The return of activity in main-belt comet 133P/Elst–Pizarro

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ABSTRACT
Comet 133P/Elst–Pizarro is the first known and currently best-characterized member of the main-belt comets, a recently identified class of objects that exhibit cometary activity but which are dynamically indistinguishable from main-belt asteroids. We report here on the results of a multiyear monitoring campaign from 2003 to 2008, and present observations of the return of activity in 2007. We find a pattern of activity consistent with seasonal activity modulation. Additionally, recomputation of phase function parameters using data in which 133P was inactive yields new IAU parameters of $H_R = 15.49 \pm 0.05$ mag and $G_R = 0.04 \pm 0.05$, and linear parameters of $m_R(1, 1, 0) = 15.80 \pm 0.05$ mag and $\beta = 0.041 \pm 0.005$ deg$^{-1}$. The comparison between predicted magnitudes using these new parameters and the comet’s actual brightnesses during its 2002 and 2007 active periods reveals the presence of unresolved coma during both episodes, of the order of $\sim 0.20$ of the nucleus cross-section in 2002 and $\sim 0.25$ in 2007. Multifilter observations during 133P’s 2007 active outburst yield mean nucleus colours of $B-V = 0.65 \pm 0.03$, $V-R = 0.36 \pm 0.01$ and $R-I = 0.32 \pm 0.01$, with no indication of significant rotational variation, and similar colours for the trail. Finally, while 133P’s trail appears shorter and weaker in 2007 than in 2002, other measures of activity strength such as dust velocity and coma contamination of nucleus photometry are found to remain approximately constant. We attribute changes in trail strength to the timing of observations and projection effects, thus finding no evidence of any substantial decrease in the activity strength between 2002 and 2007.

Key words: comets: general – comets: individual: 133P/Elst–Pizarro – minor planets, asteroids.

1 INTRODUCTION
Discovered on 1996 August 7 (Elst et al. 1996), Comet 133P/Elst–Pizarro (also designated 7968 Elst–Pizarro, hereafter 133P) orbits in the main asteroid belt ($a = 3.156$ au, $e = 0.165$, $i = 1.39^\circ$). It has a Tisserand parameter (with respect to Jupiter) of $T_J = 3.184$, while classical comets have $T_J < 3$ (Vaghi 1973; Kresák 1980). In 2005, two more objects displaying cometary activity that are likewise dynamically indistinguishable from main-belt asteroids were identified: P/2005 U1 (Read) (Read et al. 2005) and 176P/LINEAR [also known as asteroid 118401 (1999 RE70)] (Hsieh, Jewitt & Pätzold 2006). Their discoveries led to the designation of a new cometary class – the main-belt comets (MBCs) – among which 133P is also classified (Hsieh & Jewitt 2006b). A fourth MBC, P/2008 R1 (Garradd), has also since been discovered (Garradd et al. 2008; Jewitt, Yang & Haghighipour 2009).

Despite the initial excitement over the discovery of the cometary nature of 133P in 1996, no physical studies or monitoring reports were published in the refereed literature until the comet’s activity was reobserved in 2002 (Hsieh, Jewitt & Fernández 2004; Lowry...


2 OBSERVATIONS

Since 133P’s 2002 active episode, we have monitored the comet for evidence of recurrent dust emission using the University of Hawaii (UH) 2.2-m telescope and the 10-m Keck I telescope, both on Mauna Kea, the 1.3-m telescope operated by the Small and Moderate Aperture Research Telescope System (SMARTS) Consortium at Cerro Tololo and the 3.58-m New Technology Telescope (NTT) operated by the European Southern Observatory (ESO) at La Silla. All observations reported here were obtained under photometric conditions. Details of these monitoring observations are listed in Table 1.

Observations with the UH 2.2-m telescope were made using a Tektronix 2048 × 2048 pixel CCD with an image scale of 0.219 arcsec pixel⁻¹ behind Kron–Cousins BVRI filters. Observations with Keck were made using the Low-Resolution Imaging Spectrometer imager (Oke et al. 1995) which employs a Tektronix 2048 × 2048 CCD with an image scale of 0.210 arcsec pixel⁻¹.

Table 1. Observations of 133P/Elst–Pizarro.

| UT date         | Tel.  | N    | R   | Filters | $m_R^a$  | $m_{mag}^e$ | $\theta_i^j$ | $\nu^b$ | $R^b$ | $\Delta^i$ | $\omega^j$ | $\alpha_p^k$ |
|-----------------|-------|------|-----|---------|----------|-------------|-------------|--------|------|-----------|-----------|-------------|
| 2001 November 23| Perihelion | –    | –   | –     | 20.05 ± 0.02 | 20.05 ± 0.10 | 1.1 | 63.3 | 2.86 | 2.05 | 14.5 | -0.2 |
| 2002 August 19 | UH2.2 | 6    | 2500 | R     | 19.71 ± 0.01 | 19.70 ± 0.05 | 0.8 | 67.2 | 2.89 | 1.94 | 8.2 | 0.1 |
| 2002 September 7 | UH2.2 | 14   | 4200 | R     | 19.71 ± 0.02 | 19.70 ± 0.05 | 0.8 | 67.4 | 2.89 | 1.93 | 7.8 | 0.1 |
| 2002 September 8 | UH2.2 | 6    | 1800 | R     | 19.63 ± 0.05 | 19.70 ± 0.05 | 1.2 | 67.6 | 2.89 | 1.93 | 7.6 | 0.1 |
| 2002 November 06 | UH2.2 | 5    | 1500 | R     | 20.28 ± 0.03 | 20.25 ± 0.05 | 0.6 | 79.1 | 2.98 | 2.18 | 13.3 | 0.6 |
| 2002 November 27 | UH2.2 | 10   | 1200 | R     | 20.23 ± 0.02 | 20.20 ± 0.03 | 1.0 | 213.8 | 3.56 | 3.87 | 15.0 | 0.4 |
| 2003 September 22 | Keck | 9    | 900  | BVR   | 21.17 ± 0.06 | 21.07 ± 0.15 | 0.6 | 133.7 | 3.46 | 3.19 | 16.8 | 0.1 |
| 2004 September 11 | UH2.2 | 2    | 300  | R     | 20.45 ± 0.04 | 20.45 ± 0.20 | 1.3 | 144.3 | 3.54 | 2.56 | 1.5 | 0.5 |
| 2005 February 16 | Keck | 1    | 300  | R     | 20.70 ± 0.06 | 20.70 ± 0.20 | 1.2 | 144.5 | 3.55 | 2.57 | 2.1 | 0.5 |
| 2006 April 23 | UH2.2 | 12   | 3600 | R     | 21.70 ± 0.06 | 21.72 ± 0.10 | 0.8 | 245.3 | 3.30 | 3.31 | 17.1 | 0.4 |
| 2007 March 21 | UH2.2 | 4    | 1200 | R     | 20.09 ± 0.04 | 20.09 ± 0.15 | 0.9 | 265.1 | 3.12 | 2.16 | 7.1 | 0.5 |
| 2007 May 22 | UH2.2 | 6    | 1200 | R     | 20.84 ± 0.05 | 20.84 ± 0.15 | 1.0 | 270.4 | 3.07 | 2.36 | 15.4 | 0.6 |

