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ORIGINAL ARTICLE

Study of dust coma of comets 32P/Comas Sola and C/2015 V2 (Johnson) by imaging polarimetry

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Abstract

We present the results obtained from photometric and polarimetric observation of a *Jupiter family comet* 32P/Comas Sola, and a *Oort cloud comet* C/2015 V2 (Johnson), observed on February 20, 2015 (post-perihelion) and December 30, 2016 (pre-perihelion), at phase angles 9.8° and 21.6°. Both the comets show a diffuse coma in the intensity map which extends towards the tailward direction. To study the morphological structures of both the comets, intensity images are treated with digital filters. A V-shaped structure is noticed in the antisolar direction of comet 32P/Comas Sola which appears due to radial outflow of dust from the nucleus. The comet C/2015 V2 (Johnson) shows some structures with fan-shaped fine jets in the antisolar direction. It is also noticed that intensity is found to be higher in the tailward direction as compared to sunward direction in both comets. The average polarization value is estimated to be $(-1.0 \pm 0.7)\%$ at aperture radius $\sim$ 13,500 km for comet 32P/Comas Sola and $(-0.4 \pm 0.7)\%$ at aperture radius $\sim$ 12,600 km for comet C/2015 V2 (Johnson). The observed polarization values obtained from this work are compared with other comets at almost similar phase angles which showed a satisfactory agreement within the framework of the estimated errors in polarization.

Keywords Methods: observational · Techniques: polarimetric · Comets: general · Comets

1 Introduction

Comets are the small icy bodies of the solar system which spend most of their lifetime far away from the sun. Hence their subsurface materials are thought to be primordial in nature. When they come close to the sun, ejection of dust and sublimation of ice, water take place due to excessive solar radiation pressure. Comet is found to be a good polarizer of light due to the scattering of sunlight from the cometary dust particles and the fluorescence emission by the gaseous molecules. The intensity and linear polarization of the scattered light are the two main source of information regarding the optical and physical properties of the dust. Recently, polarimetric observations of some comets at different phase angles were made by several investigators to study the dust grain properties of comets: C/2013 V1 (Boattini) and 290P/Jager by Deb Roy et al. (2015a); C/2012 L2 (LINEAR) by Deb Roy et al. (2015b); C/2013 R1 (Lovejoy) by Borisov et al. (2015); C/2009 P1 (Garradd) by Das et al. (2013), Ivanova et al. (2017); C/2013 US10 (Catalina) by Kwon et al. (2017); 41P/Tuttle-Giacobini-Kresák by Rumyantsev et al. (2019); C/2014 A4 (SONEAR) by Ivanova et al. (2019) etc. Numerous modeling was done by many investigators to study the polarization properties of compact and aggregated particles (Lasue et al. 2009; Das et al. 2011; Kiselev et al. 2015; Kolokolova et al. 2015; Mazarbhuiya and Das 2017; Deb Roy et al. 2017; Halder et al. 2018; Ivanova et al. 2019; Mazarbhuiya et al. 2021 etc.).

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Observation of comet at small phase angle is a typical task as the comet is expected to be far off in the sky and appears as a faint object at such phase angles. There is also limited polarimetric observational data of comets at low phase angles as compared to data at large phase angles. Study of negative polarization at lower phase angles reveals the composition feature of the cometary nucleus as well as the dust properties, which holds great importance in cometary science. In this paper, we present results obtained from polarimetric observations of comets 32P/Comas Sola and C/2015 V2 (Johnson) at phase angles 9.8° and 21.6°, respectively, taking note that no polarimetric study of these comets have been reported so far.

