Chapter 5

Polarimetric observations of some comets

In this chapter, we have first introduced the comets under study and presented their log of the observations. After that, instrumental techniques and data reduction processes have been discussed in detail.

5.1 The recently observed comets

Polarimetric results of five recently observed comets, viz C/2009 P1 Garradd, 78P/Gehrels, C/2007 N3 (Lulin), C/2011 L4 (PANSTARRS), 290P/Jager have been reported in the present work. The concerned comets were observed and studied under the Indo-French collaborative research project funded by the Indo French Centre for the Promotion of Advanced Research (CEFIPRA, No. 4507-1). This collaboration allowed polarimetric observations of the same small object from two different observing sites in the Northern hemisphere, IUCAA Girawali Observatory (IGO) in India and Haute-Provence Observatory (OHP) in France. Some of the observations were supported by Program National of Planetology (PNP), France.

Amongst the new bright comets, comet C/2009 P1 Garradd (hereafter Garradd) was discovered on 13 August 2009 by G. J. Garradd from Siding Springs Observatory, Australia; when the comet was at 8.7 au from the Sun. It was detected on four images using the 0.5-m Uppsala Schmidt telescope and a CCD camera. The magnitude was estimated as 17.5-17.7 and the coma was described as circular and 15″ across. The first confirmation was obtained by W. Robledo (El Condor Observatory, Cordoba) on 14 August 2009. This seemingly dynamically new comet presents an almost parabolic orbit.

Comet 78P/Gehrels, also known as Gehrels 2 (hereafter Gehrels), is a periodic Jupiter Family comet. It was discovered at magnitude 15-16, during a minor planet survey in 1973, by Tom Gehrels of Lunar and Planetary Laboratory, Arizona, USA; while examining plates exposed with 122-cm Schmidt Telescope of Palomar Observatory. Numerous immediate observations allowed us to calculate the precise elliptical orbit indicating a perihelion date of November 30, 1973 and an orbital period of 7.93 years. The comet's aphelion (at 5.4 au) is in the zone of control of the giant planet Jupiter and thereby orbit of the comet is frequently perturbed.

Comet Lulin C/2007 N3 (Lulin) (Lulin hereafter) was discovered by Ye Quanzhi and Lin Chi-Sheng on 11 July 2007 using the 41-cm (16 in) Ritchey-Chretien at Lulin Observatory, Nantou, Taiwan as a part of the Lulin Sky Survey project. The object was initially described as an asteroidal object, when found by Quanzhi Ye on three images obtained by Chi-Sheng Lin. Several confirming observations were obtained; and on 17 July, J. Young (Table Mountain Observatory, California, USA) noted a coma 2-3″ across, with a bright central core. The magnitude was estimated as 18.9. B. G. Marsden calculated a parabolic orbit with the perihelion date as 14 January 2009 and the perihelion distance as 1.24 au.

Comet C/2011 L4 (PANSTARRS) (C/2011 L4 hereafter) was discovered by Richard Wainscoat (Institute for Astronomy, University of Hawaii) on 6 June 2011 with the 1.8-m Pan-STARRS 1 Ritchey-Chretien telescope at Haleakala, Hawaii, USA. The comet was discovered at a distance of nearly 7.9 au from the Sun and its magnitude, as recorded on four CCD images was within the range 19.4-19.6. Several prediscovery images have been found later, reported by S. Larson (with 154-cm reflector, Mt. Lemmon Survey in Arizona, USA on 24 May 2011) and Hidetaka Sato (with 25-cm reflector in Tokyo, Japan on 30 May 2011).

The periodic Jupiter Family comet 290P/Jager (or 1998 U3 or 2013 N1) was discovered by Michael Jager on 23 October 1998. It was recorded on 16- and

9-minutes Technical Pan Film exposures with a 0.25-m, f/2.8 Schmidt camera. It was quite widely observed visually. The perihelion and aphelion distance being 2.157 au and 10.1 au respectively with the orbital period 15.2 years.