$^a$ Telescope used (UH2.2: University of Hawaii 2.2-m telescope; Keck: Keck I 10-m telescope; NTT: 3.58-m New Technology Telescope; CT1.3: SMARTS 1.3-m telescope at Cerro Tololo ).

$^b$ Number of images.

$^c$ Total effective exposure time in seconds.

$^d$ Observed mean R-band magnitude of nucleus.

$^e$ Estimated R-band magnitude at mid-point of full photometric range (assumed to be 0.40 mag) of rotational light curve.

$^f$FWHM seeing in arcsec.

$^g$ True anomaly in degrees.

$^h$ Median heliocentric distance in au.

$^i$ Median geocentric distance in au.

$^j$ Solar phase angle in degrees.

$^k$ Orbit plane angle (between the observer and object orbit plane as seen from the object) in degrees.

Hsieh et al. (2004).
Kron–Cousins $BVRI$ filters. Observations with the SMARTS 1.3-m were made using the optical channel of A Novel Double-Imaging Camera (ANDICAM) which employs a Fairchild 447 $2048 \times 2048$ CCD with an image scale of 0.369 arcsec pixel$^{-1}$ (using $2 \times 2$ binning) and Johnson–Kron–Cousins $BVRI$ filters. Observations with the NTT in 2007 were made using the ESO Multi-Mode Instrument (Dekker, Delabre & Dodorico 1986) which employs two adjacent $2048 \times 4096$ Massachusetts Institute of Technology/Lincoln Laboratory (MIT/LL) CCDs with image scales of 0.332 arcsec pixel$^{-1}$ (using $2 \times 2$ binning) and Bessel $BVRI$ filters, while observations in 2008 were made using the ESO Faint Object Spectrograph and Camera (EFOSC2) (Buzzoni et al. 1984) which employs a Loral/Lesser $2048 \times 2048$ CCD with an image scale of 0.24 arcsec pixel$^{-1}$ (using $2 \times 2$ binning) and Bessel $BVR$ and Gunn $i$ filters.

Figure 1. Composite images of 133P from $R$-band images taken during observations detailed in Table 1. Each image is $0.5 \times 0.5$ arcmin$^2$ with 133P at the centre and arrows indicating north (N), east (E), the negative heliocentric velocity vector ($-v$) and the direction towards the Sun ($\odot$). Composite images are constructed from UH 2.2-m data unless otherwise stated and comprise total effective exposure times of (a) 2300 s, (b) 2100 s, (c) 4200 s, (d) 4200 s, (e) 500 s (on Keck, equivalent to 10 330 s on the UH 2.2-m), (f) 900 s, (g) 300 s (on Keck, equivalent to 6200 s on the UH 2.2-m), (h) 200 s (on Keck, equivalent to 4130 s on the UH 2.2-m), (i) 600 s, (j) 1200 s, (k) 1200 s, (l) 1200 s, (m) 1200 s, (n) 1200 s, (o) 3300 s, (p) 900 s (on the NTT, equivalent to 2380 s on the UH 2.2-m), (q) 4200 s (on the SMARTS 1.3-m, equivalent to 1470 s on the UH 2.2-m), (r) 4140 s (on the SMARTS 1.3-m, equivalent to 1450 s on the UH 2.2-m) and (s) 600 s (on the NTT, equivalent to 1590 s on the UH 2.2-m). Data in panels (a) through (e) were previously presented in Hsieh et al. (2004).
Except for those conducted with the SMARTS 1.3-m telescope, all observations were made while tracking our target non-sidereally to prevent trailing of the object. For SMARTS 1.3-m observations, non-sidereal tracking was not available, and as such exposure times were selected such that the trailing of the object during the course of a single exposure would be less than 0.5 arcsec, well below the typical full width at half-maximum (FWHM) seeing at the 1.3-m site.

Standard image preparation (bias subtraction and flat-field reduction) was performed for all images. Flat-fields were constructed from dithered images of the twilight sky. Photometry of Landolt (1992) standard stars and field stars was obtained by measuring net fluxes (over sky background) within circular apertures, with background sampled from surrounding circular annuli. Comet photometry was performed using circular apertures of different radii (ranging from 2.0 to 5.0 arcsec), but to avoid the contaminating effects of the coma background sky statistics were measured manually in regions of blank sky near, but not adjacent, to the object. Several (5–10) field stars in the comet images were also measured to correct for minor extinction variations during each night.

3 RESULTS AND DISCUSSION

3.1 Monitoring campaign

For all monitoring observations, individual R-band images (aligned on the object’s photocentre using linear interpolation) from each night were combined into single composite images (Fig. 1). For reference, we also show composite images from 133P’s 2002 active phase (Figs 1a–d; Hsieh et al. 2004). Activity is marginally visible in images from 2007 May 19, 2007 August 18 and 2007 September 12 (Figs 1p, 1r, 1s), while the comet’s characteristic dust trail is clearly visible in the image from 2007 July 17 (Fig. 1q). We find no evidence of activity in images from 2003 September 22 through 2007 March 21 (Figs 1e–o) and from 2008 July 1 (Fig. 1t). In all the images, even those obtained while 133P was active, the FWHM of the object’s surface brightness profile is consistent with the typical FWHM seeing at the time of night when those images were obtained, implying that little or no coma is present.

