Planetary and Space Science 118 (2015) 199–210

Contents lists available at ScienceDirect

Planetary and Space Science

journal homepage: www.elsevier.com/locate/pss

CCD polarimetry of distant comets C/2010 S1 (LINEAR) and C/2010 R1 (LINEAR) at the 6-m telescope of the SAO RAS

Oleksandra V. Ivanova [a,*], Janna M. Dlugach [a], Viktor L. Afanasiev [b], Volodymyr M. Reshetnyk [a,c], Pavlo P. Korsun [a]

[a] Main Astronomical Observatory of National Academy of Sciences, Akademika Zabolotnoho Street 27, 03680 Kyiv, Ukraine
[b] Special Astrophysical Observatory, Russian Academy of Sciences, Nizhny Arkhyz, Russia
[c] Taras Shevchenko National University, Kyiv, Ukraine

ARTICLE INFO

Article history:
Received 16 December 2014
Received in revised form
6 May 2015
Accepted 18 May 2015
Available online 27 May 2015

Keywords:
Comets
Comet C/2010 S1 (LINEAR)
Comet C/2010 R1 (LINEAR)
Polarimetry
Linear polarization
Aggregate particles
Superposition T-matrix method

ABSTRACT

We present first measurements of the degree of linear polarization of distant comets C/2010 S1 (LINEAR) and C/2010 R1 (LINEAR) at heliocentric distances $r=5.9$–7.0 AU. Observations were carried out with the SCORPIO-2 focal reducer at the 6-m telescope of the Special Astrophysical Observatory (Russia). Both comets showed considerable level of activity (significant dust comae and tails) beyond a zone where water ice sublimation is negligible (up to 5 AU). Significant spatial variations both in the intensity and polarization are found in both the comets. The slope of radial profiles of intensity changes gradually with the distance from the photocenter: from -0.7 near the nucleus up to about -1.3 for larger distances (up to 100,000 km). The variation in polarization profiles indicates the non-uniformity in the polarization distribution over the coma. The polarization degree over the coma gradually increases (in absolute value) with increasing photocentric distance from of about -1.9% up to -3% for comet C/2010 S1 (LINEAR), and from of about -2.5% up to -3.5% for comet C/2010 R1 (LINEAR). These polarization values are significantly higher than typical value of the whole coma polarization ($\sim -1.5\%$) for comets at heliocentric distances less than 5 AU. The obtained photometric and polarimetric data are compared with those derived early for other comets at smaller heliocentric distances. Numerical modeling of light scattering characteristics was performed for media composed of particles with different refractive indexes, shapes, and sizes. The computations were made by using the superposition T-matrix method. We obtained that for comet C/2010 S1 (LINEAR), the dust in the form of aggregates of overall radius $R \sim 1.3$ μm composed of $N=1000$ spherical monomers with radius $a=0.1$ μm and refractive index $m=1.65+i0.05$, allows to obtain a satisfactory agreement between the results of polarimetric observations of comet C/2010 S1 and computations.

1. Introduction

Physical nature of comets is known mainly from the observations of bright comets close to the Earth and the Sun (typically 1–2 AU). A few of the Jupiter, Neptune family comets and Kuiper-Belt objects have been investigated with space experiments, while observations at large heliocentric distances (more than 5 AU) are still scarce and episodic, thereby not covering very important stage of the development of cometary activity. Moreover, such observations are very useful in order to get more information about the origin of comets as well as their relation to Kuiper-Belt objects and Centaurs (Belskaya et al., 2008; Stansberry et al., 2008).

Activity of distant comets cannot be explained in the frame of standard model, whereas sublimation of more volatiles than water ice such as CO, CO_2, and N_2 can serve as a probable explanation of this phenomenon (Gronkowski and Smela, 1998). These comets demonstrate high activity at large heliocentric distances. Also an important specific feature of this activity is its long-term nature, in contrast to the often observed outburst activity (Ivanova et al., 2011). This feature allows to discuss the physical processes associated with such activity in more detail. An analysis of the distant cometary activity usually focuses on finding proper sources of energy required to release particles from the cometary nucleus that, in turn, leads to the formation of the observed coma. In this context reliable information on the physical properties of the cometary dust is of great importance. Available observational data show the difference between the activity of distant and short-

* Corresponding author. Tel.: +380 44 526 47 69.
E-mail address: sandra@mao.kiev.ua (O.V. Ivanova).

http://dx.doi.org/10.1016/j.pss.2015.05.009
0032-0633/

period comets (Epifani et al., 2007, 2008; Korsun et al., 2008, 2010, 2014). It is possible that the nature of the dust differs also.

Observations of distant comets in different modes (photometry, spectroscopy, and polarimetry) allow to obtain a useful information about dust properties in the cometary coma at large heliocentric distances. So far, polarimetric measurements were used to study physical properties of the dust in comets approaching the Sun. Since the dust in distant comets may differ from that in comets close to the Sun (e.g. Kolokolova et al., 2007), the measurements of polarization of distant comets are very important for study of their physical properties and evolution. However, there are no comets studied with polarimetric techniques at heliocentric distances more than 5 AU.