Thus there are two Jupiter Family comets and three non-periodic Oort cloud comets under study. This will help to understand the taxonomy and evolution of Oort family and Jupiter Family comets.

5.2 Instrumental details

5.2.1 Telescopes:

The observations were made with two telescopes in Cassegrain configuration: one in India and another in France. Starting with the instruments and its working formulae, the observation log and data reduction procedure are discussed below.

IGO: The IUCAA (Inter University Center for Astronomy and Astrophysics) Girawali Observatory, *IGO* is situated near Pune, India. It is located at $19°5'$ N latitude, $73°40'$ E longitude, 1000 m altitude.

The Cassegrain telescope has a diameter of primary as 2 m and focal ratio f /10. An instrument called IFOSC (IUCAA Faint Object Spectrograph and Camera) containing a rotating half-wave plate (HWP) and a Wollaston prism is used to measure polarization. The polarization imaging has a 4 arcmin field of view (FOV) and the resolution of CCD camera used is 0.307 arcsec per pixel.

The rotating HWP with its fast axis normal to the optical axis of the system is associated to a Wollaston prism. When the HWP rotates successively by an angle $22.5°$, $45°$ and $67.5°$ from an initial position $0°$, the position angles of the polarized components respectively rotate by $45°$, $90°$, and $135°$ from the initial position. At each position of the HWP, two orthogonally polarized beams (ordinary and extraordinary component) are recorded at the same time on the CCD frame. The separation between the ordinary and extraordinary components is 0.9 arcmin. Two successive positions of the HWP are needed to retrieve the degree of polarization and the position angle of the polarization vector (for more details on the instrument, see [Sen and Tandon, 1994], [Ramaprakash et al., 1998]). The telescope tracking-mode was cometary by differential tracking.

The intensity (I), polarization (P), and polarization angle (θ) are calculated by the expressions-

$$I = I_o(\beta) + I_e(\beta) \tag{5.1}$$

$$R(\beta) = \frac{\frac{I_e(\beta)}{I_o(\beta)} - 1}{\frac{I_e(\beta)}{I_o(\beta)} + 1} \tag{5.2}$$

$$P = 100\sqrt{R(\beta)^2 + R(\beta + 22.5)^2} \tag{5.3}$$

$$\theta = 0.5 \arctan[\frac{R(\beta + 22.5)}{R(\beta)}] \tag{5.4}$$

Where β corresponds to different HWP positions with respect to celestial NS-axis. β = $0°$, $22.5°$, $45°$ and $67.5°$. R(β)=q when β= $0°$, $45°$ and R(β)=u when β= $22.5°$, $67.5°$; where q, u are normalized Stoke's parameters.

OHP: The Observatory of Haute-Provence, *OHP* is situated near Marseille, France. It is located at $43°55'54''$ N latitude, $5°42'44''$ E longitude, 650 m altitude.

The Cassegrain telescope has a diameter of 0.8 m and focal ratio f /15. The field of view for polarization imaging is 7 arcmin. The CCD camera has 2048×2048 pixels, back-illuminated, of 13.5μm size each. The resolution per pixel is thus 0.21 arcsec. The CCD is cooled down to $-50°$C by a 5-stage Peltier system. A 4 pixels×4 pixels binning is used. The telescope tracking-mode was stellar to avoid any noticeable movement of the center during the 120 sec exposers. When the comet is faint, the signal-to-noise ratio is increased through building each polarized image by adding the 8 to 10 individual images at each position of the fast axis.

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 I_0, I_{45}, I_{90} and I_{135}). For more details on the instruments, see ([Hadamcik et al., 2010], [Hadamcik et al., 2013]).

