

Polarimetric observations of comet 67P/Churyumov-Gerasimenko during its 2008-2009 apparition

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ABSTRACT

Context. Remote observations of the light scattered by comet 67P/Churyumov-Gerasimenko dust coma are of major importance to determine the physical properties of the particles and prepare the rendezvous with the ESA/Rosetta spacecraft in 2014.

Aims. Light scattering and especially linear polarization observations allow a comparison between different coma regions and different comets, including comets that have been studied by space probes. Our aim is to retrieve physical properties of the dust particles and to characterize their evolution around perihelion passage.

Methods. Recent imaging polarimetric observations have been conducted at Haute-Provence observatory (France) on 2009 March 17-19 at 35° phase angle and at IUCAA Girawali observatory (India) on 2008 December 25-27 at 36° phase angle and on 2009 April 30-May 1 at 29° phase angle. With the imaging technique, the intensity and linear polarization variations are studied through the various coma regions. These observations are compared to other cometary data (e.g. Jupiter family comets) and to numerical and experimental simulations.

Results. The decrease in intensity as a function of the distance to nucleus in log-log scale is on average close to -1, although important variations with values down to -1.5 are noticed, in agreement with previous observations in 1982-83 and 1995-96. The intensity along the tailward direction decreases with a slope between -1.2 two months before perihelion (2009 February 28) to -1.0 two months after perihelion; the decrease is more pronounced in the sunward direction. Before perihelion, aperture polarization values are comparable to polarization values measured on other comets at similar phase angles. The sharp decrease in intensity and the feature in the tailward direction, without any difference in polarization in the coma before perihelion, could suggest the presence of large dark particles. The post-perihelion increase in intensity and in polarization suggests that an outburst has occurred. The freshly ejected dust polarizes more the

scattered light and is more sensitive to the solar radiation pressure, suggesting small micron- or submicron-sized grains.

Conclusions. Polarization and intensity variations in the coma of 67P/Churyumov-Gerasimenko are reminiscent of those noticed for some comets such as comet 81P/Wild 2 and comet 9P/Tempel 1. The presence of rather large particles can thus be suggested before and just after perihelion and the ejection of smaller grains, eventually in fluffy aggregates post-perihelion. An important seasonal effect related to the obliquity of the comet suggests that the different grains originate from different hemispheres of the nucleus.

Key words. comets: individual: 67P/Churyumov-Gerasimenko – polarization – scattering – Space missions: Rosetta – techniques: polarimetric

1. Introduction

Comet 67P/Churyumov-Gerasimenko (hereafter 67P/C-G) is the target of the European Space Agency's Rosetta mission. The spacecraft was launched in 2004 and is scheduled to rendezvous with 67P/C-G in 2014 (Glassmeier et al., 2007) when the comet will be relatively inactive, at about an heliocentric distance d_s between 3.8 AU and 3.5 AU. The Rosetta spacecraft will progressively approach the nucleus in order to release the Philae lander at about $d_s = 3.1$ AU and significantly before the perihelion, that will take place by Aug 2015. The spacecraft will observe the comet along its orbit through the perihelion and monitor the increase of cometary activity. The maximum activity is expected about one month after perihelion as for previous apparitions (Ferrin, 2005). The mission should end in December 2015 when the comet will still be active.

Comet 67P/C-G was discovered in 1969. Its orbital history indicates two encounters with Jupiter leading to a perihelion distance of 1.245 AU and an orbital period of 6.44 years (Rocher, 2009). Since its discovery, it was observed at each approach and found to be among the relatively active Jupiter family comets. It is classified as a dusty comet and is slightly C₂-to-CN depleted in the A'Hearn et al. (1995) database. Schleicher (2006) recalculated the C₂-to-CN ratios and qualified 67P/C-G as mildly depleted. Using the Planetary Camera of the Hubble Space Telescope, Lamy et al. (2007) measured a rotational nucleus period of (12.3 ± 0.27) h. From Spitzer Space Telescope observations, Lamy et al. (2008) derived an effective radius (for a sphere of equivalent volume) of about 2 km and an albedo of 0.04 for the irregular nucleus. Davidsson and Gutiérrez (2005) derived a nucleus bulk density in the range 100-370 kg m⁻³ from non gravitational forces studies. Tail, trails and neckline were observed at different apparitions (Fulle, 2004; Moreno et al., 2004; Agarwal, 2007; Kelley et al., 2008; Ishiguro, 2008). All these authors suggest the presence of very large mm to cm-sized particles pre-perihelion.

Linear polarization studies, which are independent of the number of particles in the field of view (for optically thin media), give complementary indications on the optical and physical properties inside the coma (see e.g. Levasseur-Regourd, 1999). Previous observations through similar polarimetric imaging methods (Sen et al., 1990; Renard et al., 1992; Hadamcik et al., 2003a) have allowed to confirm the presence of different regions in the coma. The different physical properties of the particles are indicated by the value of the polarization, as pointed out by in-situ observations in the coma of comet 1P/Halley (Levasseur-Regourd et al., 1986, 1999). By using successive images of comet C/1995 O1 (Hale-Bopp), the evolution of structures in the coma has been followed during hours, days and months (Hadamcik and Levasseur-Regourd, 2003b). In the jets and arcs,

the polarization was higher than in the surrounding coma indicating smaller grains and/or fluffier particles. The coma of comet C/1999 S4 (LINEAR) was observed during the complete disruption of its nucleus. Variations in the polarization associated with intensity variations allowed us to characterize large fragmenting compact particles (Hadamcik and Lvasseur-Regourd, 2003c). The polarization measured in the coma of comet 9P/Tempel 1, has shown variations correlated to the period of rotation of the nucleus before impact, and different properties of the dust ejected by the impact (Hadamcik et al., 2007a). To interpret the polarization and intensity variations, numerical and experimental simulations are currently used (Lasue et al., 2009; Hadamcik et al., 2006, 2007b, 2009).

Preliminary results about 2008-2009 observations of 67P/C-G can be found in Lvasseur-Regourd et al. (2010). In section 2, we describe the two instruments and their data reduction procedure. In section 3, we present the results for the three observing periods and emphasize the coma asymmetries by a detailed study of the intensity and polarization variations. In section 4, the results are compared to those of previous apparitions and to the results obtained for other comets especially for other Jupiter family comets (hereafter JFCs) and more active comets leading to some clues about the evolution of the physical properties in the coma.

2. Observations and data reduction

Two different telescopes were used through a France-India collaboration. The observations have been conducted at Observatoire de Haute Provence (OHP) near Marseilles in France and at the Inter-University Center for Astronomy and Astrophysics (IUCAA Girawali Observatory, 'IGO') near Pune in India.