In Fig. 2, we mark the positions where we observed 133P to be active or where others reported it to be active, as well as positions where no activity was detected (open squares and open circle).

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**Figure 2.** Orbital position plot of reported 133P observations detailed in Table 1 and in Hsieh et al. (2004). The Sun is shown at the centre as a solid dot, with the orbits of Mercury, Venus, Earth, Mars, 133P and Jupiter (from the centre of the plot outwards) shown as black lines. Solid triangles mark positions where 133P was observed to be active in 1996, solid squares mark active positions in 2002 and solid circles mark active positions in 2007. Open squares mark positions where no activity was detected in 133P between 2003 and 2007, while the open circle marks the position where 133P was observed to be inactive in 2008. Perihelion (P) and aphelion (A) positions are also marked. References: (a) 1996 July 14 (Elst et al. 1996); (b) 1996 August 9 (Elst et al. 1996); (c) 1996 August 21 and 22 (Elst et al. 1996; Pravec & Sekanina 1996); (d) 1996 August 16 and 18 (Boehnhardt et al. 1996; Hammersgren 1996); (e) 1996 October 4 (Boehnhardt et al. 1996); (f) 2002 July 13 (Lowry & Fitzsimmons 2005); (g) 2002 August 19, 2002 September 7–9, 2002 November 5–07 and 2002 December 27 and 28 (Hsieh et al. 2004); (h) 2003 September 22 (Hsieh et al. 2004); (i) 2003 December 13–15; (j) 2004 February 16; (k) 2004 October 10; (l) 2005 January 16; (m) 2005 April 10; (n) 2005 May 27 and 28; (o) 2005 December 27; (p) 2006 April 23; (q) 2006 May 22–25; (r) 2007 March 21; (s) 2007 May 19; (t) 2007 June 11 (Jewitt, Lacerda & Peixinho 2007); (u) 2007 July 17–20; (v) 2007 August 18; (w) 2007 September 12; (x) 2008 July 01, where (i)–(s) and (u)–(x) are from this work.
where we observed it to be inactive, on a plan view of its orbit. The figure shows that reports of activity in 133P are approximately confined to the quadrant following perihelion, with the earliest detection of activity occurring shortly before perihelion at a true anomaly of \( \nu \approx 350^\circ \) and the latest detection occurring at \( \nu \approx 90^\circ \). This activity profile is consistent with the hypothesis of seasonal activity modulation described in Hsieh et al. (2004) and Hsieh & Jewitt (2006a), whereby 133P’s activity is driven by the sublimation of a localized patch of exposed volatile material confined to either the ‘Northern’ or ‘Southern’ hemisphere of the body. Assuming non-zero obliquity, activity then only occurs during the portion of the orbit when that active site receives enough solar heating to drive sublimation, i.e. during that hemisphere’s ‘summer’. We note that our observations of 133P on 2008 July 1 at the NTT showed it to be inactive despite the object being observed to be active at nearly the same orbital position in 2002. We attribute this discrepancy to a combination of the low signal-to-noise ratio of this observation and the expected extremely weak activity of 133P at that point in its orbit (Hsieh et al. 2004).

### 3.2 Photometric activity detection and measurement

When no coma is clearly visible for an object, an alternate method for detecting activity is the examination of its photometric behaviour, i.e. determining whether it is consistent with an inactive object of a fixed size or whether it shows anomalous brightening over a certain portion of its orbit. This type of analysis led to the discovery of activity in 95P/(2060) Chiron (Bus, Bowell & French 1988; Tholen et al. 1988; Meech & Belton 1989; Hartmann et al. 1990). In applying this approach to 133P, we recall that Hsieh et al. (2004) originally derived linear and IAU \( H, G \) phase function solutions for 133P using data taken in 2002 when the object was visibly emitting dust. In the case of that data set, 133P’s activity was judged to contribute negligibly to nucleus photometry (as no significant coma was detected) and was thus assumed to affect phase function derivations similarly negligibly. Having since accumulated a substantial set of observations while 133P was entirely inactive, though, we can now assess the validity of this neglect by deriving new phase function solutions and comparing the results to those of Hsieh et al. (2004).

We caution that, unlike the data used by Hsieh et al. (2004), the photometric data used in this follow-up analysis (2003 September 22 to 2007 March 21) all consist of ‘snapshot observations’, which are short sequences of exposures at unknown rotational phases, instead of full light curves. This caveat is significant because rotation of the body is expected to cause deviations in measured brightness by as much as 0.2 mag from the comet’s true mean brightness at a given time (Hsieh et al. 2004). Given a sufficiently large data set, however, we expect that the average of these fluctuations will approach zero, allowing us to derive reasonably accurate phase function solutions without necessarily knowing the rotational phase at which each individual photometry point was obtained. None the less, the lack of

**Figure 3.** Phase functions for 133P. Points are estimated \( R \)-band magnitudes (normalized to heliocentric and geocentric distances of 1 au; tabulated in Table 1) at the mid-point of the full photometric range of the nucleus’s rotational light curve. Solid symbols denote photometry obtained while 133P was visibly active, while open symbols denote photometry obtained while 133P appeared to be inactive. The dashed line represents a least-squares fit (excluding photometry points for which \( \alpha < 5^\circ \) where an opposition surge effect is expected) to a linear phase function where \( m_R(1,1,0) = 15.80 \pm 0.07 \text{ mag and } \beta = 0.041 \pm 0.005 \text{ mag deg}^{-1} \). The solid line represents an IAU \((H, G)\) phase function fit where \( H_R = 15.49 \pm 0.05 \text{ mag and } G_R = 0.04 \pm 0.05 \), while the dotted lines indicate the expected range of possible magnitude variations (\( \sim \)0.2 mag) due to the object’s rotation.
rotational phase information for our snapshot observations remains a source of uncertainty.