The comet 32P/Comas Sola belongs to a "erratic" group of comets (Marsden and Sekanina 1971). This comet was discovered by J. Comas Sola on November 04, 1926, on photographs taken at the Barcelona Fabra Observatory (Mazzotta Epifani and Palumbo 2011). The nucleus of this comet is estimated to be 8.4 km in diameter; the perihelion and semi-major axis of this comet are about 1.834 AU and 4.263 AU respectively.[1] Its last perihelion was on October 17, 2014. Comas Sola is a Jupiter family comet with a current orbital period of 8.5 to 9 years (Sekanina 1985). The nucleus properties of the periodic comet Comas Sola are studied by Sekanina (1985). He derived equatorial radius of 32P/Comas Sola's nucleus which is close to 1 km and rotation period which ranges between 1.5 and 2.3 days. The size of most short-periodic comets nuclei are in the 2–10 kilometer range as found by Scotti (1994). Królikowska et al. (1998) studied the nongravitational effects in orbital motions of the periodic comet 32P/Comas Sola. Comet C/2015 V2 (Johnson) is an Oort cloud comet, with an eccentricity of 1.001 and semi-major axis of 976 AU, discovered by Jess Johnson on November 03, 2015 (Kumar and Ganesh 2018). They conducted spectroscopic observations of the comet C/2015 V2 (Johnson) and revealed that in the optical spectrum of the comet C/2015 V2, no molecular emissions were present, which was quite unusual as compared to general cometary spectra. Paradowski (2020) observed 32 comets including C/2015 V2 to determine the brightness and size of cometary nuclei. The average absolute nuclear magnitude is 16.127±0.176 as obtained by them. This comet reached its perihelion on June 12, 2017 ($r = 1.637$ AU), and its closest approach to the Earth was on June 5, 2017 ($\triangle = 0.812$ AU).[2]

This paper is organized as follows: we describe our observations and data reduction in *Sect. 2*, results in *Sect. 3* and discussion in *Sect. 4*.

[1] https://en.wikipedia.org/wiki/32P/Comas_Sol%C3%A0.

[2] https://www.universetoday.com/tag/c2015-v2-johnson/.

2 Observations and data reduction

The polarimetric observations of the comets 32P/Comas Sola and C/2012 V2 (Johnson) were carried out on February 20, 2015 (after perihelion passage, $r = 2.29$ AU) and December 30, 2016 (before perihelion passage, $r = 2.66$ AU) respectively with the help of 1.04-cm Sampurnanand Telescope of Aryabhatta Research Institute of Observational Sciences (ARIES), Nainital (ST, Latitude: 29°22′ N, Longitude: 79°27′ E, Altitude = 1951 m). This telescope has a Cassegrain focus with a focal ratio of $f/13$, which is well-equipped with ARIES Imaging Polarimeter (AIMPOL) that acts as a back-end instrument for polarimetric observation. AIMPOL consists of a Wollaston prism and a half-wave plate (HWP). The Wollaston prism is used to split the incident beam into two orthogonally polarized ordinary and extraordinary components, and the HWP alters the polarization state of the light wave. The observations were performed in R filter ($\lambda = 0.630$ μm, $\triangle\lambda = 0.120$ μm). A CCD camera of 1024×1024 pixels is used to record the images which corresponds to 1.73 arcsec per pixel with an effective field of view ∼ 8 arc minute diameter on the sky. The gain and read-out noise of the CCD camera are 11.98 e^-/ADU and 7.0 e^- respectively. The detailed description of the instrument is available in Rautela et al. (2004) and Medhi et al. (2010).

The geometrical conditions during the polarimetric observation on February 20, 2015 and December 30, 2016 are collected from the Jet Propulsion Laboratory's Horizon system of NASA and are presented in Table 1. The sky was clear and air mass was in the range 1.04–1.21 on Feb 20, 2015 where as on Dec 30, 2016, the sky was a little haze and air mass was in the range 1.39–1.57. The standard stars for null polarization and zero-point of the position angle of polarization were taken from Clemens and Tapia (1990), Das et al. (2013) and Deb Roy et al. (2015a) respectively. We observed both the high polarized and unpolarized stars, (HD 155197 and HD 109055) on February 20, 2015 and (HD 23663 and GD 319) on December 30, 2016, to find out the position of polarization plane and the instrumental polarization.

The linear polarization (p) and position angle (θ) of the polarization vector in terms of normalized Stoke's vectors q $(= Q/I)$, u $(= U/I)$ are defined by;

$$p = \sqrt{(q^2 + u^2)} \text{ and } \theta = 0.5 \tan^{-1}(u/q) \tag{1}$$

The results are shown in Table 2. Since the zero position of HWP is not systematically aligned with the north-south direction, so for the better accuracy of result we have calculated the offset angles ($\theta_0 = \theta - \theta_{obs}$) as $\sim -44°$ and $\sim -53°$ for our polarimetric observations on February 20, 2015 and December 30, 2016. The instrumental polarization

