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Imaging polarimetry and spectropolarimetry of comet C/2013 R1 (Lovejoy) ☆

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ABSTRACT

We have obtained imaging polarimetry of the comet C/2013 R1 (Lovejoy) with 2-Channel-Focal-Reducer Rozhen instrument at 2m Ritchey–Chrétien–Coudé telescope of the Bulgarian National Astronomical Observatory Rozhen in two dust continuum filters covering wavelength intervals clear from molecular emissions and centred at 4430 Å in blue filter and at 6840 Å in red filter. In imaging mode we measured the degree of linear polarisation $17.01 \pm 0.09\%$ in the blue and $18.81 \pm 0.02\%$ in the red, which is in a very good agreement with measurements of other comets at the similar phase angle. We have also obtained polarisation maps in both filters. We found a strong correlation between the spatial distribution of the polarisation and the dust colour. Spectropolarimetry of the nucleus region shows an increase of the polarisation with wavelength, and a depolarisation in the spectral regions with gas emission lines, most noticeable in C_2 emission band, which shows a polarisation of $6.0 \pm 1.1\%$.

1. Introduction

Polarimetry is sensitive to the physical properties of the dust particles: size, shape, porosity, orientation and chemical composition represented by its material complex refractive index. Polarimetric measurements give us the possibility to determine some parameters that cannot be determined through traditional intensity measurements.

The first polarimetric observations of comets were made by Arago (1854), who discovered the polarised light in the Great Comet 1819 II.

Later, observations of comets clarified some common characteristics of the polarised light, for example that usually the plane of polarisation is perpendicular to the scattering plane, and that there are variation of the polarisation in different parts of the comet (coma, tail). Contemporary polarimetric observations of comets began with the work of Öhman (1939, 1941), who observed for the first time the continuum polarisation in comets and the polarisation of the emission lines.

Most of the recent polarimetric observations of comets have been obtained by Kiselev and collaborators. Kiselev et al. (2005) have also created a database with more than 2600 measurements of linear and circular polarisation for 64 comets since 1940s.

Most of the polarimetric observations of small Solar system bodies are aimed at measuring the variation of the polarisation with phase angle (which actually is 180°-scattering angle) and also its dependence on wavelength.

From the theoretical side, many works have been carried out by Kolokolova and collaborators (Kolokolova et al., 1997, 2004; Kolokolova and Jockers, 1997).

The polarisation of the dust jet-like structures in the dust coma of the comet Hale–Bopp was obtained for the first time by Hadamcik et al. (1997) and was discussed later on in Hadamcik and Levasseur-Regourd (2003).

A recent review of all comets investigation can be found in the books by Mishchenko et al. (2010) and Kiselev et al. (2015).

Comet C/2013 R1 (Lovejoy) was discovered by Terry Lovejoy (Thornlands, Queensland, Australia) with images acquired on 2013 September 7 and 8, using his 20-cm reflector and a CCD camera.

Other polarimetric measurements of the comet C/2013 R1 (Lovejoy) are presented by Furusho et al. (2014) (imagine polarisation with the Subaru telescope) and by Rosenbush et al. (2014) (linear and circular polarimetric measurements and their modelling).

☆ Based on data collected with 2m RCC telescope at Rozhen National Astronomical Observatory.

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2. Observations

Comet C/2013 R1 (Lovejoy) was observed during a multi-instrument campaign with the 2 m Ritchey–Chrétien–Coudé (RCC) telescope of the Bulgarian National Astronomical Observatory (BNAO) Rozhen from 20 December 2013 until 07 January 2014. Because of the target brightness we could achieve a relatively high S/N ratio and obtain high accuracy of polarimetric measurements. C/2013 R1 (Lovejoy) was a new comet which approach to the inner Solar System for the first time and giving us an opportunity to investigate the pristine material from the era of the Solar System formation.

2.1. Instrumentation

Polarimetric observations were performed with the 2-Channel-Focal-Reducer Rozhen (FoReRo2) (Jockers et al., 2000) attached at the Cassegrain focus of the 2m RCC telescope. In polarimetric mode, FoReRo2 is equipped with a Wollaston prism, placed before a dichroic beam splitter, which splits the signals into two different channels, allowing us to re-construct polarimetric maps of extended objects in two spectral regions simultaneously, using narrow band filters. By replacing the filters with two grisms, we can perform spectropolarimetric measurements. An example of raw spectropolarimetric image can be seen in Fig. 1.

Imaging polarimetry was obtained in two dust continuum filters covering wavelength intervals clear from molecular emission and centred at 4430 Å and 6840 Å, having a passband of 35 Å, and 71 Å and hereafter called IF443 and IF684, respectively (see Fig. 2).

2.2. Comet C/2013 R1 (Lovejoy)

Imaging and spectropolarimetric data were obtained on December 29 and January 3 respectively, with FoReRo2. The geometrical conditions during the observations are shown in Table 1.

2.3. Data reduction

All images were pre-processed through a standard bias subtraction and flat field correction.