We compute the reduced magnitude, $m_R(1, 1, \alpha)$, of 133P at the time of each observation using

$$m_R(1, 1, \alpha) = m_{\text{mid}}(R, \Delta, \alpha) - 5 \log(R\Delta),$$

where $R$ is the heliocentric distance of the object in au, $\Delta$ is the object’s geocentric distance in au and $m_{\text{mid}}(R, \Delta, \alpha)$ is the estimated $R$-band magnitude at the midpoint of the full photometric range of the rotational light curve (Table 1). For observations of full light curves, $m_{\text{mid}}$ is determined by simply plotting the data and locating the mid-point between the maximum and minimum values of the light curve. For snapshot observations, $m_{\text{mid}}$ is generally taken to be the mean of the available photometry data with large error bars applied to reflect rotational phase uncertainties, assuming a full possible photometric range of 0.40 mag. We fit reduced magnitude values to both a linear phase function and an IAU phase function, finding best-fitting values of $m_R(1, 1, 0) = 15.80 \pm 0.07$ mag and $\beta = 0.041 \pm 0.005$ mag deg$^{-1}$ for the linear phase function where $m_R(1, 1, 0) = m_R(1, 1, 0) + \beta \alpha$.

We also find best-fitting values of $R_H = 15.49 \pm 0.05$ mag and $G_R = 0.04 \pm 0.05$ for the IAU phase function as defined in Bowell et al. (1989). Photometry obtained at phase angles of $\alpha < 5^\circ$, where an opposition surge effect is expected, is included in the derivation of the IAU phase function but omitted from the derivation of the linear phase function. We plot our best-fitting solutions in Fig. 3. A modest amount of scatter around our solutions is present, as expected, but in all the cases the deviations from the best-fitting phase functions are consistent with expected brightness fluctuations due to 133P’s rotation. Due to the uncertainty of the active status of 133P on 2008 July 01 (Section 3.1), the photometry from that night is plotted but was not included in the computation of the best-fitting phase functions.

While the slope parameters of both newly derived functions are consistent with the parameters computed in Hsieh et al. (2004) ($\beta = 0.044 \pm 0.007$ mag deg$^{-1}$; $G_R = 0.026 \pm 0.1$), both newly derived absolute magnitudes are ~0.2 mag fainter than their previously derived values [$m_R(1, 1, 0) = 15.61 \pm 0.01$ mag; $H_R = 15.3 \pm 0.1$ mag], strongly suggesting that the previously derived parameters were affected by contamination by 133P’s dust emission. This contamination is assumed to consist of a combination of coma and the portion of the dust trail (as projected in the plane of the sky) contained within the seeing disc. This suggestion of dust contamination is reinforced by Fig. 3 where we note that photometry from both 133P’s 2002 and 2007 active phases is consistently brighter than expected from our new phase function solutions. Because most of the data points from 2002 and 2007 are mean magnitudes derived from fully sampled light curves, brightness fluctuations due to rotation cannot account for the discrepancies.

Assuming that the discrepancy between an observed magnitude, $m_{\text{mid}}$, and expected magnitude, $m_{\text{exp}}$, is due to dust contamination, the scattering surface area of the dust, $A_d$, is given by

$$A_d = A_n \left( \frac{A_d}{A_n} \right) = A_n \left[ 10^{0.4(m_{\text{exp}} - m_{\text{mid}})} - 1 \right],$$

where $A_n = \pi r^2 = 1.13 \times 10^4$ m$^2$ is the scattering cross-section of the nucleus (Hsieh, Jewitt & Fernández 2009), and albedos of the nucleus and dust are assumed to be equal. Assuming optically thin dust, the total dust mass, $M_d$, can then be estimated from

$$M_d \approx \frac{4}{3} \pi \rho_a \frac{A_d}{A_n} \rho_d \left( \frac{A_d}{A_n} \right),$$

where we adopt typical dust grain radii of $a_d = 10 \mu$m and a bulk grain density of $\rho_a = 1300$ kg m$^{-3}$ (cf. Hsieh et al. 2004).

For reference, we also compute $A_{f \rho}$ (cf. A’Hearn et al. 1984) for each set of observations where the parameter is given by

$$A_{f \rho} = \frac{(2R\Delta)^2}{\rho} 10^{0.4(m_{\text{exp}} - m_{\text{mid}})/0.4} \left( \frac{m_{\text{mid}}(R, \Delta, 0)}{m_{\text{mid}}(R, \Delta, 0)} \right),$$

where $R$ is in au, $\Delta$ is in cm, $\rho$ is the physical radius in cm of a 4.0 arcsec-radius photometry aperture at the distance of the comet and $m_{R}(R, \Delta, 0)$ is the phase-angle-corrected $R$-band magnitude of the comet measured using a 4.0 arcsec-radius aperture, which we calculate using

$$m_R(R, \Delta, 0) = m_{\text{mid}}(R, \Delta, \alpha) + 2.5 \log[(1 - G)\Phi_1(\alpha) + G\Phi_2(\alpha)],$$

where $\Phi_1$ and $\Phi_2$ are given by

$$\Phi_1 = \exp \left[ -3.33 \left( \tan \frac{\alpha}{0.63} \right)^{2} \right]$$

(7) and

$$\Phi_2 = \exp \left[ -1.87 \left( \tan \frac{\alpha}{1.22} \right)^{2} \right]$$

(8) (Bowell et al. 1989).
Using equations (3)–(5), we compute \( A_d, M_d \) and \( A f \rho \) for each set of observations from 2002 to 2007 during which 133P was observed to be active, and tabulate the results in Table 2. We find that for data from 2002, dust contamination is approximately constant with a scattering surface area of \( \sim 0.20 A_n \) and a dust mass of \( M_d \sim 4 \times 10^4 \) kg contained within \( \sim 3 \) arcsec (\( \sim 4500 \) km in August–November; \( \sim 6500 \) km in December) photometry apertures. The relatively constant amount of dust over this time period explains why we were able to derive reasonably accurate slope parameters for 133P from our 2002 data despite arriving at incorrect results for the comet’s absolute magnitude due to the dust contamination.

In data from 2007 July, we find that 133P’s inferred dust coma has a strength comparable to that observed in 2002, having a scattering surface area equivalent to \( \sim 0.25 A_n \) and a dust mass of \( M_d \sim 5 \times 10^4 \) kg contained within \( \sim 4 \) arcsec (\( \sim 4700 \) km) photometry apertures. The slightly larger amount of inferred dust in 2007 could indicate a higher rate of dust production, but could also be due to different viewing geometries, given that 133P was close to opposition when observed in 2007 July. At this position, the antisolar vector for 133P points very nearly directly behind the object as seen from the Earth, causing more of the dust trail to be located within the seeing disc of the comet as projected on the sky. Given the limitations of our observations, however, we are unable to disentangle this possible projection effect from any intrinsic increase in dust production. Additionally, 133P’s apparent brightness could also have been enhanced by an opposition surge effect from the dust in its coma, although we unfortunately lack observational constraints for quantifying this effect.