2.1. Instruments

2.1.1. OHP Haute-Provence Observatory, France (43° 55' 54" N latitude, 5° 42' 44" E longitude, altitude 650 m)

The OHP 80 cm telescope is opened at f/15 in Cassegrain mode with a field of 7 arcmin on the side. The CCD camera has 2048x2048 pixels, back-illuminated, of 13.5 μm each. The resolution by pixel is thus 0.21 arcsec. A current binning of 4x4 pixels is applied. The CCD is cooled down to -50°C by a 5-stage Peltier system.

A red filter is used to avoid contaminations by the gaseous species (red R, centered on $\lambda=650$ nm, $\Delta\lambda=90$ nm). A residual contamination by the gaseous species (mainly NH_2 and [OI]) is possible but seems negligible for this dusty comet (justification in section 3.2.2). The telescope tracking-mode is stellar. Very short (20s) exposure times are necessary to avoid a significant movement of the photocenter during exposures and changes in the sky background from one image to the next one.

Four polaroid filters are mounted on a rotating wheel, with their fast axis oriented at 45° from one another, the first one corresponding to the so-called direction Zero '0'. For each orientation, a polarized intensity image is recorded (so-called Z_0 , Z_{45} , Z_{90} , Z_{135}). Z_i represents the polarized image, the integrated intensity measured through an aperture or the polarized intensity recorded by one pixel. The intensity Z , the linear polarization P and the angle θ between the direction of

polarization and the direction of the fast axis of filter 0 in the plane of observation are calculated through:

$$Z = Z_0 + Z_{90} = Z_{45} + Z_{135} \quad (1)$$

$$P = 200 \frac{\sqrt{(Z_0 - Z_{90})^2 + (Z_{45} - Z_{135})^2}}{Z_0 + Z_{90} + Z_{45} + Z_{135}} \quad (2)$$

$$\theta = \frac{(Z_{45} - Z_{135})}{(Z_0 - Z_{90})} \quad (3)$$

2.1.2. IGO, India (19° 5' N latitude, 73° 40' longitude, altitude 1000 m)

The IGO 200 cm telescope is opened at f/10 in Cassegrain mode. With the IFOSC instrument (IUCAA Faint Object Spectrograph and Camera), the spatial sampling scale at the detector is 44 μm per arcsec giving a field of 10.5 arcmin on the side.. The field of view for imaging polarimetry is reduced to about 2 arcmin radius. The CCD is back-illuminated with 13.5 μm -sized pixels, corresponding to a resolution of 0.307 arcsec by pixel. The CCD is cooled by liquid nitrogen.

To avoid contaminations by gaseous species, two narrow band ESA filters are used (blue CB $\lambda=443$ nm, $\Delta\lambda=4$ nm; red CR $\lambda=684$ nm, $\Delta\lambda=9$ nm) and a broadband Bessel red filter (R_b , $\lambda=630$ nm, $\Delta\lambda=120$ nm). Through this last filter, some contamination may exist, but as stated for the R filter used at OHP it seems to be negligible (see justification in section 3.2.1). The telescope tracking-mode is first stellar due to technical problems (that needs short exposures) and finally cometary by differential tracking. The exposure times can be found in Table 1.

A rotating half-wave plate (HWP) with its fast axis normal to the optical axis of the system is associated to a Wollaston prism. At each position of the plate, two orthogonally polarized beams are produced. The separation between the ordinary and extraordinary components is 0.8 arcmin. Two successive positions of the half-wave plate are necessary to retrieve the degree of polarization and the position angle of the polarization vector. More details on the principles of such an instrument are described in Ramaprakash et al. (1998). When the half-wave plate rotates successively of 22.5°, 45° and 67.5° from an initial position noted 0, the position angles of the polarized components rotate respectively of 45°, 90° and 135° from the initial position. As for the OHP images, the images on each CCD plate are noted Z_0 , Z_{90} (position 0 of HWP), Z_{45} , Z_{135} (position 22.5 of HWP), Z_{90} , Z_0 (position 45 of HWP), Z_{135} , Z_{45} (position 67.5 of HWP).

The polarization degree P and the position angle θ of the polarization vector depend only on ratios of polarized intensities measured on the same plate without any necessary normalization between the plates (sky transparencies, exposure times). If β is the position of HWP and $R(\beta)$ a ratio defined by

$$R(\beta) = \frac{I_e(\beta)/I_o(\beta) - 1}{I_e(\beta)/I_o(\beta) + 1} \quad (4)$$

with $I_e(\theta)$ and $I_o(\theta)$ respectively the extraordinary and ordinary image on the same plate

$$P = \sqrt{R(\beta)^2 + R(\beta + 22.5)^2} \quad (5)$$

$$\theta = 0.5 \arctan\left(\frac{R(\beta + 22.5)}{R(\beta)}\right) \quad (6)$$

Table 1. Log of the observations: Δ = Earth-comet distance; R_S = Sun-comet distance; m_v = expected magnitudes given by the JPL Horizons system ephemeris. ; α = phase angle; Sun-C PA = extended Sun-comet radius vector position angle; D = projected diameter for 1 pixel; filters: CR = narrow cometary red filter, CB = narrow cometary blue filter, R_b = broad red filter centered on 620 nm, R = broad red filter centered on 650 nm (see section 2.1). Exposure time for each polarized component image x number of images used for the results.

Date	Days to perihelion	Δ (AU)	R_S (AU)	m_v	alpha ($^\circ$)	Sun-C PA ($^\circ$)	Telescope	D (km px $^{-1}$)	Filters	Exposure time
December										
25.60	-65	1.67	1.45	14.2	35.75	70.5		370	CR	180s
26.62	-64	1.67	1.46	14.2	35.75	70.5	IGO	373	CR	120s x 2
27.59	-63	1.67	1.46	14.2	35.8	70.4	(India)	373	CB	240s x 2
27.61	-63	1.67	1.46	14.2	35.8	70.3	2m	373	CR	180s x 2
27.63	-63	1.67	1.46	14.2	35.8	70.3		373	R_b	60s x 2
March										
17.81	+17	1.72	1.26	13.5	34.7	69.9	OHP	1051	R	20s x 9
18.78	+18	1.72	1.265	13.5	34.7	70.0	(France)	1057	R	20s x 18
19.80	+19	1.73	1.27	13.5	34.6	70.2	0.8m	1057	R	20s x 21
April-May										
30.60	+61	1.99	1.44	14.5	28.9	82.3	IGO	445	R_b	360s
01.70	+62	2.00	1.45	14.5	28.7	82.7	2m	445	R_b	600s

To build a polarization map, the normalization of the sky background and the stability of the total intensity ($Z = Z_0 + Z_{90} = Z_{45} + Z_{135}$) are mandatory (exposure times if different between images have to be normalized first). A minimum series of four plates is necessary to control the stability of the sky background (mainly when the object is low on the local horizon). The four polarized components have to be separated and centered to build the total intensity image and the polarization map.

