symmetrical around the direction of the incident light, which makes the DCP to vanish [10].
3. The minute-to-minute variation of the DCP only occurs for the case of Halley, so it might be due to the lack of precision of those observations. For the other observations we find a day-to-day variation, which may be caused by the rotation and translation of the comet, and the variations that occur in its coma due to the thermal changes of its surface.
4. The predominant sign of the observed DCP might be due to symmetry reasons, related to the scattering angle. In particular, there might be a change of sign around $\theta = 90°$. This idea matches the observations: all negative values of the DCP observed by Rosenbush et al. [5] were obtained at one single scattering angle ($\theta = 134°$), but a change of sign might occur for $\theta < 90°$. In fact, it occurs in Comet C/1999 S4 when it moves from $119.1°$ to $57.9°$.

Let us assume reciprocity and mirror symmetry. Then, after applying to an incident packet of photons one single scattering event and a rotation of the scattering plane to write the Stokes parameters in the meridional plane of observation, the Stokes parameters of the outgoing light will be proportional to $(F_{11}, F_{12}\cos 2i_{rot}, -F_{12}\sin 2i_{rot}, 0)^t$, where (F_{ij}) is the scattering matrix, i_{rot} is the rotation angle, and t means transpose. As $V = 0$, then $DCP = 0$. This means that multiple scattering is necessary to produce a non-zero DCP.

DESCRIPTION OF THE RADIATIVE-TRANSFER MODEL

Let us represent a comet by a spherical cloud of dust, with a totally absorbent spherical solid shell of radius R_N in its center. The dust grains are assumed to be spherical optically inactive particles. The cloud extends to infinity but its particle number density distribution varies as $\frac{1}{R^2}$ with the distance R to the center. Packets of photons with Stokes parameters (1,0,0,0) are launched from a far plane-parallel source, their paths are tracked, and their Stokes parameters are recorded when they escape to infinity, along with the directions of escape (θ, φ). Some more details about the model can be found in [12].

RESULTS AND DISCUSSION

Let us consider a comet that is illuminated by a source in the direction and sense of axis Z. Scattered light is emitted from all regions of the comet in all directions. We focus only on packets of photons coming from a non-central small zone defined by a cone centered at $(\theta_{loc}, \varphi_{loc}) = (60°, 0°)$ with a width of $10°$.

Fig. 1 shows the results for $\tau_N = 2.5$ with $r_{max} = 200$ µm (left side), and $r_{max} = 2$ mm (right side). The rest of the input parameters are defined in the paragraph above and in Table 1. We just present results for $-90° \leq \varphi \leq 90°$ because the best statistics was achieved for those angles.

Table 1. Common input parameters for all radiative transfer calculations in the present work.

R_N	5 km
Kind of particles	spheres
Size distribution type	power-law, exponent=-3.5
r_{min}	0.05 µm
Refractive index	$1.6 + \mathrm{i}0.001$
Wavelength	0.5 µm
Number of packets of photons launched	10^8

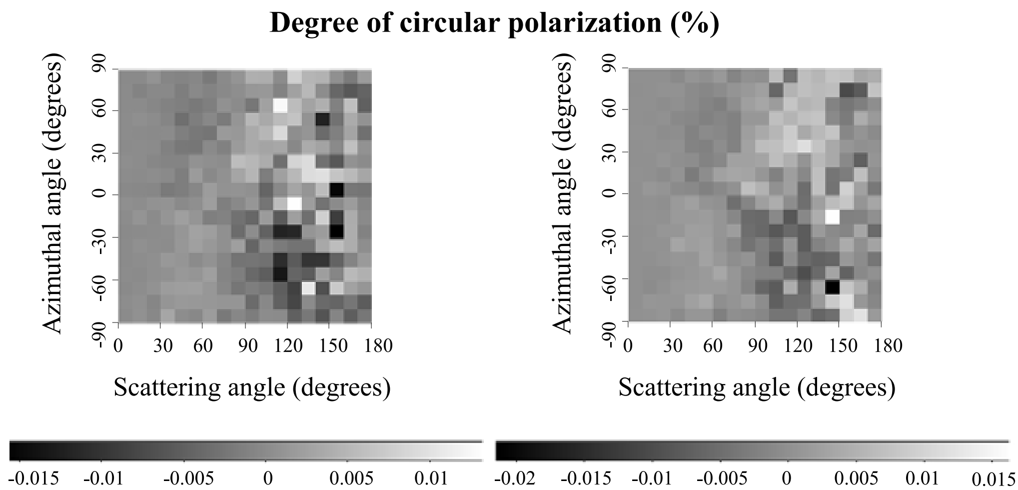

Figure 1. Results for the calculations of the DCP with our radiative transfer model by using parameters given in Table 1, $\tau_N = 2.5$ and two values of r_{max}: 200 µm for the left panel, and 2 mm for the right one.

We find three main features in the results presented in Fig. 1:

1. The upper and lower parts of both panels are color-complementary. If a certain DCP appears by any means for a certain scattering direction (θ, φ), the opposite value must be found when observing from $(\theta, -\varphi)$ because of the symmetry of the system.
2. A significant increase of the maximum DCP occurs when increasing r_{max}. This means that large particles make a very significant contribution to the DCP, especially considering that they are the least abundant (see Table 1).
3. The calculated values of the DCP are about one or two orders of magnitude below those of the observations.

We would like to remark that multiple scattering in the coma of a comet matches all features of the observed DCP, except for the order of magnitude of the calculated values.

Any other kind of grains (in size, shape or composition) may yield higher calculated values of the DCP.

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