Near opposition photometry of comet C/2007 N3 (Lulin)

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ABSTRACT

Observations of comet C/2007 N3 (Lulin) were made at phase angles close to opposition (1°–7°–10°). Photometric observations were carried out during 2009 February 24–28, in the International Halley Watch (IHW) blue and red continuum and \( R \) broad-band using a photopolarimeter mounted on the 1.2-m telescope at Mount Abu Infrared Observatory. In all the bands, a significant linear increase in brightness with decreasing phase angle is detected for the above phase angle range. The phase coefficient \( \beta = 0.040 \pm 0.001 \text{ mag deg}^{-1} \) estimated in the IHW red (6840 Å) filter band] is found to be independent of wavelength. No non-linear opposition surge is observed for phase angle > 1°7. The linear increase in brightness with decreasing phase angle in the range mentioned earlier can be explained using the shadow hiding model. The colour of the comet is found to be similar to the solar colour, indicating the dominance of grains larger than 0.1 \( \mu \text{m} \). A dip in the brightness of about 0.20 mag is seen at the phase angle \( \sim 6°5 \).

Key words: methods: observational – techniques: photometric – comets: general – comets: individual: comet C/2007 N3 (Lulin).

1 INTRODUCTION

Comet C/2007 N3 (Lulin) was discovered as an asteroidal object by Quanzhi Ye on images acquired by Chi Sheng Lin in the course of the Lulin Sky Survey, and later Young reported it showing marginal cometary appearance on CCD images taken with the Table Mountain 0.61-m telescope (Ye 2007). In 2009 February the comet not only was closest to the Earth but also happened to be close to opposition. It has been observed that in the region within a few degrees of zero phase angle, the reflectance of many Solar system bodies and also of particulate samples measured in the laboratory increases non-linearly as the phase angle decreases (see Hapke 1993, for a review). This is known as ‘the opposition effect’ (Gehrels 1956). The first attempt to explain the opposition effect was offered as a consequence of the reduction of mutual shadows cast between regolith grains as phase angle decreases (see Hapke 1963, 1986). However, this hypothesis fails to explain the strong opposition effect observed in highly reflecting media (see Brown & Cruikshank 1983; Harris et al. 1989). An alternative explanation of the opposition surges in highly reflecting media was offered by Shkuratov (1985), Muinonen & Lumme (1990) and Hapke (1990) invoking the hypothesis of coherent constructive interference, also called coherent backscattering. Hapke (1993, 1998) applied it to explain the opposition surge in lunar samples. Coherent backscattering has also been invoked to explain the reflectance and backscattering of Saturn’s ring (Mishchenko 1992a,b; Mishchenko & Dlugach 1992; Horn et al. 1996).

It would be interesting to investigate if comets show the opposition surge when observed in near backscattering geometry. There have been attempts in the past to observe the opposition surge in comets (e.g. Kiselev & Chernova 1981; Millis, Ahearn & Thompson 1982; A’Hearn et al. 1984; Meech & Jewitt 1987). Though Kiselev & Chernova (1981), A’Hearn et al. (1984) and Millis et al. (1982) have reported enhanced backscattering in comets P/Ashbrook–Jackson, Bowell (19821) and P/Stephan–Oterma, respectively, Meech & Jewitt (1987) re-analysed the data and found no opposition surge greater than \( \sim 20 \) per cent; instead a small linear phase coefficient in the range 0.02–0.04 mag deg\(^{-1}\) for the phase angle \( \beta < 30° \) is estimated. Delahodde et al. (2001) have studied the phase function of the nucleus of comet 28P/Neujmin I covering \( \alpha = 0°6–14°5 \) and have reported a phase trend with opposition surge.

Comet C/2007 N3 (Lulin), which was near opposition during our observing run (i.e. February 24–28), presented an opportunity to investigate the opposition effect. However, comet C/2007 N3 (Lulin) happened to be close to opposition, i.e. phase angle (Sun–comet–Earth angle \( \alpha \) reaching 0°) at \( \sim \text{UT 08:00, 2009 February 26 (local day time)} \); by the time we could begin observations on February 26, the comet’s phase angle had increased to 1°7. The comet was bright enough to carry out high signal-to-noise ratio photometric observations, and in this communication we present results based on photometric observations of comet C/2007 N3 (Lulin) during 2009 February 24–28 when the phase angle ranged from 1°7 to 10°.