Given these various possible contributing factors to 133P’s enhanced brightness on 2007 July 17 and 20, we are unable to determine whether 133P was more active on these dates compared to 2002 August 19 through 2002 November 7. We can conclude, however, that coma contamination is present in nucleus photometry performed for 133P during both observing periods, and that the measured magnitude enhancements suggest at least comparable levels of activity in each case.

The remainder of our photometry from 133P’s 2007 active phase is derived from incomplete light-curve information, and as such coma estimates at these times have much larger uncertainties than at other times. We find no definitive evidence of a coma on 2007 May 19, but find that the inferred comae on 2007 August 18 and 2007 September 12 are far stronger (\( \sim 0.65 A_n \)) than in any other observations, a rather unexpected discovery given the minimal amount of time elapsed since our 2007 July observations. We suggest that the large inferred dust contribution to nucleus photometry in August and September could be at least partly due to geometric effects. As can be seen in Figs 1(q)–(s), the orientation of the projection of the dust trail appears to change over this period of time. We caution that poor seeing during our August and September observations and the small aperture (1.3-m) of the telescope used to obtain these data mean that the observed morphology (namely, the near disappearance of the dust trail) cannot be considered entirely reliable. If the observed morphology is believed, however, much of the precipitous increase in 133P’s apparent coma strength between July and August could be due to the dust trail becoming almost directly aligned behind the nucleus in August and September, thus becoming unavoidably included within our photometry apertures.

We can account for this viewing geometry effect by integrating the scattering surface area of the visible dust trail measured in July data (discussed below; Section 3.4) and then assuming that it all

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Figure 4. Simultaneous B-, V-, R- and I-band light curves, phased to a rotation period of \( P_{rot} = 3.471 \) h, for 133P obtained using the NTT on 2007 July 17 and 20.

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falls within the photometry aperture used to measure the nucleus magnitudes in August and September. The net increase in dust scattering surface area implied by photometry between 2007 July 20 and 2007 August 18 is $\sim0.40A_n$. The integrated scattering surface area of the dust trail on 2007 July 20 over the first 30 arcsec from the nucleus (the trail becomes too faint to measure reliably beyond this point), however, is $\sim0.20A_n$, accounting for only about half of the observed increase in dust contamination between July and August. The remainder of the observed increase could be partly due to distant material in the dust trail that was too diffuse to detect in trail form in July data, but nevertheless contributed positively to nucleus photometry when projected directly behind the nucleus in August and September. It seems unlikely, however, that half of the dust in the trail could go undetected in our July data, and as such we surmise that at least part of the increase must in fact be due to a real increase in dust production, which of course would certainly be plausible at this early stage in 133P’s active phase.

### 3.3 The light curve revisited

#### 3.3.1 Search for rotational colour variations

During our 2007 NTT run when 133P was active, we observed the comet in continuously cycling filters ($VRI$ on 2007 July 17 and $BVRI$ on 2007 July 20). Observations were made in this way to allow us to obtain deep imaging of 133P in multiple filters and also construct simultaneous light curves in each filter. These light curves then allowed us to search for surface colour inhomogeneities that, for example, may constrain the position of the localized active site hypothesized by Hsieh et al. (2004). These light curves, phased to a rotational period of $P_{rot} = 3.471$ h (Hsieh et al. 2004), are plotted in Fig. 4. Then, to assess colour variation as a function of rotational phase for each filter pair, we use linear interpolation to obtain the magnitudes of the object in the second filter at times of observations in the first filter and then plot the differences (Fig. 5), again phased to $P_{rot} = 3.471$ h.

We find mean nucleus colours of $B - V = 0.65 \pm 0.03$ mag, $V - R = 0.36 \pm 0.01$ mag and $R - I = 0.32 \pm 0.01$ mag. These values are somewhat different from the mean colours found for 133P by Hsieh et al. (2004), but are within the range of individual values measured in that work. We regard the colour measurements presented here to be more accurate since our repeated multifilter observations of 133P here allowed us to account for both rotational magnitude variations (via light-curve interpolation) and minor extinction variability (using field stars as references for making differential photometric corrections). The single sets of multifilter observations used to make 133P’s previous colour measurements did not permit either of these corrective measures.

Upon examining individual colour measurements, we find no conclusive evidence of rotational colour inhomogeneity. We find maximum colour variations of only $\Delta(B - V) = 0.11 \pm 0.13$ mag, $\Delta(V - R) = 0.06 \pm 0.07$ mag and $\Delta(R - I) = 0.08 \pm 0.08$ mag, where the non-systematic distribution of even these small variations indicates that they are most likely due to ordinary measurement uncertainties. We note that this result does not rule out the possibility that 133P’s active area exhibits a different colour signature than inactive surface material. First, the coma that is likely present (Section 3.2) should act to obscure colour variations on the nucleus.
surface, with the precise amount of obscuration varying with rotational phase as the ratio of the nucleus’s scattering cross-section to the coma’s cross-section changes.

Furthermore, under the seasonal heating hypothesis (Hsieh et al. 2004; Hsieh & Jewitt 2006a), the active site is in fact expected to be illuminated by the Sun at all rotational phases when near perihelion (assumed to be close to solstice) when these observations were made. The nucleus orientation at this time allows the active site to receive maximal solar heating but also means that the active site is always in the line of sight as viewed from the Earth. We suggest that more favourable conditions for detecting colour inhomogeneities will occur around 133P’s next pre-perihelion equinox (i.e. near ν ∼ 270°). Based on prior observations (Section 3.1), the nucleus should be largely coma-free over this portion of the orbit, and at equinox the active site should pass into and out of the line of sight as the nucleus rotates, maximizing any colour variations. We therefore encourage additional rotationally resolved colour measurements of 133P between late 2011 and early 2012.