The program of photometric and spectral studies of distant comets with a high level of activity beyond Jupiter's orbit was started at the 6-m BTA telescope of the Special Astrophysical Observatory of the RAS (SAO RAS, Russia) in 2006. A series of spectroscopic and photometric data for these comets were obtained (Korsun et al., 2006, 2008, 2014). So far a few spectra for distant comets (with $q>5$ AU) were published. The spectra of well-known periodic comet 29P/Schwassmann–Wachmann 1 show the CN and ionic emissions at distances of ~6 AU from the Sun (Cochran et al., 1980; Cochran and Cochran, 1991; Korsun et al., 2008). Ionic emissions were also detected in the spectra of long period comet C/2002 VQ94 (LINEAR) at the distance of 8.36 AU from the Sun (Korsun et al., 2014). Nevertheless, no emission exceeding 3σ level was found in the spectra of comets C/2003 WT42 (LINEAR) (Korsun et al., 2010) and C/2006 S3 (LONEOS) (Rousselot et al., 2014). Also after spectra processing of comet C/2010 S1 (LINEAR) (Ivanova et al., 2015) and C/2010 R1 we concluded that only continuum was detected (without any emissions in the spectra of distant comets).

Therefore we have started a comprehensive program of polarimetric observations of active distant comets using the modified universal focal reducer SCORPIO-2 (Afanasiev and Moiseev, 2011) mounted in the prime focus of the 6-m BTA telescope of the SAO RAS.

In this paper, we present and analyze the first results of polarimetric observations of two distant comets C/2010 S1 (LINEAR) (hereafter C/2010 S1) and C/2010 R1 (LINEAR) (hereafter C/2010 R1). Comet C/2010 S1 was detected on September 21.36, 2010 as asteroidal object of around 18th magnitude at heliocentric distance $r=8.85$ AU and geocentric distance $\Delta=8.54$ AU. Follow-up observations showed that the comet had a bright coma and a tail. The comet has a perihelion distance of 5.89 AU and passed on May, 2013, an orbit inclination $i=125.3°$ and eccentricity $e=1.0018997$ (Marsden, 2010a, 2010b).

Comet C/2010 R1 was discovered also as non-active object of 21st magnitude on September 4.15, 2010, at heliocentric and geocentric distances equal to 7.15 and 6.66 AU, respectively. In follow-up observations performed at Magdalena Ridge 2.4-m reflector, it was found that this object had both coma and small tail. The comet reached perihelion at 5.6 AU in 2012 May, and had $i=156.9°$ and $e=1.36652$ (Marsden, 2010a, 2010b).

2. Observations and reduction

Observations of comets C/2010 S1 and C/2010 R1 were carried out at the 6-m BTA telescope (SAO RAS, Russia) with the focal reducer SCORPIO-2 (Afanasiev and Moiseev, 2011). Comet C/2010 S1 was observed through Johnson's V filter in the polarimetric mode on November 25, 2011, when $r=7.01$ AU and $\Delta=6.52$ AU. The phase angle of the comet was $\alpha=7.3°$. On November 12, 2012, the comet was observed through the g–sdss filter ($\lambda=4640$ Å, FWHM = 1262 Å) at $r=6.05$ AU and $\Delta=5.87$ AU, and the phase angle $\alpha=9.4°$. Comet C/2010 R1 was observed through the r–sdss filter ($\lambda=6122$ Å, FWHM = 1149 Å) on February 6, 2013. The heliocentric and geocentric distances were 5.94 AU and 5.57 AU, respectively, and $\alpha=9.2°$. Table 1 presents the log of observations, specifying the date of observations (the mid-cycle time), the name of comet, the heliocentric and geocentric distances, the phase angle, the position angle of the scattering plane, the filter, the total exposure and number of images, and the mode of observations.

2.1. Instruments

An E2V-42-90 CCD chip of 2048 × 2048 pixels was used as a detector. A full field of view of the detector is 6.1′ × 6.1′ with an image scale of 0.18″/pix. To increase the signal/noise ratio of the observed data binning of 2 × 2 was applied to the polarimetric images. For the measurements of polarization, an optical scheme consisting of rotating phase plates and a fixed polarization analyzer was selected. The two Wollaston prisms, designated WOLL-1 and WOLL-2, and a dichroic polarization filter (POLAROID) were used as the polarization analyzers. For our observations of the distant comets, we used two modes: dichroic polarization filter and Wollaston prism WOLL-1.

2.1.1. Polaroid

The dichroic polarization analyzer mounted in the focal reducer is intended for the measurements of linear polarization of extended objects. The analyzer can be set in three fixed positions by the angle 0° and ±60°. The intensities in three angles of the polaroid

Table 1
Log of the observations.

Date, UT	Object	r[a], AU	Δ[b], AU	α[c], deg	[d] deg	Filter	T_{exp}, s /N[e]	Mode
Nov. 25.63, 2011	C/2010 S1	7.01	6.52	7.3	92.5	V	10/3	Image
Nov. 25.71, 2011	C/2010 S1	7.01	6.52	7.3	92.5	V	30/18	Impol
Nov. 12.66, 2012	C/2010 S1	6.05	5.87	9.4	70.9	g–sdss	10/3	Image
Nov. 12.69, 2012	C/2010 S1	6.05	5.87	9.4	70.9	g–sdss	30/20	Imapol
Feb. 06.13, 2013	C/2010 R1	5.94	5.57	9.2	285.4	r–sdss	60/3	Image
Feb. 06.18, 2013	C/2010 R1	5.94	5.57	9.2	285.4	r–sdss	30/16	Imapol

[a] Heliocentric distance.
[b] Geocentric distance.
[c] Phase angle.
[d] Position angle of the extended Sun-target radius vector.
[e] The exposure time / number of images.