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Photometry of distant active comet C/2010 S1 (LINEAR)

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We present the results of photometric observations of a dynamically new comet C/2010 S1 (LINEAR), conducted on June 18, 2012. The comet demonstrated a considerable level of physical activity at a heliocentric distance of 6.3 AU. The brightness, measured under a phase angle of 8.9 degrees, was equal to $14.55^m \pm 0.06^m$ and $14.21^m \pm 0.04^m$ in V- and R-bands, respectively. The brightness distribution over the coma was found to be inversely proportional to the projected onto the sky plane nucleocentric distance, with a slope of approximately -1. Therefore, the calculated $Af\rho$ parameter, approximately 8400 cm and 8200 cm for V and R filters, respectively, was used to estimate the dust production rate. Assuming a steady outflow of dust particles from the nucleus, the dust production rate was estimated to be between 20 and 60 kg/s, depending on the assumed value of the grain's albedo. The V–R colour index obtained from the near-nucleus region of the coma is in agreement with the solar V–R colour index, and does not indicate significant reddening of the reflected solar radiation in the spectral region of 540–683 nm.

Key words: comets: individual: C/2010 S1, photometry, dust production

INTRODUCTION

Small bodies from the outskirts of the Solar System are considered to be relatively unmodified remnants of the early stage of the solar system formation. Therefore, they can retain information about the abundance of volatile materials in comet progenitors, as well as the local temperature conditions at the stage of their origin. Being scattered in the inner region of the Solar System, some cometary nuclei become relatively active at heliocentric distances larger than 4 AU. Different physical mechanisms, which can trigger physical activity at such large heliocentric distances, are widely discussed, however the problem is still unresolved [9, 11, 12]. The monitoring of dynamically new comets at large heliocentric distances can reveal various patterns of development of the comets' activities, and provide data for studying the brightness evolution and dust composition of their comae [9]. Furthermore, this is also a means to discriminate between different physical mechanisms triggering and sustaining the comet's activity.

Comet C/2010 S1 is a dynamically new comet which was discovered on September 23, 2010 by the LINEAR team as an asteroid-like object of approximately 18^m. Follow-up observations revealed a bright coma and faint tail. Having a perihelion at 5.89 AU, the comet moved beyond the zone where the water ice sublimation can be significant, therefore it provided an opportunity to monitor its distant activity over a large segment of its orbit. In the present work we have studied the properties of the comet based on photometric observations collected when C/2010 S1 was at a heliocentric distance of 6.35 AU and at a distance of 6.53 AU from the Earth. The objective here was to investigate the morphology of the cometary atmosphere, estimate the dust production rate of the cometary nucleus, and calculate B–V colour of the innermost region of the cometary coma.

OBSERVATIONS

The observations were conducted on June 18, 2012 at the observation station of Taras Shevchenko National University of Kyiv located at village Lisnyky. The total brightness of the comet was approximately 15^m. Several parameters of the comet's orbit such as a perihelion distance (q), an orbital inclination (i) and a moment of the perihelion passage (T), as well as geometric circumstances for a mean UT moment of the observations (a heliocentric distance, r, geocentric distance, Δ, and phase angle, α), are presented in Table 1. The 14-inch Kyiv Internet telescope Celestron 1400XTL was used for the observations. The CCD ST8XML receiver has 1530×1020 pixels with a pixel size of $9\times9\,\mu$m. Since 2×2 binning was applied during the observations, one pixel corresponded to $0.95''$/pix and the full field of the camera was approximately $12'\times8'$. The images were obtained through broadband V and R filters centred at 0.543 and 0.676 μm with half-widths (FWHM) of 0.090 and 0.160, respectively. Fifteen images in the V-band and fifteen images in the R-band with exposure time of 40 s were acquired during the night. Airmasses varied from 1.26 to 1.31. The images of

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SA110 were obtained for absolute calibration of the comet images [7]. The sequence of five images was observed with the exposure time of 40 s under the airmass of 1.5. There were no complementary observations of the standard stars to calculate the extinction coefficients, therefore the standard extinction coefficients for V- and R-bands were used [2]. The twilight sky was observed for the flatfield correction.

DATA PROCESSING

The photometric processing of the data comprised three steps: standard photometric reductions, preliminary processing of the comet images, and photometric measurements of the comet images and standard star images. The standard reductions, which were applied on both the comet images and the standard star images, included bias subtraction, corrections with dark frames, and a flat field normalization procedure.