Table 1 Log of the observations at R filter. Object, UT date, UT time, heliocentric distance (r), geocentric distance ($\triangle$), apparent total visual magnitude (m_v) (taken from the Jet Propulsion Laboratory's Horizon system of NASA), phase angle (α), position angle of extended Sun – comet radius vector (ϕ), and exposure time (time for one exposure × number of exposures used for the results) during the observations

Object	Date	Time (UT)	r (AU)	$\triangle$ (AU)	m_v	α (°)	ϕ (°)	Expo. time (s)
32P/Comas Sola	Feb 20, 2015	21:30 – 22:10	2.29	1.36	14.9	9.8	251	200 × 4
C/2015 V2(Johnson)	Dec 30, 2016	21:30 – 23:00	2.66	2.51	11.4	21.6	306	150 × 4

Table 2 Results of standard polarized and unpolarized stars at R filter. p and θ from literature Das et al. (2013), Deb Roy et al. (2015a), Clemens and Tapia (1990). p_{obs} and θ_{obs} from observations. Offset angle is calculated using the relation: $\theta_0 = (\theta - \theta_{obs})$

Date	Star	p (%)	θ (°)	p_{obs} (%)	θ_{obs} (°)	θ_0
February 20, 2015	HD 155197	4.27±0.03	102.88	4.28±0.19	147.05	−44.17
February 20, 2015	HD 109055	0.015	NA	0.19±0.17	3.5	–
December 30, 2016	HD 236623	5.37±0.03	93.04	5.42±0.06	146.5	−53.46
December 30, 2016	GD 319	0.09±0.09	140	0.10±0.70	157.5	−17.5

and it's error are estimated to be 0.175 and 0.17 on Feb 20, 2015 and 0.1 and 0.7 on Dec 30, 2016. The size of 1 pixel (the scale) at the comet distance is 1688 km (∼ 1700 km) for the comet 32P/Comas Sola, and 3138 km (∼ 3150 km) for C/2015 V2 (Johnson).

We have analyzed the CCD recorded images using an astronomical image processing software IRAF (Image Reduction and Analysis Facility). Each image is bias and flat field corrected. The Wollaston prism and the rotatable HWP form the two orthogonally polarized components of a single object in the CCD camera. The two perpendicularly polarized images (I_e and I_o) obtained in a single plate (for a particular rotation angle of the HWP) are then trimmed with the same dimension. Thus, a total of eight images having the same dimension are obtained for 0°, 22.5°, 45° and 67.5° rotation of the HWP for each observation. Since the comet is not bright enough, the signal-to-noise ratio of each polarized component is enhanced by adding the images for each orientation of the HWP.

We have estimated the sky background by using standard task in IRAF and then subtracted the average value of sky background from the scientific image. It is quite a tough job to estimate the sky background because the dusty coma may extend over far distance. Generally, sky background is measured in several positions at the edge of scientific image from the photocenter because some signal might be present there. So, it is important to measure sky background very carefully so that the signal of coma could be negligible. We have measured the average value of sky background at the edge of each frame of scientific image and subtracted from the scientific image. The method of sky background subtraction depends on the object and sky condition at the time of observation.

3 Results

3.1 Intensity images

The intensity images are obtained by adding two polarized components (extraordinary, I_e and ordinary, I_o) with a proper alignment. Thus, the total intensity is given by $I = (I_e + I_o)_{0^\circ} = (I_e + I_o)_{22.5^\circ} = (I_e + I_o)_{45^\circ} = (I_e + I_o)_{67.5^\circ}$. The intensity images with contours are shown in Fig. 1(i) and (v). The dimension of the intensity images are ∼ 34,000 km × 34,000 km for the comet 32P/Comas Sola and ∼ 63,000 km × 63,000 km for the comet C/2015 V2 (Johnson). The position angles of the Sun – Comet radius vector are 251° and 306° for the comets 32P/Comas Sola and C/2015 V2 (Johnson).