The intensity (I), the measured polarization (P), and polarization angle (θ) are calculated by the expressions-

$$I = I_0 + I_{90} = I_{45} + I_{135} \tag{5.5}$$

$$P = 200\frac{\sqrt{(I_0 - I_{90})^2 + (I_{45} - I_{135})^2}}{I_0 + I_{90} + I_{45} + I_{135}} \tag{5.6}$$

$$\theta = 0.5\arctan[\frac{I_{45} - I_{135}}{I_0 - I_{90}}] \tag{5.7}$$

Correlation between the notation of the polarized components of two observatories: For OHP, the images at fast axis positions $0°, 90°$ (noted I_0, I_{90}) correspond to ordinary and extraordinary components of a image at position β=0 of HWP in IGO. Similarly (I_{45}, I_{135}), (I_{90}, I_0), (I_{135}, I_{45}) of OHP corresponds to position $\beta = 22.5°, 45°, 67.5°$ of HWP in IGO respectively.

The position angle of the polarization plane relative to the plane which is perpendicular to the scattering plane is given by-

$$\theta_r = \theta - \theta_0 - (\phi \pm 90) \tag{5.8}$$

($\theta - \theta_0$) being the position angle of the polarization plane measured in the equatorial reference system. θ is the position angle of the polarization plane in the instrumental reference system and θ_0 is the position angle of the polarization axis of one polarized filter (measured for each observing run by observation of standard stars). The position angle of the scattering plane (ϕ) is known for each date. For symmetry reasons, it is defined between $0°$ and $180°$ and can be deduced from the value of the Sun-comet radius vector position angle (PA in Table 2). The sign between the parentheses, in Eq. (5.8), is chosen to ensure the condition $0° < (\phi \pm 90°) < 180°$. θ_r is generally of about $0°$ for comets observed at phase angles larger than inversion angle (about $22°$) and $90°$ for that observed below inversion angle. The polarization $P_r = Pcos(2\theta_r)$, with $P_r = P$ for θ_r= $0°$ and $P_r = -P$ for θ_r= $90°$.

5.2.2 Filters:

Table 5.1: Central wavelength and band passes of the filters.

Observatory	Filter	Central Wavelength λ nm	Bandpass $\triangle\lambda$ nm	Possible contaminations
IGO	ESA comet red CR_{IGO}	684	9	None
	ESA comet blue CB_{IGO}	443	4	None
	Bessel red R_{IGO}	630	120	C_2, NH_2, [OI]
	Near infrared I_{IGO}	900	80	
OHP	ESA comet red CR_{OHP}	684	9	None
	ESA comet blue CB_{OHP}	443	4	None
	Thuan-Gunn red R_{OHP}	655	90	C_2, NH_2, [OI]
	Near infrared I_{IGO}	810	150	

Table 5.1 describes the central wavelength and band pass of various filters used during observations. Two narrowband ESA comet red (CR_{IGO}) and comet blue (CB_{IGO}) filters and two broadband Bessel red (R_{IGO}) and near-infrared (I_{IGO}) were used at IGO. At OHP also, two narrowband ESA comet red (CR_{OHP}) and comet blue (CB_{OHP}) filters and two broadband Thuan-Gunn red filter (R_{OHP}) and near-infrared (I_{OHP}) were used. The CR_{IGO}, CB_{IGO} filters defined by ESA are used to avoid gaseous contaminations in the red and blue continuum. In the R_{IGO} filter, the remaining contaminations may exist mainly by C_2, NH_2 and [OI]. They are reduced in the R_{OHP} filter for which NH_2 is the main eventual contaminant. The comet at large distance (3.3 au) did not show any emission line, but at smaller heliocentric distances, the comet may be more active with some more gaseous emissions. Nevertheless, the comet was found to be depleted in C_2 by [A'Hearn et al., 1995], at similar heliocentric distance than our observations and in that case the main contamination may be due to NH_2.

5.3 The observation of five comets

Under the said Indo-French joint campaign, the five comets mentioned above were observed in polarimetric mode by Indian and French astronomers from two observatories viz. IGO, India and OHP, France.