2.2. Data reduction

Each individual image is bias and flat field corrected. To control that errors are not included in polarization values due to the averaging of the intensity on the field, calculations are made with and without flat field correction. The difference was negligible in comparison with other errors. The sky background is estimated in a region outside of the coma and free of faint stars (usually between the two polarized images of the same plate for IGO observations). A gravity center algorithm method is used to find the position of the photocenter of the comet on each polarized image. Only the brighter pixels close to the photocenter (typically 16) are taken into account. To avoid artifacts, the images are centered with a precision of 0.1 pixel. For the April-May observations at IGO, the cometary differential tracking with relatively long exposure times due to the faintness of the comet made it difficult to have such a precision on the centering.

The same procedure is applied to the three series of observations after separation of the four polarized components. Intensity images are obtained by adding two individual images: either (Z_0+Z_{90}) or ($Z_{45}+Z_{135}$). The successive polarized component images with the same orientation and the successive intensity images have to be similar. The comet being faint, the signal over noise

ratio is increased through building each polarized image by adding the individual images for each orientation of the fast axis. This method has been systematically used for the OHP observations. It was not always possible to use it for the December observations at IGO, some technical problems with the rotation of HWP not allowing the use of the whole data set.

Finally all the polarized components are added to build the intensity image. The radial decrease of intensity is studied first. On the image, the intensity is integrated in increasing apertures. An average intensity value is calculated for each distance to the photocenter by dividing the intensity in one pixel thickness annulus by the number of pixels in the annulus (radial profiles on Fig. 1).

Horizontal panel 1 on Fig. 2 presents the geometry of the observations for the three periods together with Sun and stars movement directions. It indicates that the cometary orbit plane is close to the ecliptic plane in projection on the sky. Intensity images (in negative) are presented on horizontal panel 2, Fig. 2. Main dust features are observed: on December in a cone towards the antisolar direction, on March in a South-East fan prolonged by an antisolar structure and a spike in the solar direction. On April-May a faint dust ejection is detected all around the photocenter with a slight increase mainly in the South direction. To better study the intensity decrease with increased photocentric distance, isophotes are drawn with a log scale (panel 3, Fig. 2). To emphasize the high gradient regions on the intensity images (as commonly used to find jet features), treated intensity images are also built (panel 4, Fig. 2) by a rotational gradient method (Larson and Sekanina, 1984). Cuts in the intensity images show the decrease in intensity through the different regions of the coma (Fig. 3).

Polarization values through circular apertures centered on the photocenter on the polarized components images are obtained by applying formula (2) and are compared to other comets polarization values (Fig. 4). Finally maps of polarization are obtained by the combination of four consecutive individual polarized images (Fig. 5). The polarization position angle θ is calculated by formula (3) or (6). Since the 0 position of one of the polarized filter or of HWP is not systematically aligned with the North-South celestial direction or with solar direction, the θ_0 angle has to be measured on standard stars for each observational period, in order of retrieving $(\theta - \theta_0)$.

2.3. Log of the observations

The Log of the observations and the characteristics of filters can be found in Table 1. The heliocentric distance range is relatively narrow within 1.45 to 1.26 AU. The phase angle does not change significantly from pre- to post-perihelion observations, it only decreases from about 37° to 29° post-perihelion. Before perihelion narrow band and broadband continuous filters have been used, while post-perihelion broadband filters have been used.

In December and April-May the seeing was smaller than 0.8 arcsec, in March it was smaller than 1.5 arcsec. On May 1, comet 67P/C-G was only observable during less than one hour and some star trails were present.

2.4. Standard stars

Polarization standard stars have been observed during all observational periods to control the non-polarization of the systems and to measure the position angle θ_0 of the fast axis of the polarization filters or of HWP (Table 2). The polarization values are similar to values obtained in previous

Table 2. Standard stars and their polarization P and position angle PA for the literature values. P_{obs} and PA_{obs} for the measurements. The chosen values for PA_{obs} are the closest to the expected ones. NA= not available

	Star	P(%)	PA ($^{\circ}$)	$P_{obs} (^{\circ})$	$PA_{obs} (^{\circ})$	$\theta_0 (^{\circ})$
IGO	GD319	0.09±0.09	140	0.6±0.3	113	27±10
December	C191B2B	0.09±0.06	157	0.2±0.1	131	
2008	HD25443	5.13±0.06	134	4.0±0.5	111	
	HD94851	0.06±0.02	NA	0.2±0.1	22.5	
	HD251204	4.04±0.07	147	2.4±1.1	117	
OHP	GD319	0.09±0.09	140	0.06±0.05	134	-4±10
March	HD251204	4.04±0.07	147	4.4±0.2	153	
2009	HD155197	4.38±0.03	103	4.2±0.15	117	
	HD155197	4.38±0.03	103	3.9±0.4	118	
IGO	HD94851	0.06±0.02	NA	0.33±0.08	67	0±10
April-	HD147084	4.46±0.03	32	4.17±0.2	42	
May	HD155197	4.38±0.03	103	4.57±0.07	95	
2009	HD155197	4.38±0.03	103	4.43±0.07	94	

publications (Bastien et al., 1988; Turnshek et al., 1990; Schmidt et al., 1992). Position angles are not completely defined after calculations. Different measurements for the same period help to estimate θ_0 which are indicated in the last column of Table 2.

3. Results

The intensity variations are first presented, through slopes of intensity radial profiles and comparison with an isotropic coma. The different coma morphologies are then presented and important asymmetries are pointed out for the first two periods of observations. To have a more precise description of these asymmetries, cuts in the solar-antisolar directions and in the perpendicular directions are made. Finally, variations in the polarization are pointed out.

3.1. Intensity images

3.1.1. Intensity radial profile

The decrease in intensity as a function of photocentric distance in log-log scale is on average close to -1 for distances up to about 20000 km for December observations and up to about 60000 km for March observations. Nevertheless, this decrease is not uniform. Close to the photocenter, the slope is dominated by the seeing (less than 2 pixels for each observational period). Further away, the radial decrease is small (slope between -0.7 and -0.8), but values such as -1.5 are obtained pre- and post-perihelion between 2000 km and 8500 km in December and between 4500 km and 40000 km in March 2009 (Fig. 1). The slope of the decrease is -1 at distances larger than 10000 km in December and larger than 50000 km in March. The important radial decrease in intensity is noticed through the whole set of filters (narrow blue and red, broad red). On April-May observations, the

slope of the radial decrease is -1 (as for an isotropic coma), except in the inner coma where it is very small (-0.4 between 2000 and 3500 km, i.e. more than four times the seeing radius).