3.3.2 Implications for 133P’s pole orientation

For reference, we remove the estimated dust contamination from both our 2002 and 2007 light-curve data, and overplot the two sets of light curves (Fig. 6). Each of the two sets of data is phased self-consistently to $P_{\text{rot}} = 3.471$ h, although given the great difficulty of phasing data together that are separated by almost 5 years to such a short rotational period, the 2002 and 2007 data are simply aligned by eye. Due to the two-peaked nature of 133P’s light curve, though, there is an ambiguity in performing this alignment. In one case (Fig. 6a), the data can be aligned such that the light-curve shape and photometric range appear largely unchanged between the two observation epochs. In the second case (Fig. 6b), the data can be aligned such that the photometric range of light curve appears to decline to $\Delta m_R \sim 0.25$ mag in 2007 from $\Delta m_R \sim 0.35$ mag in 2002. In the latter case, it should be recalled that the coma contribution to the data plotted has already been subtracted, and as such the change in photometric range cannot be attributed to differences in the amount of coma. Unfortunately, due to the incomplete sampling of the light curve in 2007, it is not possible to resolve the ambiguity between these two cases.

This ambiguity is significant because of the implications of photometric range behaviour for the orientation of 133P’s rotational pole. To gain more insight as to how the photometric range of 133P should change depending on pole orientation and observing geometry, we simulate its light-curve behaviour using the model presented in Lacerda & Jewitt (2007). We assume a simple prolate ellipsoidal shape for the nucleus of 133P and render it at various observing geometries and rotational phases. At each rotational phase, the light reflected back to the observer is integrated to generate light-curve points. The 2002 September coma-corrected photometric range for 133P was measured to be $\Delta m_R = 0.35$ mag, and so we use a nucleus axis ratio of $a/b = 10^{0.39}$ (it should be noted that this is a lower limit due to the unknown projection angle at the time). We use a Lommel–Seeliger ‘lunar’ scattering function (cf. Fairbairn 2005) which has no free parameters and is appropriate for simulating the
Figure 7. Prolate ellipsoidal representation of 133P rendered as seen from the Earth during the 2002 September (upper panel) and 2007 July (lower panel) observing campaigns. The pole orientation is set such that \( \nu_{\text{sol}} = 0^\circ \) and obliquity is assumed to be \( \varepsilon = 30^\circ \). A white line segment indicates the position and orientation of the rotational pole, and black equator and meridian lines are drawn on 133P's idealized surface to guide the eye. Cross-sections at various rotational phases are displayed from top to bottom along the left of each panel, with the corresponding model light curve plotted in the right portion of each panel.

low albedo (\( p_R = 0.05 \pm 0.02; \) Hsieh et al. 2009) surface of 133P. To simplify the geometry, we neglect the small orbital inclination (\( i = 1.4^\circ \)) of 133P and assume that it is coplanar with the Earth (i.e. \( i = 0^\circ \)).

The seasonal heating hypothesis implies that 133P is at solstice when close to perihelion, i.e. has a true anomaly at solstice of \( \nu_{\text{sol}} \approx 0^\circ \), and also requires that the object has non-zero obliquity (\( \varepsilon \neq 0^\circ \)). In principle, \( \nu_{\text{sol}} \) could potentially have any value from \( \nu_{\text{sol}} \approx 0^\circ \) to \( 45^\circ \), since the temperature of the hemisphere where 133P's active site is located will begin to rise due to solar heating before the spin axis direction is actually aligned with the Sun. The seasonal heating hypothesis is inconsistent, however, for pole orientations for which \( \nu_{\text{sol}} \approx 90^\circ \), or \( \varepsilon = 0^\circ \). We simulate the light-curve behaviour of 133P for \( \nu_{\text{sol}} = 0^\circ \), \( 40^\circ \) and \( 90^\circ \). The first and third pole orientations are limiting cases that are consistent and inconsistent with the seasonal heating hypothesis, respectively. The intermediate geometry, in which solstice is reached approximately halfway through the active portion of the orbit, is meant to test how sensitive we are to the exact longitude of the pole. Because we assume zero orbital inclination, each case sets the ecliptic longitude of pole, and the ecliptic latitude is defined by the choice of obliquity. We simulate obliquities of \( \varepsilon = 0^\circ \), \( 10^\circ \), \( 20^\circ \) and \( 30^\circ \). Only \( \varepsilon = 0^\circ \) is inconsistent with the seasonal hypothesis. Rendered samples of 133P, where we assume \( \nu_{\text{sol}} = 30^\circ \), are shown in Figs 7–9.

Fig. 10 shows the expected photometric range in 2002 September and 2007 July for each pole orientation. As expected, the photometric range changes in opposite directions for \( \nu_{\text{sol}} = 0^\circ \) and \( 90^\circ \), whereas the intermediate pole orientation (\( \nu_{\text{sol}} = 40^\circ \)) produces only a small change between the two epochs. The absolute value of \( \Delta m_R \) in the figure depends on the assumed axis ratio and is unimportant in this analysis, in which we are primarily concerned with relative changes. The key feature is the variation of the range between the two epochs. The two possible scenarios indicated by the data (cf. Fig. 6) are (a) where both the 2002 and 2007 photometric ranges are similar (\( \Delta m_R \sim 0.35 \) mag) and (b) where the 2002 photometric range (\( \Delta m_R \sim 0.35 \) mag) is larger than the 2007 range (\( \Delta m_R \sim 0.25 \) mag). Inspection of Fig. 10 shows that the first scenario is consistent with low obliquity (\( \varepsilon \lesssim 10^\circ \)) and any of the considered pole
Return of activity in comet 133P/Elst–Pizarro

Figure 8. Prolate ellipsoidal representation of 133P rendered as seen from the Earth during the 2002 September (upper panel) and 2007 July (lower panel) observing campaigns. The pole orientation is set such that $\nu_{\text{sol}} = 40^\circ$ and obliquity is assumed to be $\varepsilon = 30^\circ$. A white line segment indicates the position and orientation of the rotational pole, and black equator and meridian lines are drawn on 133P’s idealized surface to guide the eye. Cross-sections at various rotational phases are displayed from top to bottom along the left of each panel, with the corresponding model light curve plotted in the right portion of each panel.

orientations. The second scenario is only consistent with a solstice around $\nu_{\text{sol}} = 0^\circ$ and significant obliquity ($\varepsilon \gtrsim 20^\circ$). Both scenarios rule out a pole orientation where $\nu_{\text{sol}} = 90^\circ$ if there is also significant obliquity.