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2 OBSERVATIONS AND ANALYSIS

Photometric observations of comet C/2007 N3 (Lulin) were made during the period 2009 February 24–28 with a two-channel photopolarimeter (Deshpande et al. 1985; Joshi et al. 1987), mounted on the 1.2-m telescope of Mount Abu Infrared Observatory (MIRO) operated by the Physical Research Laboratory (PRL), Ahmedabad. The instrument is equipped with the IAU’s International Halley Watch (IHW) continuum filters [3650/80 Å (UC), 4845/65 Å (BC); Osborn et al. 1990] and broadband filter $R (\lambda = 6400 \AA; \Delta \lambda = 1580 \AA)$. We have been regularly using the IHW filters for observations of comets (Joshi et al. 1987; Sen, Joshi & Deshpande 1991; Ganesh et al. 1998; Joshi, Baliyan & Ganesh 2002, 2003; Ganesh, Joshi & Baliyan 2009; Joshi, Ganesh & Baliyan 2010), and every time before use we check their characteristics. Using the same filter set facilitates comparison of different cometary data observed by us.

Most of the observations were made with aperture 26 arcsec (corresponding to a projected diameter of 16 150 km). In addition to the observations with IHW filters, we also made observations with the $R$-band filter using different apertures – 10, 20, 26 and 54 arcsec (projected diameter varying from ∼3000 to 16 000 km; see Table 1) – to study the brightness as a function of radial distance from the cometary nucleus. All the observations were made under dark sky conditions, the comet being more than 3 mag brighter than the sky. None the less, to take care of the sky brightness, observations were made alternately centred on the photocentre of the comet and on a region of the sky more than 30 arcmin away from the comet (along the antitail direction). The cometary magnitudes were calculated after subtracting sky brightness. Observed cometary magnitudes were converted to the standard system using observations of solar type stars HD 88725 and HD 76151.

3 RESULTS AND DISCUSSION

The observation log with cometary parameters and our results is given in Table 1. The entries include date, JDT (= JD – 245 4880), RA and Dec., heliocentric ($r$) and geocentric ($\Delta$) distances, phase angle ($\alpha$), aperture used (Ap), projected diameter (ProDia), filter, total integration time (IT) and magnitude (Mag). The observed magnitudes reported here were corrected for extinction and then converted to the standard magnitude system using observations of

![Table 1. Photometric observations of comet C/2007 N3 (Lulin). Listed entries are date, JDT (= JD – 245 4880), right ascension (RA) and declination (Dec.) of the comet at the time of observation, heliocentric range ($r$), geocentric range ($\Delta$), phase angle ($\alpha$), aperture (Ap), projected diameter on comet (ProDia), filter, total integration time (IT) and magnitude (Mag).](image-url)
solar analogues. To estimate instrumental magnitude, several observations of shorter integration time (say 40 s in R band and 200 s in narrow bands) were taken and then the average value of magnitude and its statistical error were calculated. Details of the observing procedure are the same as discussed in Joshi et al. (2010). The error in magnitude listed in Table 1 is the total error that includes observational error, error in atmospheric extinction and the error due to the transformation of magnitude to the standard system. 

Fig. 1 shows r, Δ and α at the time of observation taken from the HORIZONS ephemeris (Giorgini et al. 1997). The comet was closest to the Earth on 2009 February 24 (Δ = 0.41 au and with the 26 arcsec aperture the projected diameter of the comet is 7700 km). The sampled area projected on the comet is not large enough to average out the small-scale inhomogeneities. There might be a possibility of the BC band being contaminated by the C₂ emission band lying close to it. To address this possibility, we looked at the spectra provided by Buil (private communication)¹ for 2009 February 22 (the nearest date to our observing run), and notice that the C₂ emission band close to the BC (4845 Å) band partly overlaps with it. The upper limit of contamination of the BC band by this feature is estimated to be <10 per cent. The colour of the comet, as discussed in Section 3.1, is close to the solar colour. This supports the view that the contamination of the comet’s BC magnitude due to the neighbouring C₂ emission band is negligible. Furthermore, the comet’s heliocentric distance has not changed significantly during the observing run to affect the above inference.

3.1 Spectral energy distribution and the phase curve

Fig. 2 shows the continuum energy distribution of C/2007 N3 (Lulin). In this figure observed magnitudes are plotted against the mean wavelength of the filter band. For comparison, the energy distribution of the solar analogue star HD 76151, which was observed during the observing run, is also plotted. It is seen that during the observing run the comet’s colour is similar to the solar colour. On February 24 the comet is observed through two apertures: 26 and 54 arcsec (projected diameters 7700 and 16 300 km, respectively).

There is an indication that the comet’s colour through the larger aperture is slightly bluer. This could be due to the disintegration of larger grains into smaller grains as they move out resulting in a higher population of submicron size grains in the outer coma. Observations on all the dates with 26 arcsec aperture show the comet’s colour to be similar to the solar colour.