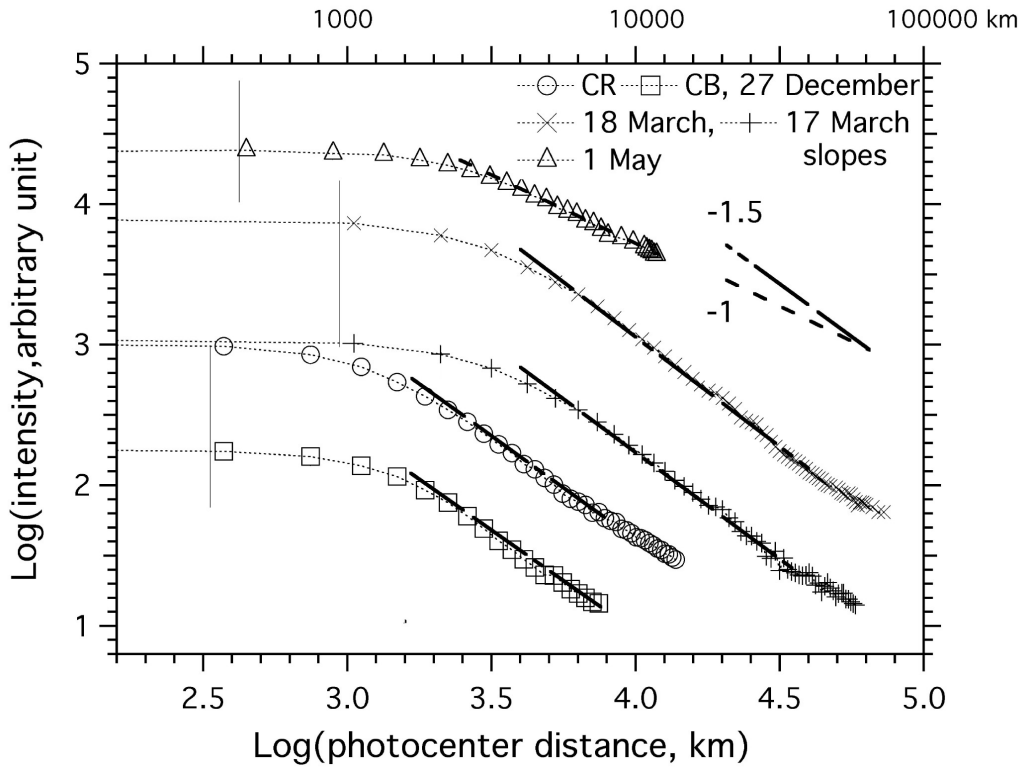


Fig. 1. Radial profiles for the 3 observational periods. About two months before perihelion and some weeks after, the slope in the intermediate part of the coma is steep (-1.5). It has the classical -1 value 2 months post-perihelion (as for an isotropic emission of dust). At large distances from the photocenter, typically more than 10000 km on December 2008 and more than 50000 km on March 2009, it is of about -1 . Vertical lines indicate the seeing radius limits for each period (respectively less than 330 km in December, 1050 km in March and 450 km in April-May).

On the December and March radial profiles, the steep decrease in intensity is limited in space to an increasing photocentric distance (respectively 8500 km and 40000 km). It may originate in a change of geometry or in an outer displacement of the region where this steep decrease is noticed. In the latter case, the velocity of the particles in projection on the sky is tentatively estimated to $(4.5 \pm 2) \text{ m s}^{-1}$ by dividing the increase of the heliocentric distance at the change of slope by the time between the observations).

3.1.2. Coma morphologies

On Fig. 2 intensity, isophotes and treated intensity images (Larson-Sekanina) are presented. The isophotes are in log scale for the intensity, with identical steps for the three periods. The coma is clearly asymmetric in December and March. In December, a large tailward structure (PA = 70°), which could be the end edge of a cone (PA between 70° and 130°) is noticed. For March observations, a bright structure at about PA = 250° is observed in the antisolar direction (prolonged

by a tailward structure at $PA = 80^\circ$). At the same period, dust is also ejected in a region between $PA = 90^\circ$ and $PA = 230^\circ$ (South-East). Several jet features are present on all the images through all filters. For April-May observations, the coma appears quasi-circular in projection on the sky with some dust towards the South-South-East direction. On the isophotes, the inner coma appears slightly elongated in the sunward direction. On the treated images, a faint feature seems to be present in the solar direction and in the South-East.

In March, the magnitude (11-12) is smaller by about 2 than its expected value on the ephemeris. Amateur astronomers (e.g. Seichi, 2009) have also observed an increase of intensity, which was still observable by the middle of March. It decreases progressively and is no more observable at the end of April. An outburst may be suspected to be responsible for this increase.

3.1.3. Profiles through the intensity images

On Fig. 3, the variation of the intensity is more precisely studied by cuts through the intensity images. The average radial decrease is also presented for comparison (measured on the same images than the different cuts). The coma, as described in section 3.1 for the two first periods, is highly asymmetric. Nevertheless for April-May observations, the intensity decrease depends also on the direction and the apparent featureless coma might originate in a geometric effect.

The central regions are affected by the seeing (less than one pixel radius for each period, corresponding respectively to 330 km, 1050 km and 450 km). Further away, at larger distances but smaller than about 2200 km in December and 4200 km in March, the slopes increase progressively. The small values except in March in the South-East direction (fan direction) may be partially due to the seeing but also to particles moving slowly away from the nucleus. For distances in the 2200 km to 8500 km in December and in the 4200 km to 40000 km in March, the slopes are steep except in the antisolar direction, where they have an average value of -1.2 in December and March, decreasing to -1 in April-May. In March, in the antisolar direction, the distance interval may be separated in two parts: (4200-16000) km with a slope of -1.3 and (16000-40000) km with a slope of -1.1. On March 17 and 19, for all directions, the distances and slopes are similar to those obtained on March 18.

The asymmetry of the coma is well characterized by the differences in the slopes for each period. The coma is limited to relatively small distances in the North-West direction. In December, the decrease is very important in the solar direction. In March, it is slightly smaller due to the presence of the feature in the antisolar direction, limited to 40000 km projected distance. In March, the slope in the South-East direction (-1.4) is less steep than in the solar direction, probably due to the emission of fresh dust. An interpretation in terms of properties of the particles is given in section 4.1.