Pre-processing of the images with the comet consisted of cleaning of the images from bright stars located close to the cometary coma, subtracting the background signal, shifting all the images to the same centre and stacking them together to obtain a resultant image. In order to clean the area in the vicinity of the comet, the images of the nearby bright stars were carefully replaces with the surrounding background signal. Then the background level was calculated and removed, images were shifted and stacked together. Median procedure between stacked images was applied to increase the signal-to-noise ratio. A sequence of apertures of different sizes was applied to perform photometric measurements of the comet image and retrieve the brightness profile. The largest aperture was equal to 45 pixels and corresponded to a distance of 225000 km in the projection on the sky plane at the geocentric distance of the comet. The raw and final images of comet C/2010 S1 are depicted in Fig. 1 and Fig. 2, respectively.

Fig. 3 represents the total flux in the measured units (ADU) integrated along radius-vectors of different lengths for each position angle (the position angle is measured from the North direction counterclockwise, thus through the East). The lengths of the radius-vectors are represented as a legend in the figure. The figure shows that the comet image has the elongated coma extending along the radius vector directed to the position angle of approximately 80° (i. e., to the Sun). The several enhancements are seen in the figure. Growth of the signal around 140° is likely due to the faint background stars, which were difficult to remove because they were partly embedded in the coma. The scatter around the background level in a segment of the position angles between 220° and 320° is caused by remnants of the bright star (see Fig. 1). In order to check if the enhancements between 0°–180° are caused by radiation pressure acting on released grains, or possibly it is an anti-tail, we built the brightness distribution over the coma with Monte Carlo model [6]. The model image, which was made in the cometocentric coordinate system, proved that the elongated coma was indeed directed opposite to the Sun direction. The model image being projected on the sky plane coincided well with the observed one.

In order to make the absolute calibration of the measured flux from the comet, the frames with SA110 field were processed: the background signal was removed afterward photometric measurements with the aperture of 12 pixels, which corresponded approximately to 3×FWHM, were performed for each standard star belonging to SA110 field.

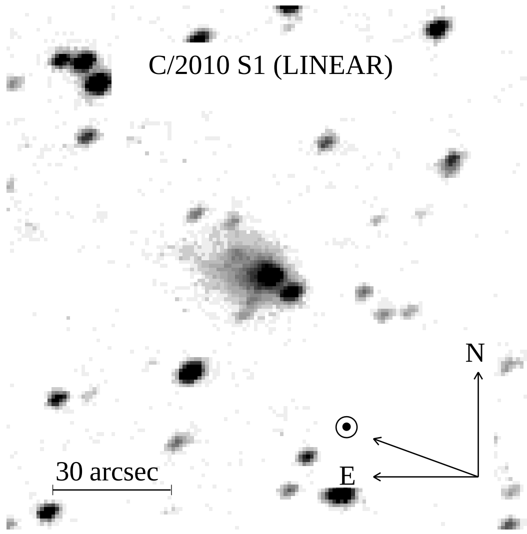

Fig. 1: The raw image of comet C/2010 S1. North, East, the sun ward direction, and the scale bar are indicated.

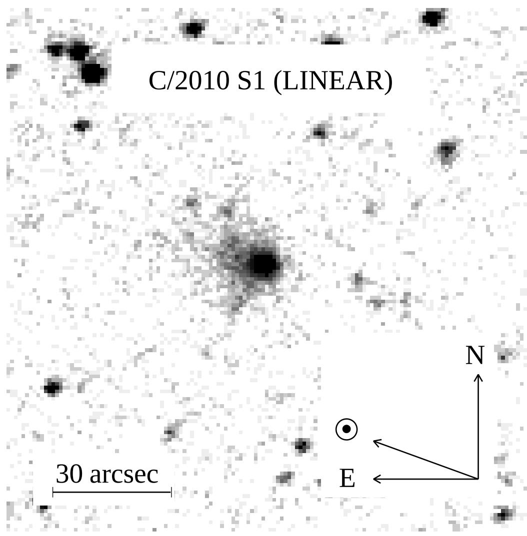

Fig. 2: The final cleaned median-combined image of comet C/2010 S1. North, East, the Sun ward direction, and the scale bar are indicated.