Clearly, additional and more complete light-curve observations at different points in 133P’s orbit are needed to clarify how 133P’s photometric range varies with orbit position, constrain the object’s pole orientation and determine whether the seasonal heating hypothesis remains plausible. Given our current data, we can neither confirm nor reject the plausibility of seasonal activity modulation as described by Hsieh et al. (2004). While the pattern of activity of 133P along its orbit appears consistent with the seasonal heating hypothesis, the discovery of an incompatible pole solution could indicate that activity is in fact modulated by factors other than obliquity, for example shadowing of the active site by crater walls or other local topographic features. In Fig. 11, we use our model to forecast the photometric range behaviour of 133P over 1.5 orbits from its perihelion passage in 2007 August and to its aphelion passage in 2016 January. We plot solutions for four pole positions, two consistent with the seasonal heating hypothesis ($\varepsilon = 20^\circ$, $\nu_{\text{sol}} = 0^\circ$, and $\varepsilon = 20^\circ$, $\nu_{\text{sol}} = 40^\circ$) and two inconsistent with that hypothesis ($\varepsilon = 20^\circ$, $\nu_{\text{sol}} = 90^\circ$ and $\varepsilon = 0^\circ$). The observability of 133P during this period is also indicated in the figure, and should assist in planning observations that are best suited for discriminating between the various pole orientations that we consider here.

3.4 The dust trail revisited

To produce deep composite images from our 2007 NTT data, we use linear interpolation to shift the multiple images obtained in each filter to align the photocentres of the nucleus in each image, and sum the resulting shifted images. To measure the surface brightness profiles of the dust trail in these composite images, we then rotate the images to make the trail horizontal in the image frames and measure the net flux in rectangular apertures placed along the length of the trail (cf. Hsieh et al. 2004). The dimensions of these equally sized apertures are set to lengths (along the direction of the trail) of 5 pixels and widths (perpendicular to the trail) of 6 pixels (approximately equal to the FWHM of the trail cross-section on each night). The net fluxes in these apertures are then converted to net fluxes per linear
Figure 9. Prolate ellipsoidal representation of 133P rendered as seen from the Earth during the 2002 September (upper panel) and 2007 July (lower panel) observing campaigns. The pole orientation is set such that $\nu_{\text{sol}} = 90^\circ$ and obliquity is assumed to be $\varepsilon = 30^\circ$. A white line segment indicates the position and orientation of the rotational pole, and black equator and meridian lines are drawn on 133P's idealized surface to guide the eye. Cross-sections at various rotational phases are displayed from top to bottom along the left of each panel, with the corresponding model light curve plotted in the right portion of each panel.

We plot the resulting surface brightness profiles for both 2007 July 17 and 20 in Fig. 12. From these plots, we see that the trail profile does not change significantly between the two nights. We also note that there are minimal differences in the profiles of the trail as observed in different filters, indicating that the colours of the dust along the trail are consistently similar to those of the nucleus. To quantify this observation, we measure the surface brightness of the trail as observed on 2007 July 20 in each filter in a single aperture approximately 5 arcsec (15 pixels or $\sim$6000 km) in length and 1 arcsec (3 pixels or $\sim$1200 km) in width placed along the trail. Seeking to minimize the effect of the nucleus on our trail photometry, we place the nearest edge of this aperture $\sim$3.0 arcsec from the nucleus photocentre. We find surface brightnesses of $\Sigma_B = 24.88 \pm 0.17$ mag arcsec$^{-2}$, $\Sigma_V = 24.35 \pm 0.05$ mag arcsec$^{-2}$, $\Sigma_R = 24.04 \pm 0.05$ mag arcsec$^{-2}$ and $\Sigma_I = 23.70 \pm 0.07$ mag arcsec$^{-2}$, giving colours of $B - V = 0.53 \pm 0.18$ mag arcsec$^{-2}$, $V - R = 0.31 \pm 0.07$ mag arcsec$^{-2}$ and $R - I = 0.34 \pm 0.09$ mag arcsec$^{-2}$ consistent with the colours of the nucleus found in Section 3.3.

We also wish to know how trail morphology changes between 133P’s 2002 and 2007 active episodes. The most obvious difference between the two observing epochs is that the dust trail of 133P is significantly shorter in our 2007 data than in 2002 (despite composite images from each epoch being of approximately equivalent effective exposure time), extending only $\sim$30 arcsec from the nucleus in 2007 observations, compared to nearly 3 arcmin in 2002 (Hsieh et al. 2004). In terms of trail width, the observed mean FWHM of the trail on 2002 September 7 over the first 10 arcsec of the trail, as measured from the edge of the nucleus’s seeing disc (taken to be $2.5 \times$ the FWHM seeing), was measured to be $\theta_o = 1.3$ arcsec. This observed value corresponds to an intrinsic FWHM of $\theta_i = 0.9$ arcsec ($\sim$1300 km in the plane of the sky), which is computed using

$$\theta_i = \left( \theta_o^2 - \theta_s^2 \right)^{1/2},$$

where the FWHM seeing was $\theta_s = 0.9$ arcsec on 2002 September 7. For comparison, the observed FWHM of the trail on 2007 July 17 was $\theta_o = 1.9$ arcsec, corresponding to $\theta_i = 1.3$ arcsec ($\sim$1500 km in the plane of the sky), where $\theta_s = 1.4$ arcsec. Given that viewing geometries (parametrized by...
Return of activity in comet 133P/Elst–Pizarro

Figure 10. Expected photometric ranges for 133P during the 2002 September and 2007 July observing campaigns for pole solutions where (a) $\nu_{\text{sol}} = 0^\circ$, (b) $40^\circ$ and (c) $90^\circ$. Each panel shows predicted photometric ranges for obliquities $\varepsilon = 0^\circ$, $10^\circ$, $20^\circ$ and $30^\circ$, as labelled. The seasonal heating hypothesis is consistent with the pole orientations represented in (a) and (b), but not (c).

Figure 11. Photometric range for 133P predicted by four different pole solutions for the period between its 2007 July perihelion passage and 2016 January aphelion passage. Dark lines correspond to solutions that are consistent with the seasonal heating hypothesis, while light lines correspond to solutions that are inconsistent with that hypothesis. Grey areas indicate times when 133P is at solar elongations less than $80^\circ$, i.e. approximately when it is observable for fewer than 4 hours in a single night.