3.2. Linear polarization

Aperture polarization corresponds to the integrated flux through apertures measured on the images. The influence of the aperture size is studied and the values derived from narrow and broadband filters are compared. Polarization values as a function of phase angle are characteristic of cometary dust average physical properties. The data are thus compared to previous phase curves obtained for comet 67P/C-G and for other comets (see section 4). On the polarization maps, regions where

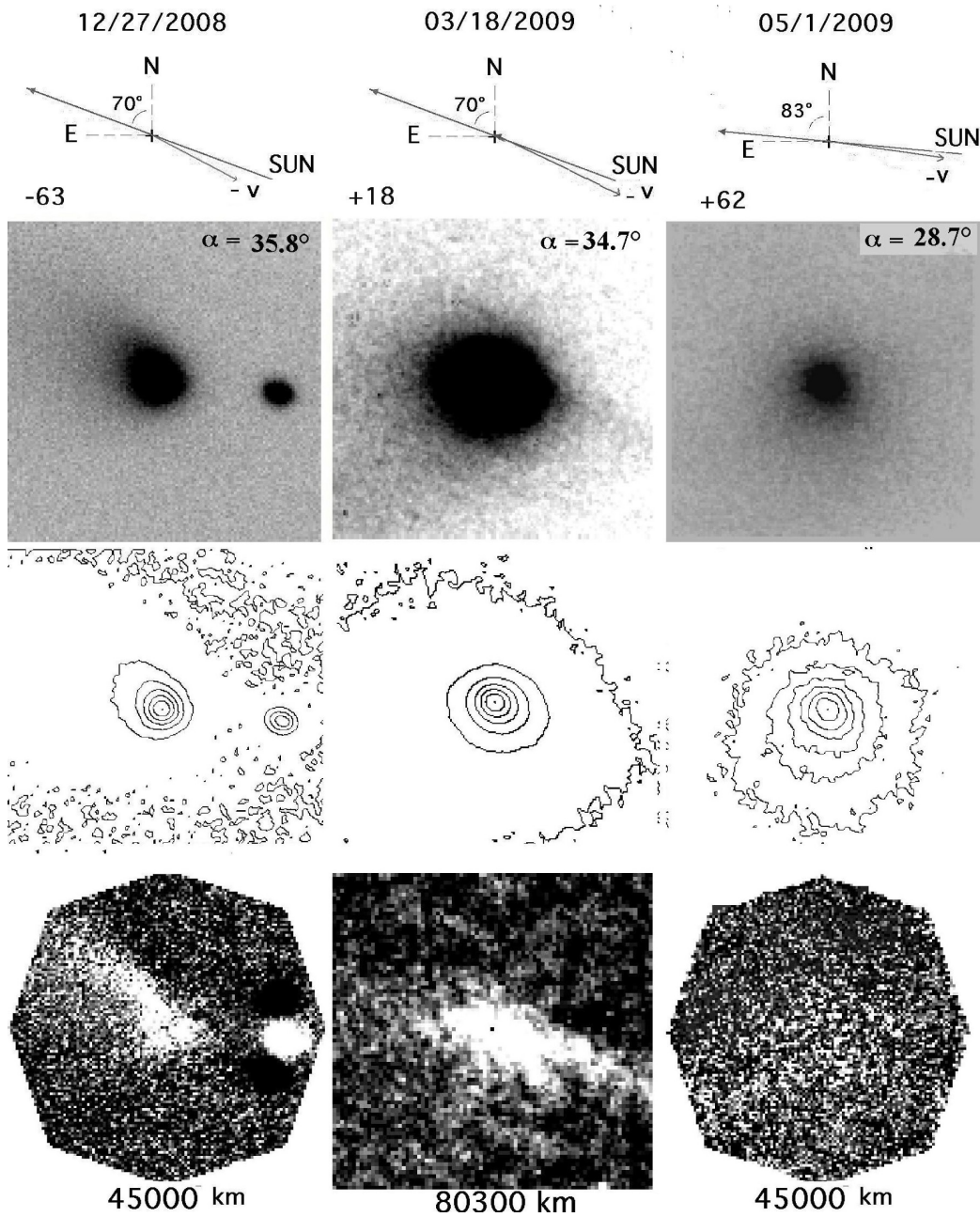


Fig. 2. Dust coma of 67P/C-G in the 2008-2009 apparition pre- and post-perihelion. Horizontal panel 1 (upper): orientation with Sun and stars movements from JPL's ephemeris; days to perihelion. Panel 2: Intensity images (negative). Panel 3: Isophotes for intensities with the same log scale. Panel 4 (lower) Rotational gradient treated images. (Note that relatively faint stars appear on the images)

dust is freshly ejected from the nucleus and has different physical properties than those of the surrounding particles are tentatively detected.

3.2.1. Aperture polarization

The polarization through increasing aperture sizes is presented in Table 3 for the different filters and periods. The polarization phase curve is presented in Fig. 4.

Table 3. Polarization in percent as a function of aperture diameter. D = projected diameter. Filters: see Table 1 caption. S/N: signal over noise ratio ≤ 3 . Star trails in the cometary coma. In the error bars, systematic errors (subtraction of the background, error bars on the standard stars) are included

Date	D	3000	6000	12000	24000
2008-2009	Filters	(km)	(km)	(km)	(km)
December					
25.60	CR	4.0±0.7	4.5±0.4	4.5±0.5	S/N
26.62	CR	4.1±0.8	4.8±0.5	4.8±0.8	S/N
27.59	CR	4.2±0.3	4.4±0.3	4.4±0.3	S/N
27.59	CB	4.4±0.5	4.5±0.5	4.5±0.5	S/N
27.63	R _b	4.5±0.3	4.4±0.5	3.9±0.5	3.8±0.8
March					
17.81	R	5.2±1.0	5.1±0.3	5.6±0.4	5.8±0.5
18.78	R	6.3±0.9	4.9±0.3	5.2±0.3	5.2±0.3
19.80	R	5.9±1.1	5.8±0.5	5.6±0.3	5.4±0.3
April-May					
30.60	R _b	2.7±0.8	2.5±0.8	2.5±1.1	S/N
01.70	R _b	2.5±0.5	2.3±0.5	2.3±0.8	Star trails

Only small changes in polarization values with aperture are observed through the filters (narrow or broadband). For December observations, there is no difference in polarization between the red and blue wavelengths (cometary narrow filters and red broad filter) at these intermediate phase angles (35°) for this dust rich comet. These results confirm the negligible contaminations by the emission lines of the gaseous species through the broadband filters. The relatively large variations in polarization in the inner coma ($D \leq 3000$ km), up to 1 % in March can hardly be attributed to the nucleus rotation, since they are within the error bars (average value 5.8 ± 0.4).

The polarization after perihelion is clearly higher than before perihelion, while the phase angle has decreased. Such an increase in polarization is likely to be the result of dust ejected during the outburst some days after perihelion correlated to the increase in intensity (section 3.1.2). Two months after perihelion (April-May), the polarization has decreased as expected with the decrease of phase angle, although it is possibly slightly above the remaining value.

3.2.2. Polarization maps

Polarization maps are retrieved for the two first periods. For the April-May observations, as noticed in section 2.3, star trails are too close to the photocenter to retrieve a polarization map. Sixty days before perihelion (December), the polarization map is quite uniform in a field of view of 12000 km diameter, without any feature, indicating that there is no major difference in the physical properties of the dust between the tailward structure and the other parts of the coma, including the region surrounding the photocenter.

Three weeks after perihelion the polarization close to the photocenter is about 6 %. The polarization in the features is (4-6) % for a surrounding polarization of (2-3) %. The features are mainly found in the South and sunward directions but also tailward. Figure 5 presents the polarization map for 18 and 19 March observations. A median filter was applied on the images. The higher polariza-

tion regions are correlated to the features observed on the rotational gradient intensity images (Fig. 2). The main features have the same orientation on the two dates; they seem to be more extended on March 19.