To analyze the morphology of two comets, an enhancement technique is applied to highlight low-contrast structures of the cometary coma. We have used a rotational gradient technique developed by Larson and Sekanina (1984), division by azimuthal average and azimuthal renormalization filtering (Samarasinha and Larson 2014; Martin et al. 2015). The Larson-Sekanina filter is one of the most applied filters to study the coma morphology that was used by many investigators in past. The resulting images lose all possible photometric information after filtering and explore hidden variations of brightness inside the coma. The division by azimuthal averaged profile generates a more representative background in the case of gas species and for non-spherically symmetric outflows. However, azimuthal renormalization adjusts the azimuthal values for a given radius to be within a certain range. We have used IRIS, an Astronomical Image-Processing Software, to process the images of comets with Larson-Sekanina Filter. To process the images with azimuthal average and azimuthal renormalization

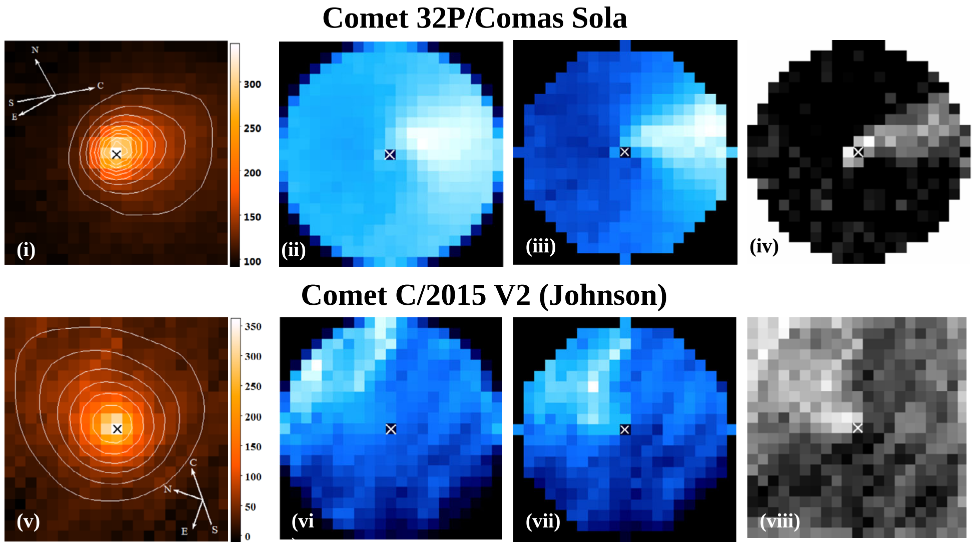

Fig. 1 Intensity images of comet 32P/Comas Sola obtained with R-filter treated with digital filters: (i) direct image with contours (the levels are in ADU), (ii) azimuthally average filter; (iii) azimuthal renormalization filter; and (iv) the Larson-Sekanina filter. The field of view for all four images is ∼ 34,000 km × 34,000 km. Intensity images of C/2015 V2 (Johnson) obtained with R-filter treated with digital filters: (v) direct image with contours (the levels are in ADU), (vi) azimuthally average filter; (vii) azimuthal renormalization filter; and (viii) the Larson-Sekanina filter. The field of view for all four images is ∼ 63,000 km × 63,000 km. The '×' mark denotes the optical center of the comet. The position angles (PA) of extended Sun (S) – Comet (C) radius vector are 251° (for 32P/Comas Sola) and 306° (for C/2015 V2 (Johnson)) respectively

filters, some programs are used which are available in the link: *http://www.psi.edu/research/cometimen* (Samarasinha et al. 2013). In Fig. 1, unprocessed and processed images using three digital filters are shown. The detailed information about the different enhancement techniques are nicely presented by Picazzio et al. (2019) and references therein.

Both the comets show a diffuse asymmetric coma extended in the tailward direction. The shape of the coma, as well as the distribution of the surface brightness, give an idea on the cometary activity. In all processed images of comets 32P/Comas Sola and C/2015 V2 (Johnson) (Fig. 1: (ii), (iii) (iv), (vi), (vii) and (viii)), some morphological features are seen in all filters. In comet 32P/Comas Sola, a strong dust jet feature seems to be present in the antisolar direction. A V-shaped structure appears as radial outflow of dust from the nucleus. If the structures for different filters are compared, one can see them changing shape and intensity. These changes are probably correlated with the velocity and size of the dust particles outflowing from nucleus surface. In comet C/2015 V2 (Johnson), structures are well observed in the antisolar direction with fan-shaped fine jets.