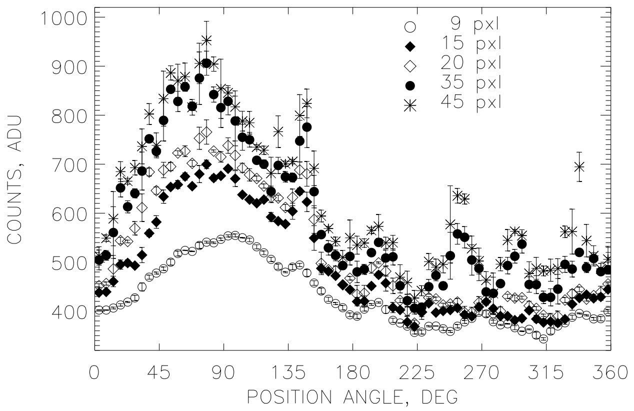

Fig. 3: The total count integrated along the radius vector (from 9 to 45 pixels) for each position angle from 0° to 360°. The position angle starts at North and increases in the counterclockwise direction through the East.

In order to calculate the apparent magnitude of the comet at the given wavelength and for the given aperture size, the following standard equation was used:

$$m_{com} = 2.5 \log \left(\frac{N_{com}}{N_{str}} \right) + m_{str} - k_{\lambda} \Delta M$$

here, N_{com} is the total count from the comet image for the given aperture size per 1 second, N_{str} is the total count from the star image per 1 second, k_{λ} is the main extinction coefficient for the given wavelength, ΔM is the difference between the comet and star airmasses.

The brightness of the comet evaluated with the aperture size of 12 pixels is equal to $14.55^m \pm 0.06^m$ and $14.21^m \pm 0.04^m$ for V- and R-bands, respectively. The colour index CI_{V-R} equals $0.34^m \pm 0.07^m$. This value is consistent with the difference between the solar magnitudes at the wavelengths corresponding to the effective wavelengths of V and R filters (-26.76 and -27.10, respectively). It points out that there is no significant reddening of the reflected solar radiation in the spectral region of 540–683 nm.

$Af\rho$ PARAMETER AND THE DUST PRODUCTION RATE

Since the cometary spectra did not reveal molecular emissions seen above the reflected solar continuum, it was possible to use the images obtained through the wide V and R filters for the analysis of the cometary dust environment. Vorontsov-Veliaminov [13] and then Konopleva [4] proved that surface brightness of a comet atmosphere varies as $\sim \rho^{-1}$ at the sky-plane, provided that both the dust production rate of a nucleus and the velocities of ejected particles are constant. C/2010 S1 surface brightness profile was examined within the range of the radius vectors corresponding to the projected distances between 40000 and 200000 km in the sky plane. The slopes of -0.98 ± 0.02 and -1.12 ± 0.03 were extracted for the V and R colour bands respectively. Therefore, the $Af\rho$ technique was used as a measure of the dust production rate of the cometary nucleus [1]. The $Af\rho$ parameter is widely used in order to compare the data obtained at different observing sites, epochs, and under the different viewing geometries. A'Hearn et al. [1] provided the definition of the Af as a product of grain's albedo, A, and a filling factor, f. The latter is the ratio of particle total cross section to the projected field of view. A simple steady-state coma model is implied for the definition of the $Af\rho$ technique, therefore the constant dust production rate from a nucleus and constant velocities of ejected particles are expected. Under this condition the product of Af and ρ (the projection of the field of view on the sky plane) is aperture-independent and can be used to derive the dust production and to compare the activity level of different comets. The following equation is widely used for the calculation of the $Af\rho$ parameter:

$$Af\rho = \left(4r^2 \Delta^2 10^{0.4(\mathrm{m}_{\odot} - \mathrm{m}_R)} \right) / \rho. \qquad (1)$$

Here, the $Af\rho$ value is expressed in cm; Δ is the comet geocentric distance expressed in cm; r is the comet heliocentric distance, expressed in AU; ρ is the aperture size projected in to the sky plane at the comet geocentric distance and expressed in cm; $\mathrm{m}_{\odot}$ and m_R are the apparent magnitudes of the Sun and the comet for the given filter. Calculated values of $Af\rho$ equal to 8400 ± 600 cm and 8200 ± 1000 cm for V and R filters, respectively. The errors were estimated by the differentiation of the equation (1) taking into account the uncertainties of the comet and solar magnitudes. The measured magnitudes of the comet were not reduced to 0° phase angle, that means that estimated with Eq. (1) $Af\rho$ correspond to the specific phase angle of 8.9°.