The angle θ_0 between the polarization vector and the fast axis of filter 0 at each observational period is quasi-uniform on the whole field, without any measurable deviation and equal to $(122 \pm 15)^\circ$ in December, $(159 \pm 10)^\circ$ in March and $(77 \pm 15)^\circ$ in May. The angles $\theta - \theta_0$ between the polarization vector and the solar direction are respectively equal to $(95 \pm 15)^\circ$, $(91 \pm 10)^\circ$ and $(77 \pm 20)^\circ$. As expected the results lead to a polarization vector perpendicular to the solar direction.

The polarization maps are different in March as compared to December indicating dust with physical properties closer to those usually observed for active comets.

4. Discussion

4.1. Comparison between the different periods of observation

The different changes in morphology may be due to changes in the orientation of the rotational axis of the nucleus as compared to the Sun position (seasonal effects). Before perihelion (about 2 months), the sunward feature may correspond to a rotating jet ejecting material in a cone with its side-end on the North-East direction. It might also come from dust slowly pushed back in the tail direction. The absence of change in polarization indicates that on the average, the physical properties of the particles remain similar inside the whole coma. The significant decrease in the slope of the intensity around the photocenter may be due to large particles mainly concentrated at short distances to the nucleus and not too sensitive to the solar radiation pressure.

After perihelion (about 3 weeks), the sunward structure may correspond to an antitail (perspective view, see e.g. Agarwal et al., 2007b). Nevertheless, the polarization variations inside the coma indicate that particles ejected in the South-East direction in a large fan present different physical properties, the antitail being mainly made of large particles previously ejected. A part of the dust seems to be sensitive to the solar radiation pressure; it can be made of smaller grains (submicron or micron-sized) eventually in fluffy aggregates with a greater velocity than the large more compact particles (larger than hundreds of micrometers). From March 18 to March 19 the structures seem to extend mainly in the South direction (Fig. 5).

The absence of major features in April-May (except perhaps in the solar and South-East directions) may correspond to a change in geometry, as well as to a decrease in activity at increasing heliocentric distances. The slopes, close to (-1), suggest that the very large grains are no more predominant in the coma. The absence of jet features suggests a quiet coma mainly made of small grains probably in fluffy aggregates.

4.2. Comparison with previous observations of 67P/C-G

4.2.1. Intensity

Such steep slopes as those observed before perihelion and just after had also been previously observed during the 82-83 and 95-96 apparitions (Schleicher, 2006). A post-perihelion outburst was noticed about one month after perihelion for the 1996-1997 and 2002-2003 apparitions (Kidger, 2003). On the secular light curve a decrease of activity (intensity decrease) usually appears about

100 days before perihelion (Schulz et al., 2004; Ferrin, 2005). Post-perihelion, the envelope of the light curve remains the same than the inbound leg whenever the comet activity is continuously detected. The maximum in intensity actually occurs about one month after perihelion. The magnitude variations, that we observe seems to be the result of a seasonal effect and not of an outburst with a sudden decrease of magnitude.

Tozzi et al. (2009) have observed 67P/C-G before perihelion at different decreasing heliocentric distances (3 AU to 1.3 AU). From the variations and evolution of intensity images of the coma, they conclude that very large particles (mm to cm-sized) moving very slowly in the coma are present. They do not find any variation with wavelength related to the presence of the large particles and exclude the presence of sublimating organic grains. The authors estimate the average velocity of the particles (from the progressive extension of the coma) to be in the 0.3 ms^{-1} to 3.5 ms^{-1} range for decreasing heliocentric distance. The velocity we obtain in section 3.1.1 is quite comparable.

Fulle et al. (2009), using data available from recent and previous apparitions have modeled the dust environment of the comet and estimated the evolution of tail, trail and antitail. Their conclusions are similar to those of Tozzi et al. (2009) with emission of mm to cm-sized particles before perihelion. They also suggest an important seasonal effect with the North pole illuminated by the Sun before perihelion and the South pole after perihelion. From the increase of the velocity of the particles, together with coma and tail models, they conclude on the emission of small grains post-perihelion from the South hemisphere. They also suggest that the autumn equinox took place in January 2009, i.e. before perihelion. As suggested in the present work, the particles seem to be mainly large before perihelion, while numerous small grains (probably included in large fluffy aggregates) are ejected at the time of maximum activity, about three weeks after perihelion. Later on, two months after perihelion, the activity decreases while small grains seem to dominate in the coma (spring on the South hemisphere).

4.2.2. Polarization

The aperture polarization values we obtained for the 2008-2009 apparition are compared to those obtained for other comets and to previous observations of 67P/C-G (Fig. 4). Two main classes of comets have been defined by their aperture polarization. At larger phase angles than $(30-40)^\circ$, active comets with well confined jets present a higher polarization than less active comets (see e.g. Hadamcik and Lvasseur-regourd, 2003a). The polarization values measured before perihelion on December 2008 are between the two synthetic curves corresponding respectively to trigonometric fits on all the available data for active comets and for other comets (they are very close to one another at phase angles smaller than 40°). The values obtained about three weeks after perihelion in March are above the curves by about 1 %. The April-May values are just above the curves by about 0.5 % but the difference is within the error bars and it is difficult to conclude. As noticed in Lvasseur-Regourd et al. (2004), the polarization values obtained by Myers and Nordsieck (1984) and Chernova et al. (1993) are close to the synthetic phase curves but not on them (Fig. 4). Myers and Nordsieck used a spectropolarimeter, possibly leading to small differences with results from aperture polarimetry (some coma regions are not in the slit). The data corresponding to their observations six weeks before perihelion and about 2.5 months after are below the synthetic phase curves by approximately 1 %. The value obtained on 1982 November 17, ten days after perihelion, is just

above the curves by about 0.5 %; it corresponds to an increase of about 1.5 % as compared to Myers and Nordsieck (1984) phase curve. Chernova et al. (1993) have observed the comet three weeks after perihelion by aperture polarimetry in the blue domain and at a phase angle of 27.2° ; their value corresponds to a polarization level similar to our April-May observation in the red domain at 28.8° . Indeed, neither in our observations nor in Myers and Nordsieck (1984) observations, any noticeable color effect has been noticed. For all polarization measurements, except perhaps post-perihelion, 67P/C-G may be classified as a low P_{max} comet, which is typical of JFCs (Kolokolova et al., 2004) with large dark particles. This classification is in agreement with the absence of silicate features in the infrared at wavelengths close to $10 \mu\text{m}$ for observations made pre-perihelion in 1982 (Hanner et al., 1985).