At the time of our observations, the polarimetric optics of FoReRo2 included a Wollaston prism but not a retarder waveplate, preventing us from adopting a beam-swapping technique to minimise instrumental effects (see, e.g., Bagnulo et al., 2009). Previous experience showed that polarimetric observations with FoReRo2 were affected by non-negligible and non-constant instrumental polarisation. In an attempt to mitigate this problem, we decided to obtain observations at two instrument position angles, one with the principal plan of the Wollaston prism aligned to the scattering plan (i.e., the plan defined by the sun, the comet and the observer) and one perpendicular to it. By denoting with $f^{\parallel}$ and $f^{\perp}$ the fluxes in the parallel and in the perpendicular beams, and with $k_{\parallel}$ and $k_{\perp}$ the transmission functions in the parallel and in the perpendicular beam of the Wollaston prism respectively, the observed quantity is

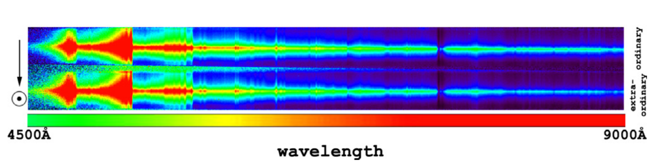

Fig. 1. Spectropolarimetric image of comet C/2013 R1 (Lovejoy).

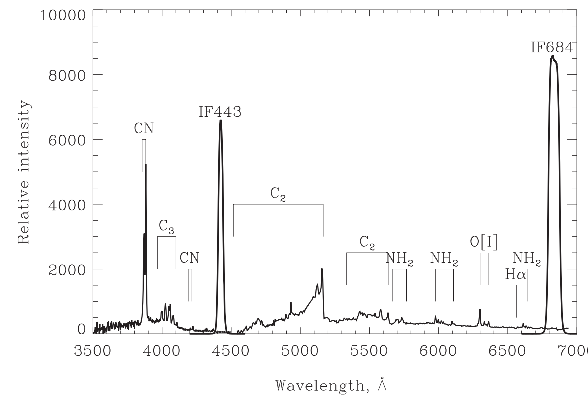

Fig. 2. Continuum filters transmission curves (IF443 and IF684) overplotted on a comet spectrum.

Table 1
Observing log.

Date	r[a], AU	Δ[b], AU	α[c] (deg)	Obs. mode
20 December 2013	0.8132	0.8562	72.2	HRS[d]
21 December 2013	0.8123	0.8765	71.1	HRS
22 December 2013	0.8118	0.8965	70.1	HRS
23 December 2013	0.8118	0.9161	69.1	HRS
24 December 2013	0.8122	0.9355	68.1	HRS
29 December 2013	**0.8210**	**1.0305**	**63.0**	**ImPol**[e]
30 December 2013	0.8240	1.0495	62.0	NBF[f]
31 December 2013	0.8275	1.0675	61.0	H_2O^+
03 January 2014	**0.8405**	**1.1205**	**58.1**	**SPol**[g]
08 January 2014	0.8631	1.1865	54.6	NBF & H_2O^+

[a] Heliocentric distance.
[b] Geocentric distance.
[c] Phase angle.
[d] High resolution spectroscopy.
[e] Imaging polarimetry.
[f] Gas and dust coma imaging in narrow band filters.
[g] Spectropolarimetry.

$$\frac{\hat{Q}}{I} = \frac{1}{2}\left[\left(\frac{f^{\parallel}-f^{\perp}}{f^{\parallel}+f^{\perp}}\right)_{\mathrm{PA}=\phi+90^{\circ}} - \left(\frac{f^{\parallel}-f^{\perp}}{f^{\parallel}+f^{\perp}}\right)_{\mathrm{PA}=\phi}\right]$$
$$= \frac{1}{2}\left[\frac{k_{\parallel}(I+Q)-k_{\perp}(I-Q)}{k_{\parallel}(I+Q)+k_{\perp}(I-Q)} - \frac{k_{\parallel}(I-Q)-k_{\perp}(I+Q)}{k_{\parallel}(I-Q)+k_{\perp}(I+Q)}\right]$$
$$= \frac{(k_{\parallel}+k_{\perp})^2 IQ - (k_{\parallel}-k_{\perp})^2 IQ}{(k_{\parallel}+k_{\perp})^2 I^2 - (k_{\parallel}-k_{\perp})^2 Q^2}$$

where ϕ is the angle is the angle between the direction Object-North Pole and the direction Object-Sun. If $k_{\parallel} \simeq k_{\perp}$ we obtain

$$\frac{Q}{I} \simeq \frac{\hat{Q}}{I}.$$

where Q/I is the reduced Stokes parameter Q measured assuming as a reference direction that one perpendicular to the scattering plane. We did not measure U/I, assuming that for symmetric reasons it is probably zero. Of course, the images were combined together after a 90° rotation.

3. Results

3.1. Aperture polarimetry

The aperture photometry with a circular aperture with a radius of 13×10^3 km on the comet was performed to measure the intensity of the two orthogonal polarised beams $f^{\parallel}$ and $f^{\perp}$. The