3.2 Intensity profiles

The brightness profile through the different directions in a cometary coma is an important tool to study the physical properties of dust grains. Intensity of comet 32P/Comas Sola and C/2015 V2 (Johnson) along sunward (I_{SW}) and tailward (I_{TW}) direction throughout the coma are shown in Table 3 and 4. In Figs. 2 (i) and (ii), we have plotted the intensity against the photocentric distance to study the spatial variation of intensity in the sunward and the tailward direction. The central nucleus regions are affected by the atmospheric seeing. The seeing radius is estimated to be ∼ 3400 km on February 20, 2015, and ∼ 6300 km on December 30, 2016. So, the virtual aperture radius is taken from 2 pixel to 10 pixel with an increment of 1 pixel in case of both comets. It is already mentioned in Section-2 that the size of 1 pixel

Table 3 Intensity of comet 32P/Comas Sola along sunward (I_{SW}) and tailward (I_{TW}) direction throughout the coma. Here, d is the photocentric distance (in km) and S/N is the signal-to-noise ratio. d is taken from 2 pixel to 10 pixel with an increment of 1 pixel where the size of 1 pixel (the scale) at the comet distance is 1688 km. The intensity image is created with combination of four frames each having 200 sec exposure time

log (d) (in km)	log (I_{SW})	S/N	log (I_{TW})	S/N
3.528	2.379	15	2.460	17
3.704	2.236	13	2.354	15
3.829	2.124	12	2.263	14
3.926	2.066	11	2.204	13
4.006	2.044	11	2.164	12
4.072	2.008	10	2.130	12
4.130	2.003	10	2.130	12
4.182	2.000	10	2.118	11
4.227	1.987	10	2.103	11

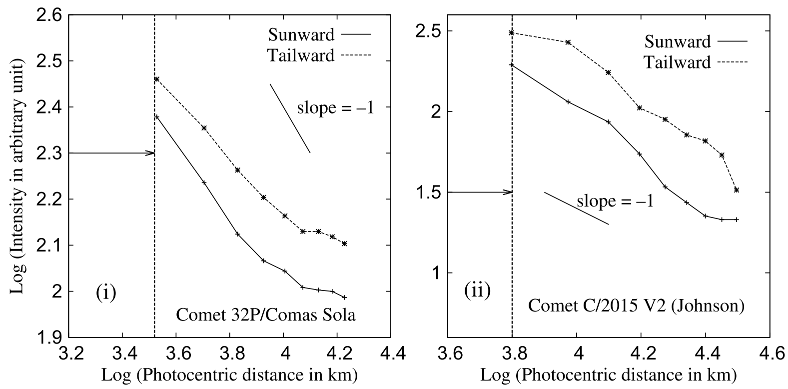

Fig. 2 Cuts through the coma sunward and tailward profile for comets (i) 32P/Comas Sola and (ii) C/2015 V2 (Johnson). Vertical dashed line represents the seeing radius limit for the observed night. A slope of −1 is plotted for reference

Table 4 Intensity of comet C/2015 V2 (Johnson) along sunward (I_{SW}) and tailward (I_{TW}) direction throughout the coma. Here, d is the photocentric distance (in km) and S/N is the signal-to-noise ratio. d is taken from 2 pixel to 10 pixel with an increment of 1 pixel where the size of 1 pixel (the scale) at the comet distance is 3138 km. The intensity image is created with combination of four frames each having 200 sec exposure time

log (d) (in km)	log (I_{SW})	S/N	log (I_{TW})	S/N
3.798	2.290	14	2.488	17
3.974	2.060	11	2.429	16
4.099	1.936	9	2.242	13
4.196	1.736	7	2.023	10
4.275	1.533	6	1.951	9
4.342	1.435	5	1.855	8
4.400	1.352	5	1.818	8
4.451	1.330	5	1.730	7
4.497	1.330	5	1.514	6

(the scale) at the comet distance is 1688 km for the comet 32P/Comas Sola, and 3138 km for C/2015 V2 (Johnson). For both the comets, it is observed that the intensity falls off stiffly with increase of the photocentric distance in both directions. The intensity is higher in the tailward direction as compared to that in Sunward direction for both the cases.

The intensity (I) is related with photocentric distance (d) by the relation: $I = kd^m$, where, k is the scaling factor for the coma and m is the power law index which is obtained from the slope of intensity profile. When $m = -1$, it is called *canonical slope* which represents the steady and isotropic coma (Jewitt and Meech 1987; Goidet-Devel et al. 1997; Lamy et al. 2009). Further, $m < -1$ indicates that the dust is pushed in the tail by the solar radiation, replenishing the tailward regions (Hadamcik et al. 2014). Many investigators in past made the intensity profiles of their target comets to study the intensity versus photocentric distance (Hadamcik et al. 2007, 2014; Das et al. 2013; Deb Roy et al. 2015a,b; Ivanova et al. 2015; Hadamcik et al. 2016, etc.).