The dust ejected after perihelion seems to be more polarized than before perihelion. Moreover, some features present on the polarization maps are reminiscent of those observed in more active comets. The dust is pushed towards the tail with a greater speed than before perihelion. In projection on the sky, the smaller grains are seen in the same line of sight than the large grains ejected before perihelion; such smaller grains may be the constituents of large fluffy aggregates.

4.3. Comparison to other Jupiter family and active comets

Albedo values of 67P/C-G dust obtained during previous apparitions are summarized in Hadamcik and Lvasseur-Regourd (2009) together with their phase angle variation. They are compared to those obtained for some JFCs and comet 1P/Halley. Geometric albedo values in the 0.04 and 0.06 range are found (Fig. 5 in Hadamcik and Lvasseur-Regourd, 2009 and references therein). Fulle et al. (2009) suggest an albedo between 0.05 and 0.06. This very low albedo and the presence of large fluffy aggregates can be the reason of the constancy (or slight increase) of polarization through large apertures mainly three weeks post-perihelion. Indeed large aggregates induce a slight increase in polarization whenever fragmentation of the aggregates take place (see e.g. Hadamcik et al., 2009 for the experimental simulations).

In spite of the relative faintness of 67P/C-G during its last return, activity is obvious from coma asymmetries and features. Within the 29° - 36° phase angle range, significant differences in polarization cannot be expected. However, the post-perihelion increase in polarization is a clue to the presence of smaller grains in fast moving particles for the freshly emitted dust. Such an increase has also been observed for other comets (see e.g. Dollfus et al., 1988, for 1P/Halley; Tozzi et al., 1997, for C/1996 B2 Hyakutake; Hadamcik and Lvasseur-Regourd, 2003c, for C/1999 S4 LINEAR). For the two last cases, they were observed when the nucleus broke down in smaller fragments ejecting numerous fragmenting particles and gas, which does not seem to be the case for comet 67P/C-G.

A comparison with comet 26P/Grigg-Skjellerup is of interest, since remote observations by Jockers et al. (1994) of this relatively faint comet have been modeled by Fulle et al. (1994) and since this comet was observed in-situ by the Optical Probe Experiment onboard the Giotto spacecraft (Lvasseur-Regourd et al., 1993). In the inner coma (closer distance to nucleus about 270 km), important intensity and polarization variations were observed (Renard et al. 1996). The color and polarization variations allowed these features to be interpreted as jets and an eventual small fragment. From the intensity gradients, McBride et al. (1997) have modeled the dust profile and

confirmed the results relative to the presence of jets and of a small fragment of 10-100 m at about 1000 km from the nucleus. The OPE brightness results have been degraded to the ground-based resolution and geometry, leading to a perfect agreement with Fulle's model results.

Comet 81P/Wild 2 is a dust rich relatively active comet for which, like 67P/C-G, only some of the features have counterparts on the polarization maps (Hadamcik and Levasseur-Regourd, 2003a). Indications on the dust properties have been obtained by the in situ Dust Flux Monitor onboard Stardust (Tuzzolini et al., 2004). Important local variations were observed, some of them being interpreted by swarms of fragmenting fluffy aggregates (Clark et al., 2004). Particles captured on aerogels in the coma are indeed either large compact grains, or fluffy aggregates of tiny grains (Hörz et al., 2006). The later type may be present post-perihelion in 67P/C-G coma, with a relative abundance increasing with time (seasonal effect).

As in the case of 67P/C-G, the polarization value retrieved for comet 9P/Tempel 1 before Deep Impact event was between the values corresponding to the two synthetic curves (Hadamcik et al., 2007a). Variations in polarization have been observed in the inner coma of 67P/C-G (section 3-2.1). These variations cannot be related with certainty to the nucleus rotation as for 9P, for which an important decrease in intensity was also observed in some directions as well as an important polarization decrease with increasing distance to the photocenter. During the Deep Impact event, small fast moving grains were found to be ejected in the coma. The increase in intensity during the ejection was sudden; it is progressive for comet 67P/C-G but a similar increase in polarization was observed. The fast moving grains ejected by Deep Impact were likely to originate from the subsurface. A similar origin may be suggested for the grains coming from the South hemisphere of comet 67P/C-G.

5. Conclusions

Complementary light scattering observations of the coma of comet 67P/C-G were performed in France and India during three periods: on December 2008, two months before perihelion, on March 2009, three weeks after perihelion and on April-May 2009, two months after perihelion. They allow to conclude on a change in the physical properties of the ejected dust related to seasonal variations. From the steep radial decrease of intensity before perihelion and just after, large slowly moving compact dark particles seem to be present in the coma. An absence of any feature on the polarization map indicates that the dust properties are in average the same in all directions. After perihelion a correlated increase of intensity and polarization (as compared to before perihelion) suggest the emission of fluffy aggregates of small grains. All these results confirm the results obtained by different techniques during previous apparitions indicating that the main physical properties of the dust do not change from one apparition to the next. The coma seems to be dominated by large grains originating from one hemisphere pre-perihelion and by small grains from the other hemisphere post-perihelion.

Comet 67P/C-G is a dust rich Jupiter family comet. By its restricted activity, it can be compared to comet 26P/Grigg-Skjellerup. It is similar to comet 9P/Tempel 1 by the large particles emitted before perihelion. It is also similar to comet 81P/Wild 2 by the likely presence of fluffy aggregates after perihelion. The surface or subsurface origin of the particles will be only given by the Rosetta in situ measurements. Rosetta all along its rendezvous with 67P/C-G should encounter dust par-

ticles consisting of large conglomerates only observable from the spacecraft (MIDAS, GIADA detection).