The $Af\rho$ was used to estimate the dust production rate of the cometary nucleus following the approach presented in Weiler et al. [14]. In order to calculate the dust production rate, several assumptions about dust particles populating the coma should be made. Adopting parameters, such as outflow velocities of particles, their optical properties, and the size frequency distribution of particles, we took into account the discussion recently given by Fink and Rubin [3], as well as the results of modelling of dust environment of some distant comets with Monte Carlo model [5, 6]. We assumed that dust particles in comae of distant comets are large enough: the minimum and maximum radii of dust were set at 5 and 10^3 μm respectively. The calculation was made for the different values of particle's Bond albedo: 0.1, 0.2, and 0.3. The high albedo of the dust particles populated the coma can be justified by the presence of icy grains and is consistent with recently re-

Table 1: Some orbital parameters of C/2010 S1 and geometric conditions of the observations.

Date of observations, UT	Orbital parameters			Geometric conditions		
	q, AU	i, degrees	T	r, AU	Δ, AU	α, degrees
2012 June 18.95943	5.89	125.3	2013/05/20.3	6.35	6.53	8.90

ported results of near-infrared spectroscopy of the comet [15]. The author found the presence of 1.5 and 2.0 micron absorption features in the spectrum of the comet likely due to amorphous water ice at a heliocentric distance of 5.9 AU [15]. The phase function was adopted in a form of $10^{-0.4\times\beta\times\alpha}$, independent on the grain size. This expression was chosen because the observations were conducted under low phase angle α of 8.9°, which is close to backscattering direction. The phase coefficient, β, was assumed to be equal to 0.04. The normalized size frequency distribution function $f(a) = a^{-n}$ was used with a power index n equal to -4.0. The equation for dust density was taken from Newburn and Spinrad [10]. The expression for expansion velocities of grain particles was taken from Korsun et al. [6] in a form of $v(a) \sim r^{-0.5} \times a^{-0.5}$, which provides the range of velocities between $2-15$ m/s for the particle sizes fallen in the interval of 1000–10 μm. Estimated values of the dust mass production rates of the cometary nucleus do not differ much for the two colour bands and equal to about 60 kg/s, 30 kg/s, and 20 kg/s assuming the grain albedo of 0.1, 0.2, and 0.3, respectively.

BRIEF CONCLUSIONS

The results of the analysis of the photometric observations of distant comet C/2010 S1 (LINEAR) are presented. The observations were obtained at the observation station of Taras Shevchenko National University of Kyiv located at village Lisnyky. The orbital characteristics of the comet point out that it belongs to the class of dynamically new comets, which are genetically connected to the Oort cometary cloud. Although a perihelion of the comet orbit was at the distance of 5.89 AU and, therefore, the comet moved beyond the water ice sublimation zone, its bright coma and faint tail had been already seen at the discovery. The results presented in our work confirm the high level of physical activity of C/2010 S1.

The distribution of the integrated flux from the cometary image over the position angle shows the elongated coma, up to approximately 30 px (approximately 140000 km in the sky plan projection) and directed to the position angle of about 80°.

The $Af\rho$ parameter calculated within the aperture size of 12 pixels ($\sim 11''$) equals to 8400 ± 600 cm and 8200 ± 1000 cm for V and R filters, respectively.

The dust production rate of the cometary nucleus was estimated based on the $Af\rho$ parameter. It falls into the interval between 20 and 60 kg/s depending on the adopted grain albedo. The dust production rate of C/2010 S1 is probably considerably lower than the dust production rates of comets C/1995 O1 Hale-Bopp and C/2007 D1 (LINEAR). Both comets demonstrated very high activity having dust production rates about 1000 kg/s at the same large heliocentric distances [8, 9, 14].

The colour-index, CI_{V-R}, of C/2010 S1 amounts to $0.34^m \pm 0.07^m$ that is comparable with the solar colour index. It means that no significant reddening of the reflected solar radiation by the near nuclear part of the coma was detected in the interval of $540 - 683$ nm.

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