Comet Garradd reached its perihelion on 23 December 2011, at a solar distance (R) of about 1.55 au. Earth-based observations were favorable until early

March 2012, where its distance to Earth (Δ) went down to about 1.27 au. Comet Garradd observations, from October 2011 to March 2012, corresponded to increasing solar distances (R) from 1.33 to 1.93 au, to decreasing Earth distances (Δ) from 2.10 to 1.33 au, and to phase angles remaining between 28° and 35°, i.e., in a region where differences between cometary dust presenting a low polarization and cometary dust presenting a high polarization are already detectable.

Last perihelion of comet Gehrels occurred on 12 January 2012. It was observed for 2 nights in October 2011 from IGO; about 3 months before the perihelion. In January 2012; just 12 days after the perihelion it was observed for 1 night from OHP. Lastly, 1 month after that, the comet was again observed for 2 nights in February 2012 from IGO. During the observing periods the comet's geocentric distance increased from 1.21 to 2.28 au, the visual magnitude lied between 11.5 and 12.6, and its solar phase angle varied between 15.21° and 28.31°.

Two months after its last perihelion (10 January 2009), the comet Lulin was observed from OHP during the period 17 to 20 March 2009 at a geocentric distance 0.9 au, while the phase angle varied between 35.7° and 36.7°.

Perihelion of comet C/2011 L4 was attained on 10 March 2013. The comet was observed on 6 and 7 May 2013 from OHP, two months after the perihelion at a geocentric distance 1.5 au and phase angle 38°.

Last perihelion of Jager occurred on 12 March 2014. From OHP, it was observed on 27 and 28 January 2014 at a geocentric distance of 1.3 au, when phase angle was between 14°-15°.

Along with them, some polarimetric standard stars were also observed during each observational run with different filters. They are used to calibrate instrumental reference system.

Table 5.2: Log of observations of comets under study.

The comet	Date of observation	Observatory	α°	Sun-C PA°	Δ (au)	R (au)	Resolution (km/pixel)	Filter
C/2009 P1 (Garradd)	21-22 Oct,2011	IGO	30.9-30.8	69-68	2.1-2.11	1.61	470	CB_{IGO}, CR_{IGO}
	26 Oct,2011	OHP	30.3	64	2.11	1.6	1290	R_{OHP}
	23-25 Jan,2012	OHP	34.8-35.2	317-315	1.68-1.64	1.6-1.61	1030-1000	CR_{OHP}, R_{OHP}
	18-20 Feb,2012	IGO	34.7-34.3	285-281	1.35-1.34	1.74	300	$CR_{IGO}, R_{IGO}, I_{IGO}$
	17-19 Mar,2012	OHP	28.5-28.3	172-165	1.37-1.33	1.96-1.93	840-810	CB_{OHP}, CR_{OHP} R_{OHP}, I_{OHP}
78P/Gehrels	21-22 Oct,2011	IGO	15.2	72	1.21	2.12	270	CR_{IGO}, R_{IGO}
	24 Jan,2012	OHP	28.3	68	2	2.01	1200	R_{OHP}
	19-20 Feb,2012	IGO	25.5	71	2.28	2.03	500	R_{IGO}
C/2007 N3 (Lulin)	17-20 Mar,2009	OHP	35.7-36.7	97-96	0.9	1.5	135	R_{OHP}, I_{OHP}
C/2011 L4 (PANSTARRS)	6-7 May,2013	OHP	38	310-309	1.5	1.3	235	R_{OHP}, I_{OHP}
290P/Jager	27-28 Jan,2014	OHP	14-15	104-103	1.3	2.1	195	R_{OHP}, I_{OHP}

Δ = distance to Earth; R = solar distance; α = phase angle; Sun-C PA = extended Sun-comet radius vector position angle (All the data have been reported from http://ssd.jpl.nasa.gov/horizons.cgi.)