The variation of intensity profile can be studied from Figs. 2 (i) and (ii), by estimating the change of slopes. The slopes are estimated from $d \sim 3400$ km to 16,900 km for 32P/Comas Sola and ~ 6300 km to 28,200 km for C/2015 V2 (Johnson). For comet 32P/Comas Sola, when d is between 3400 km to 11,800 km, the intensity falls with a slope of -0.69 ± 0.05 in the sunward direction and -0.62 ± 0.02 in the tailward direction. However, the slope is found to be -0.13 ± 0.03 in the sunward direction and -0.17 ± 0.05 in the tailward direction, when d is from 11,800 km to 16,900 km. Again, for C/2015 V2 (Johnson), the slope is obtained as -1.58 ± 0.08 in the sunward direction and -1.26 ± 0.09 in the tailward direction when d is between 6300 km to 28,200 km (see Table 5).

The difference between the slopes from the standard canonical model suggests about various ongoing physical phenomenon such as the temporal change in dust production, effect of solar radiation pressure (segregation of particle size and mass), change in optical properties, which may lead to the variation of slopes from the standard canonical coma model (Das et al. 2013 and references therein). The difference between slopes at different cometocentric distance suggest non-isotropic dust emission from cometary nucleus. Variation of slope in term of brightness profile signifies the variation in relative dust concentration with the increase of photocentric distance. This variation may occur due to solar radiation pressure which changes velocity outflow of dust particles depending on their size. Also, some other ongoing evolutionary mechanisms play an important role in steepening or flattening out the intensity profile (Deb Roy et al. 2015a).

3.3 Aperture polarization

Polarization values at different apertures are computed considering all the properly aligned polarization components. The degree of linear polarization is either negative or positive, by definition. Since the sign of polarization depends on the position angle of the plane of polarization with respect to the scattering plane in the equatorial reference system, the values P_r and θ_r for the scattering plane are connected

Table 5 Intensity profile variation along sunward and tailward direction throughout the coma. Here, d is the photocentric distance (in km) and m is the slope of intensity profile

Comet	d (in km)	log (d)	m Sunward	m Tailward
32P/Comas Sola	3400 – 11, 800	3.528 – 4.072	−0.69 ± 0.05	−0.62 ± 0.02
	11, 800 – 16, 900	4.072 – 4.227	−0.13 ± 0.03	−0.17 ± 0.05
C/2015 V2 (Johnson)	6300 – 28, 200	3.798 – 4.451	−1.58 ± 0.08	−1.26 ± 0.09

Table 6 Polarization values for the comet 32P/Comas Sola at different aperture radii or photocentric distances (d)

d (km)	5100	6800	8400	10, 100	11, 800	13, 500	15, 200	16, 900
P_r (in %)	−1.6±1.1	−1.1±0.8	−0.9±0.7	−0.8±0.5	−0.8±0.5	−1.0±0.7	−1.1±0.8	−1.1±0.8

Table 7 Polarization values for the comet C/2015 V2 (Johnson) at different aperture radii or photocentric distances (d)

d (km)	6300	9400	12, 600	15, 700	18, 800	22, 000	25, 100	28, 200	31, 400
P_r (in %)	−2.5±1.7	−1.0±1.7	−0.4±0.7	−0.4±1.3	−0.2±0.8	−0.5±1.3	−0.4±1.3	−0.7±1.1	−1.0±1.2

with the quantities P_{obs} and θ_{obs} using the following relation (Chernova et al. 1993):

$$P_r = P_{obs}.cos(2\theta_r), \quad \theta_r = \theta_{obs} - (\phi \pm 90°), \qquad (2)$$

where ϕ is the position angle of the scattering plane and the sign in the bracket is chosen to ascertain the condition $0 \leq \phi \pm 90° \leq 180°$. If θ_r is either 0° or 90°, the linear polarization will be either close to the scattering plane or perpendicular to it.