The difference in trail strength in 2002 and 2007 could be due to several factors. The simplest explanation is that the activity was actually weaker in 2007 due to depletion of exposed volatile material on 133P by the previous outburst. This explanation, however, is at odds with our findings of comparable dust ejection velocities for the two observing epochs (above), and comparable dust enhancement of the nucleus brightness (Section 3.2). A more likely explanation is that by the time our 2007 NTT observations were made, 133P was no more than 4 months into its current active phase, whereas it had been active for about a year by the time it was observed on 2002 September 7. Thus, 133P may simply have not yet reached its peak level of activity by the time we observed it with the NTT.

In order to further compare 133P’s activity level in 2002 and 2007, we measure the profile of 133P’s trail in $R$-band data from 2002 September 7 using the procedure described above, i.e. using rectangular apertures placed along the length of the trail with lengths of 5 pixels and widths of 6 pixels each. We then compare the resulting profile to the mean $R$-band trail profile from 2007 (Fig. 13), finding that the trail is notably weaker in 2007 than it was in 2002.

The out-of-plane viewing angles, $\alpha_{\text{pl}}$ in 2002 and 2007 were comparable, we therefore find that the computed intrinsic width of the dust trail is approximately equal in both our 2002 and 2007 observations. As Hsieh et al. (2004) found the primary factor controlling 133P’s trail width to be particle ejection velocity, this result suggests that sublimation took place with comparable intensity in both 2002 and 2007.

In order to further compare 133P’s activity level in 2002 and 2007, we measure the profile of 133P’s trail in $R$-band data from 2002 September 7 using the procedure described above, i.e. using rectangular apertures placed along the length of the trail with lengths of 5 pixels and widths of 6 pixels each. We then compare the resulting profile to the mean $R$-band trail profile from 2007 (Fig. 13), finding that the trail is notably weaker in 2007 than it was in 2002.
explain why the trail appeared to be so much shorter in 2007 than in 2002.

4 SUMMARY

Key results are as follows.

(i) Monitoring observations of 133P show no evidence of activity from UT 2003 September 22 through UT 2007 March 21. This result is consistent with the seasonal activity modulation hypothesis proposed by Hsieh et al. (2004) which predicted that, following its 2002 outburst, 133P should remain inactive until approximately late 2007.

(ii) A recomputation of 133P’s phase function parameters using inactive data yielded the new IAU phase function parameters of $H_R = 15.49 \pm 0.05$ mag and $G_R = 0.04 \pm 0.05$, and linear phase function parameters of $m_R(1, 1, 0) = 15.80 \pm 0.05$ mag and $\beta = 0.041 \pm 0.005$ mag deg$^{-1}$. While these new values for $G_R$ and $\beta$ are similar to the values computed by Hsieh et al. (2004), the values for $H_R$ and $m_R(1, 1, 0)$ computed here are $\sim 0.2$ mag fainter than previously derived values, a discrepancy we attribute to previously undetected dust contamination.

(iii) The comparison of 133P's newly computed IAU phase function with rotationally averaged magnitudes found during its 2002 active outburst reveals the presence of unresolved coma with a dust scattering surface area of the order of $\sim 0.20$ of the nucleus cross-section. Similarly, unresolved coma and trail material of the order of $\sim 0.25$ of the nucleus cross-section is found in the images taken on 2007 July 17 and 20, increasing to $\sim 0.65$ of the nucleus cross-section in August and September as the dust trail appears to become projected almost directly behind the nucleus as viewed from the Earth.

(iv) From NTT observations obtained in 2007, we find mean nucleus colours of $B - V = 0.65 \pm 0.03$, $V - R = 0.36 \pm 0.01$ and $R - I = 0.32 \pm 0.01$, and no evidence of colour inhomogeneities on 133P’s surface (although we hypothesize that inhomogeneities will be more effectively searched for between late 2011 and early 2012). Additionally, we find from the same observations that the dust trail shares approximately the same colours as the nucleus.

(v) Examination of coma-corrected light-curve data for 133P from 2002 and 2007 indicates a possible reduction of photometric range from $\Delta m_R \sim 0.35$ mag in 2002 to $\Delta m_R \sim 0.25$ mag in 2007, although this result is inconclusive due to incomplete sampling of the light curve in 2007. Additional observations will be needed to determine how 133P’s photometric range actually varies with orbital position and what implications these variations have for constraining the object’s pole orientation. Our present constraints on pole orientation do not currently permit us to confirm or reject obliquity-related seasonal activity modulation as a plausible mechanism for explaining 133P’s active behaviour.

(vi) While 133P’s dust trail appears shorter and weaker in 2007 data as compared to 2002 data, other measures of activity strength (dust ejection velocity and dust contamination of nucleus photometry) during the two outburst events are found to remain roughly constant. We suggest that the weaker trail observed in 2007 could simply be due to the fact that observations were made at an earlier stage in 133P’s active phase than in 2002, and that there is no
Return of activity in comet 133P/Elst–Pizarro

377

Figure 13. Surface brightness profiles of the 133P dust trail, normalized to nucleus brightness, for composite images from observations made on 2002 September 7 (3900 s effective exposure time; equivalent to 1475 s on the NTT) using the UH 2.2-m telescope, and 2007 July 17 (900 s effective exposure time) and 2007 July 20 (540 s effective exposure time) using the NTT.

conclusive evidence of any substantial decrease in activity strength between 2002 and 2007.

ACKNOWLEDGMENTS

We thank John Dvorak, Dave Brennen, Dan Birchall, Ian Renaud-Kim and Jon Archambeau at the UH 2.2-m; Greg Wirth, Cynthia Wilburn and Gary Punawai at Keck, Michelle Buxton and various queue observers at NOAO, and Leonardo Gallegos at the NTT for their assistance with our observations, and Matthew Knight for a prompt and helpful review. We appreciate the support of this work through STFC fellowship grant ST/F011016/1 to HHH, NASA planetary astronomy grants to DJ and SCL, a Royal Society Newton Fellowship grant to PL, the National Optical Astronomy Observatory and the ESO.

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