5.4 Basic reduction and calibration of imaging data

CCD image is a matrix of numbers; each number represents the brightness in that pixel. Several steps are involved in the production of different scientific images from the raw exposures recorded by the detector. An overview of these steps is given here.

5.4.1 Software used:

The NOAO (National Observatory of Astronomical Observation) software package "Image Reduction and Analysis Facility (IRAF)" is used for the reduction and analysis of scientific data. The IRAF system provides a good selection of programs for general image processing and graphics applications, plus a large selection of programs for the reduction and analysis of optical astronomy data. The IRAF Command Language (CL) is the user's interface to the IRAF system. The CL organizes many system and application tasks (programs) into a logical hierarchy of packages. A package is a collection of logically related tasks, and is represented to the user using a particular type of menu. The CL is designed to serve both as a command language and as an interpreted programming language. New tasks or entire packages may be added to the CL at any time by entering simple declarations. Hence the CL environment can be easily extended by the user. (for details please see [Tody, 1986], [Coenen and Grange,], [Shames and Tody, 1986]) . To study the comets, new tasks have been written in CL environment for data analysis.

5.4.2 Course of actions:

Image cleaning: The first goal of image reduction is to correct two types of errors in the CCD data: additive and multiplicative errors. To correct additive errors, we simply subtract something from the image and to correct multiplicative errors, we simply divide the image by something.

Additive errors arise from two primary sources: bias offset and dark current. A 'dark' is simply an image taken by the CCD for the same exposure length and temperature as the exposure it is meant to correct with the shutter closed. A 'dark' will correct both ‘bias offset’ and ‘dark current’. A ‘bias’ frame is essentially a zero length dark frame, so it corrects bias offset, but not dark current. Research CCDs (like in IGO, OHP) are cryogenically cooled (usually to liquid nitrogen temperature -77 K), so that they do not suffer from dark current. Thus data from a cryogenically cooled CCD need only be corrected by a bias frame.

Multiplicative errors can arise from several sources: differences in quantum efficiency, illumination differences (vignetting), and dust halos. All of these represent a difference in sensitivity from pixel to pixel in the chip. Thus different pixels need to be multiplied by unlike values to match dissimilar sensitive pixels. This is normally achieved by taking images of a photometrically flat surface (such as the inside of the observatory dome, or the twilight sky) called a ‘flat field’. The purpose of flat fielding is to ensure that there are no spatial variations in the sensitivity of the detector. Since the brightness of this surface is constant, any variations in the recorded image (the ‘flat field’ image) must be due to variations in the sensitivity of the detector. These variations can then be removed from the target observation by dividing every pixel value in the target image by the corresponding pixel value in the flat field image.

The mathematical representation of the basic reductions to correct additive and multiplicative errors is:

$$Scientific\ Image = \frac{(Raw\ Image - bias)}{(flat - bias)} \times (mean\ value\ of\ flat)$$

Centering: Centre of comet is determined from the brightest pixel of concerned region and thus, is called optical centre or optocenter of the comet. The position of the optocenter of the comet on each image is determined using a gravity center algorithm. The arrays holding the parallel and perpendicular component images need to be aligned so that the same pixel in each array corresponds to the same position on the sky. The polarized components are centered with a precision of 0.1 pixels to avoid artifacts. It is not always possible to have such a high precision on the centering due to faintness of images.

Stability testing: Fluxes through apertures with diameters of 5, 10, and 15 pixels centered on the optocenter are measured for each polarized component

$(I_0; I_{45}; I_{90}; I_{135})$. For each set of four images, the stability of fluxes at different apertures of polarized components is controlled from these measured fluxes of each individual polarized component. If a difference greater than 1% is detected between the fluxes (I_0+I_{90}) and $(I_{45}+I_{135})$ for 15 pixels on the successive images, the image is rejected. This is because in less than ten minutes interval between the successive images, they have to be same.