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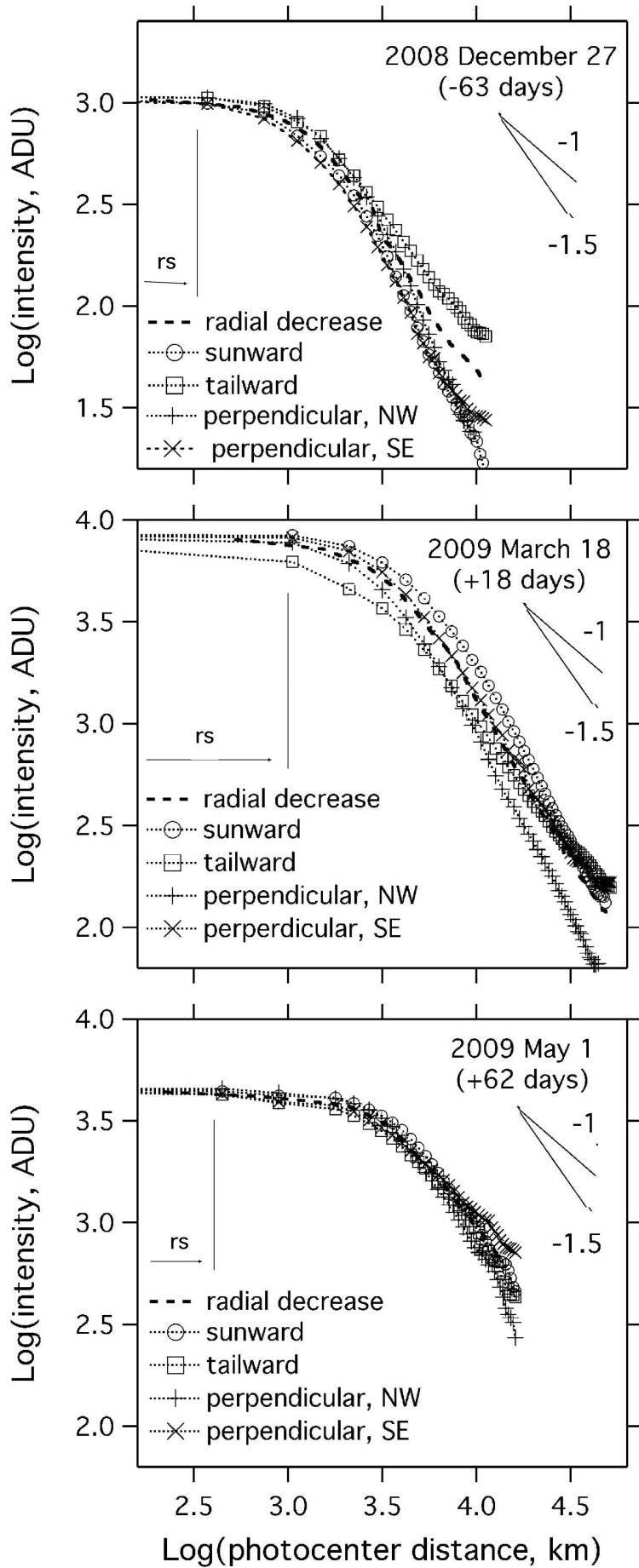


Fig. 3. Cuts through the coma sunward, tailward and in perpendicular directions for the 3 periods of observations. Slopes of -1 and -1.5 are indicated on the graphs. Vertical lines indicate the seeing radius limit (rs)

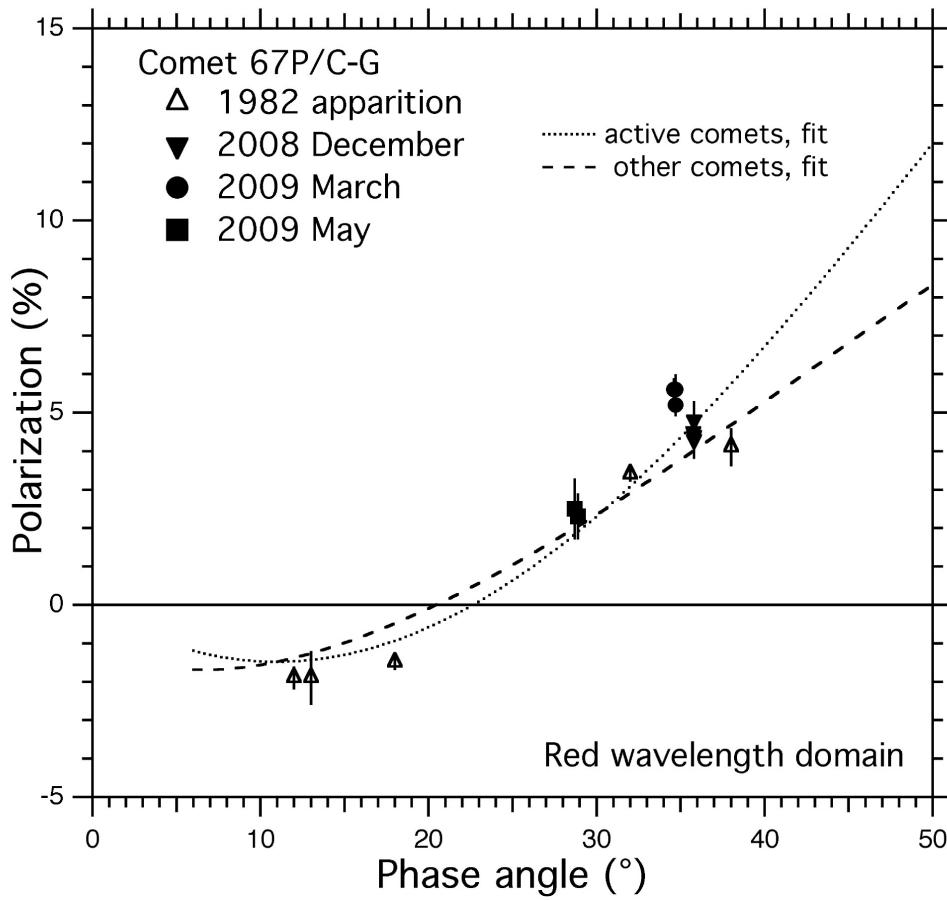


Fig. 4. Comet 67P/C-G polarization observations at its 2008-2009 return, as compared to its 1982 apparition (Myers and Norsiedk, 1984) and to synthetic polarization phase curves for other comets.

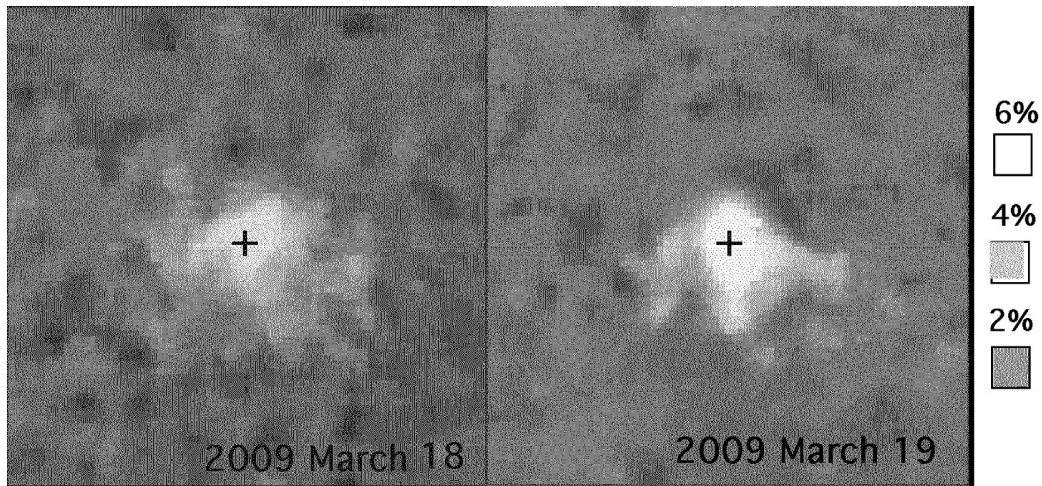


Fig. 5. Polarization map in March 2009. FOV: 40000 km. + = photocenter.