For 32P/Comas Sola, the aperture polarization values are shown in Table 6. The virtual aperture radius is taken from 3 pixel to 10 pixel with an increment of 1 pixel in case of comet 32P/Comas Sola (the size of 1 pixel is ∼ 1700 km). This comet shows negative polarization values at different apertures, starting from its photocenter. The average polarization is found to be (−1.0±0.7)% at aperture radius ∼ 13, 500 km for 32P/Comas Sola, and it shows almost uniform polarization value at different apertures. Table 7 shows the aperture polarization of the comet C/2015 V2 (Johnson). The virtual aperture radius is taken from 2 pixel to 10 pixel with an increment of 1 pixel in case of comet C/2015 V2 (Johnson) (the size of 1 pixel is ∼ 3150 km). The average polarization value is estimated to be (−0.4±0.7)% at aperture radius ∼ 12, 600 km. Also the error measurements are noted to be high in the outer coma due to faintness.

In Fig. 3, polarization versus phase angle is plotted for eleven observed comets at R-filter (λ = 0.630 μm) taken from the Database of comet Polarimetry by Kiselev et al. (2017) along with our observed data for comets 32P/Comas Sola and C/2015 V2 (Johnson). The references mentioned in the database for different comets are 1P/Halley (Chernova et al. 1993), 67P/Churyumov-Gerasimenko (CG) (Hadamcik et al. 2010), 78P/Gehrels (Choudhury et al. 2014),

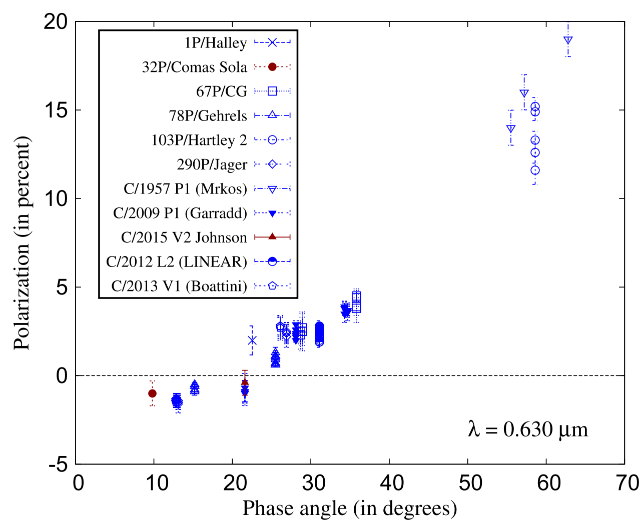

Fig. 3 Polarization versus phase angle plot for different observed comets including comets 32P/Comas Sola and C/2015 V2 (Johnson) at R-filter (λ = 0.630 μm) (Comet Hale-Bopp data is not taken). The average polarization of 32P/Comas Sola is (−1.0±0.7)% at aperture radius ∼ 13, 500 km whereas the value for C/2015 V2 (Johnson) is (−0.4±0.7)% at aperture radius ∼ 12, 600 km. The linear polarization data of different comets are taken from the Database of Comet Polarimetry by Kiselev et al. (2017)

103P/Hartley 2 (Hadamcik et al. 2013), 290P/Jager (Deb Roy et al. 2015a), C/1957 P1 (Mrkos) (Martel 1960), C/2009 P1 (Garradd) (Das et al. 2013; Hadamcik et al. 2014), C/2012 L2 (LINEAR) (Deb Roy et al. 2015b) and C/2013 V1 (Boattini) (Deb Roy et al. 2015a). Among them, comets Halley, Comas Sola, Churyumov-Gerasimenko (CG), Gehrels, Hartley 2 and Jager are *short-period comets*; C/Mrkos and C/Johnson, and C/Boattini are *non-periodic* *comets*; and C/Garradd and C/LINEAR are *long-period comets*. The polarization values obtained from this work are compared with other comets at almost similar phase angle and a satisfactory agreement within the framework of the estimated errors in polarization is noticed.

4 Discussion

To have the largest insight in the basic physical properties of cometary dust grains at different regions of coma, our photometric and polarimetric results are compared with other polarimetric observations done by various researchers.

The brightness of the comet derived from the imaging polarimetry gives a well-defined idea about dust properties present in the coma including special features like jet, fan etc. In recent years, many investigators drawn the brightness profile along different direction of the extended coma to get a complete picture of the coma (Hadamcik et al. 2007, 2010, 2014, 2016; Ivanova et al. 2015, 2019; Stinson et al. 2016; Rosenbush et al. 2017; Ivanova et al. 2019 etc.).