Sky Background: The raw data stores numbers which are proportional to the combined sky and object intensity transmitted by the analyser (plus noise). The sky may be polarized, which can affect the polarization calculation of the desired target. The intensity of the background night sky thus needs to be estimated and subtracted from each of the aligned arrays. The sky background is estimated from a region outside the coma and free of faint stars. For OHP, the background is subtracted from each polarized component to measure polarization using Eq. (5.6). But in the case of IGO, any background subtraction is not necessary to calculate aperture polarization using Eq. (5.3). For intensity images, background is subtracted from each polarized component for both the observatories.

Standard stars: The standard stars are used to estimate the residual instrumental polarization and to determine the origin of the instrumental reference system θ_0 discussed in section (5.2). The optical axis of the instrumental system about which fast axis (of HWP and polaroid filter) is rotated should be aligned with celestial NS axis. But, in general, they are not aligned. That difference is found out using standard stars. There are some common standard stars listed in ([Turnshek et al., 1990], [Schmidt et al., 1992]).

The above mentioned standard steps have been followed for reduction and calibration of raw data.

Table 5.3: Polarized and unpolarized standard stars.

	Star	P (%)	PA(°)	P$_{obs}$ (%)	PA$_{obs}$(°)	θ_0(°)
OHP; Mar,2009	GD319 (V)	0.09±0.09	140	0.06±0.05	134	6
	HD251204 (V)	4.04±0.07	147	4.4±0.2	153	-6
	HD155197 (V)	4.38±0.03	103	4.2±0.15	117	-14
	HD155197 (V)	4.38±0.03	103	3.9±0.4	118	-15
IGO; Oct,2011	HD251204 (V)	4.04±0.07	147	4.6±0.1	27±8	120
	HD43384 (V)	2.94±0.04	169.8±0.7	2.91±0.1	39±5	130.8
OHP; Oct,2011	HD236633 (R)	5.376±0.028	93.04±0.15	5.25±0.10	92±1	1.04
	HD21447 (B)	0.017±0.03	28.63±0.3	0.02±0.02	25±4	3.63
	BD+59°389 (R)	6.43±0.02	98.1±0.02	6.20±0.16	103±2	-4.9
	HD251204 (R)	4.27±0.028	147±2	4.32±0.10	138±10	9
OHP; Jan 2012	HD21447 (B)	0.017±0.03	28.63±0.3	0.02±0.05	24±5	4.63
	G191B2 (B)	0.09±0.06	147	0.02±0.02	129±10	18
	HD236633 (R)	5.376±0.028	93.04±0.21	5.41±0.05	98±8	-4.96
IGO; Feb,2012	HD25443 (R)	4.734±0.045	133.65±0.28	4.854±0.1	132.28±1	1.37
	HD25443 (V)	5.127±0.061	134.23±0.34	5.1±0.2	132.5±5	1.73
	BD+59°389 (R)	6.43±0.022	98.14±0.10	6.4±0.1	105±8	-6.86
	BD+59°389 (V)	6.701±0.015	98.09±0.07	6.5±0.1	91±8	7.09
OHP; Mar,2012	HD155197 (R)	4.274±0.027	102.88±0.18	4.1±0.2	114±5	-11.12
	HD155197 (V)	4.38±0.03	103	4.05±0.15	93±10	10
	GD319 (B)	0.045±0.047	140.79	0.07±0.1	161±10	-20.21
	GD319 (V)	0.089±0.093	140.15	0.08±0.1	135±10	5.15
OHP; May,2013	HD251204 (V)	4.04±0.07	147	4.3±0.2	139±10	8
	HD251204 (R)	4.27±0.028	147±2	4.35±0.2	135±10	12

Observations in red (R), blue (B), and (V) filters. P and PA from the literature ([Turnshek et al., 1990], [Schmidt et al., 1992]), P$_{obs}$ and PA$_{obs}$ from observations, θ_0 = (PA - PA$_{obs}$).