In the following we discuss the light curve and the phase curve of the comet. For this purpose, magnitudes, denoted as m_1, 1, α), are referred to at Δ and r equal to 1 au by subtracting the term 2.5 log(Δ r²) from the observed magnitudes. The light curves [LCs; i.e. m(1, 1, α) versus time (JD)] of C/2007 N3 (Lulin) are plotted in Fig. 3(a) and the phase angles at the time of observation are marked. LCs in different filter bands are annotated in the figure. It is seen that comet gets brighter as α decreases. During the pre-opposition phase we have observations only at two phase angles, 6.69 and 5.75, with the comet being brighter at lower phase angle. The phase curve is better covered during the post-opposition phase, the minimum phase angle, at which observations are made, being ~1/7. The comet was not observable when it was close to zero phase (local day time). During post-opposition phase, a clear increase in brightness with decreasing α is observed. This is consistent in all the filter bands. To look at the change in brightness with phase, we have plotted m(1, 1, α) versus α in Fig. 3(b). No opposition surge is noticed for the observed range in α, only a slight increase in brightness with decreasing α is detected. We checked for the linearity in the phase curve by plotting the flux against the phase angle and found it to be linear in all the bands.

¹ See his website http://www.astrosurf.com/buil/
observations for $\alpha < 1.7^\circ$ to comment on the opposition surge (i.e. any non-linear increase in brightness) as $\alpha$ approaches $0^\circ$.

The phase curve shows one interesting feature – at phase angle near 6.5° the brightness shows a decrease in BC and RC bands. As there are no observations (including the R band) between phase angles 6.4 and 9.4°, it is difficult to comment on the actual trend. The phase curve in R band shows a sudden decrease in brightness at phase angle $>10^\circ$ but unfortunately we do not have data in BC and RC in this range to make a comparison. As discussed earlier, the sampled area projected on the comet is not large enough to average out the small-scale inhomogeneities which might cause fluctuations in the brightness. However, with the present data it is difficult to quantify this.

We have estimated the phase coefficient (i.e. slope of the phase curves) ignoring the dip, discussed in the previous paragraph. The estimated slopes in 4845, 6840 Å and R bands are, respectively, $0.036 \pm 0.002$, $0.040 \pm 0.001$ and $0.041 \pm 0.003$ mag deg$^{-1}$. Within the estimated error, the phase coefficients in all the filter bands might be taken to be the same, i.e. the phase coefficient is independent of the wavelength. The shadow hiding model can explain this kind of brightening of the comet with decreasing phase angle. Meech & Jewitt (1987) have reported similar results on some other comets studied by earlier researchers (see Section 1). However, the phase coefficient in the present case is slightly higher than the values reported by Meech & Jewitt (1987). Though Delabodde et al. (2001) have reported a phase trend with opposition surge ($\alpha = 0.6^\circ$–$14.5^\circ$) in the case of the nucleus of comet 28P/Neujmin 1, it is very likely that the cometary nucleus surface behaves differently (similar to asteroids) from the dust particles in the coma.

3.2 Radial profile of the brightness

As mentioned earlier in Section 2, we have made observations in R band through various apertures (10, 20, 30 and 54 arcsec) to study the behaviour of the cometary brightness with distance from the photocentre. The radial profile of brightness in the R band is plotted in Fig. 4 for February 24 and 28. The procedure of getting the radial distribution of the brightness is the same as described in our earlier papers (Ganesh et al. 2009; Joshi et al. 2010). On February 24 the brightness drops at a distance of $\sim 2000$ km. As the sampled area on the comet is not large, the possibility of observing an inhomogeneous projected area cannot be ruled out. Later, on February 28 the brightness distribution is smooth apart from a slight depression beyond 2000 km.

4 CONCLUSIONS

The following conclusions are drawn from the present study of comet C/2007 N3 (Lulin).

(i) The colour of the comet is similar to the solar colour, indicating that the grain size is larger than 0.1 µm.

(ii) Significant brightness enhancement with decreasing phase angle is observed. The phase coefficient, $\beta$, is found to be $0.040 \pm 0.001$ mag deg$^{-1}$ which is independent of the wavelength. These findings support the shadow hiding model to explain the increase in brightness with decreasing phase angle.

Figure 4. Radial brightness variation as observed on 2009 February 24 and 28. Error bars are $\pm \sigma$. 
(iii) A dip of $\sim 0.20$ mag in the brightness at the phase angle $\sim 6.5^\circ$ is observed in the continuum narrow bands which might be due to the presence of inhomogeneities in the coma.

(iv) Brightness drops smoothly radially outward apart from a slight depression near 2000 km, especially on February 24.

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