In our study, the intensity is found to be higher in the tailward direction as compared to that in sunward direction for both the comets 32P/Comas Sola and C/2015 V2 (Johnson). Similar trend was observed in the comet C/2010 S1 (LINEAR) (Ivanova et al. 2015) and in the comet C/2012 L2 (LINEAR) (Deb Roy et al. 2015b). For the comet 32P/Comas Sola, the slopes are estimated from $d \sim 3400$ km to 16,900 km. When d is between 3400 km to 11,800 km, the intensity falls with a slope of -0.69 ± 0.05 in the sunward direction and -0.62 ± 0.02 in the tailward direction. However, the slope is found to be -0.13 ± 0.03 in the sunward direction and -0.17 ± 0.05 in the tailward direction, when d is between 11,800 km to 16,900 km. For the comet C/2015 V2 (Johnson) the slope is obtained as -1.58 ± 0.08 in the sunward direction and -1.26 ± 0.09 in the tailward direction when d is between 6300 km to 28,200 km. The primary reason for intensity variation is due to temporal changes in the dust production. The slopes for comet 32P/Comas Sola obtained from the intensity profile variation along sunward and tailward direction are estimated to be < -1. The slope less than –1 in 32P/Comas Sola suggests that the dust is pushed in the tail by the solar radiation, restoring the tailward region. However for the comet C/2015 V2 (Johnson), a sharp fall in slope > -1 is observed in the intensity profile.

Aperture polarimetry of the whole coma provides useful information on the bulk physical properties of dust particles and also explores the polarization distribution at different photocentric distances. The variation of polarization degree with the photocentric distance can be an evidence of differences in the physical properties of the dust grains over the cometary coma. This is very useful tool to classify the comets depending on polarization variation with a change in aperture. The dusty comets show uniform polarization over the whole coma but the comets with the gas domination shows high polarization near the photocenter and then shows a steep fall in the polarization value with the increase in aperture (Manset and Bastien 2000; Rosenbush et al. 2002; Kiselev et al. 2004; Jewitt 2004). Kolokolova et al. (2007) summarized published polarization data for different gas and dust rich comets. They explored that the comets have a major difference in the polarimetric behavior with increase of the aperture size. On the basis of the polarization distribution derived from the aperture polarimetry, the comets are classified as *dust rich* and *gas rich* comets. The comets in which the polarization do not show any radial dependence on the aperture size are termed as dust rich comets and the comets showing strong radial fall in polarization value with increase of aperture are called as gas rich comets.

At $\alpha = 9.8°$, we have estimated the average aperture polarization as $(-1.0 \pm 0.7)\%$ for the comet 32P/Comas Sola when heliocentric distance (r) was 2.29 AU. The results obtained by other investigators at the phase angle close to $\sim 10°$ are now discussed. Joshi et al. (2010) observed the comet 17P/Holmes at $\alpha = 13.6°$ through aperture polarimetry when $r = 2.49$ AU. They reported linear polarization value of -1.1% at $\lambda = 0.684$ μm and aperture diameter 11,751 km. The observed polarization for comet C/2013 V1 (Boattini) is found to be $(-1.4 \pm 0.3)\%$ at $\alpha = 12.8°$ (when $r = 2.42$ AU), whereas 290P/Jager shows $(-1.6 \pm 0.3)\%$ polarization at phase angle 13° (when $r = 2.34$ AU) (Deb Roy et al. 2015a). They found that the integrated aperture polarization value is almost uniform with the increase of projected diameter for both the comets. The non-radial dependence of polarization of two dusty comets C/2013 V1 (Boattini) and 290P/Jager on the aperture size at comparable phase angles is also being observed in comet 32P/Comas Sola. The comet C/2009 P1 (Garradd) at $\alpha = 21.6°$ (when $r = 2.52$ AU), shows the negative polarization value -0.9% (Das et al. 2013). At $\alpha = 21.6°$, we have estimated the average polarization value of the comet C/2015 V2 (Johnson) as $(-0.4 \pm 0.7)\%$ when $r = 2.66$ AU. The estimated polarization values obtained from this work are compared with other comets at almost similar phase angles (data taken from Kiselev et al. 2017). A satisfactory agreement within the framework of the estimated errors in polarization is observed.

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Data Availability The optical polarimetry data of two comets will be shared on a reasonable request to the corresponding author.

Code Availability Not applicable.

Declarations

Competing Interests The authors declare that they have no conflicts of interest.

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