COMET 169P/NEAT

Prospects for Forward-Scattering Brightness Enhancement in December and Visual Observation of the Bare Nucleus As Early As Mid-January

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Abstract: I present a light curve for the unusual short-period comet 169P (NEAT), based on observations from 2005-06 and 2009. The object is active for only a roughly 90 day (or lesser) interval centered near perihelion (T = 2009 Nov. 30.30 UT, q = 0.608 AU). My solution for total visual magnitude, applicable for $r \leq 1$ AU, is $m_1 = m_0 + 5 \log \Delta + 2.5\, n \log r$, where Δ and r are the Earth-comet and Sun-comet distances, $m_0 = 16$ is the "absolute magnitude" (as viewed at Δ = 1 AU = r), among the faintest for any comet, and n = 12, which bespeaks an unusually steep heliocentric brightness dependence ($\sim r^{-12}$), reflecting a rapid "turn on" and "turn off." Its intrinsic faintness notwithstanding, this comet could become as bright as m_1 = 7-8 for southern hemisphere observers in mid-December owing to enhanced brightness from both forward-scattering by coma dust (minimum scattering angle θ_{min} = 40.5° on Dec. 19.9 UT) and close proximity to Earth (Δ_{min} = 0.194 AU on 2010 Jan. 12.1 UT). Based on my forward-scattering model (Marcus 2007a, b), the dust continuum brightness could be enhanced by a factor of 7.3, or −2.2 magnitude, near the time of near θ_{min}, offering an opportunity to image dust features in the coma, although with elongations as low as ε = 28° then, the conditions will be challenging. Observations from this apparition should help to better define the light curve, which is currently rather uncertain in the active phase, particularly post-T. After the "turn off" of activity as early as mid-January, the bare nucleus should become visible in modest aperture instruments. I present here a predictive ephemeris to aid observers. It provides the total magnitude m_1, taking into account the scattering function of coma grains, and nuclear magnitude V_N, taking into account the nucleus phase function.

1. Introduction

At discovery in March, 2002, this comet was an asteroidal object, designated then as 2002 EX_{12}, but at its return in 2005, observers noted a short tail, qualifying its identification as comet P/2002 EX_{12} = 169P/NEAT (Green 2005), the acronymn "NEAT" standing for the JPL/NASA "Near Earth Asteroid Tracking" program which was based at Haleakala, HI and Mt. Palomar (see Marsden 2009). The comet is unusual in its low level of activity, restricted to a short interval centered roughly on perihelion, which occurred several weeks ago on T = 2009 Nov. 30.30 TT at a distance q = 0.608 AU from the Sun. This near-dormancy may imply a great dynamic age, and indeed, the existence of an associated mature meteor stream, the annual alpha-Capricornids (e.g., Jenniskens 2008), implies that this comet and/or its progenitor has been around for quite a while. Its period (P = 4.20 yr) is the second shortest of periodic comets, led only by 2P/Encke (P = 3.30 yr) (Marsden and Williams 2008). 169P has been under observation in the current apparition since the spring of this year, initially by deep CCD imaging, and since Nov. 18 by several visual observers using moderate-aperture telescopes (see below).

The comet was also unexpectedly found by K. Battams, Naval Research Laboratory, in STEREO spacecraft HI-1B images on Nov. 12.9 and Nov. 21, and identified by B. G. Marsden as 169P, with forward-scattering (Marcus 2007a) “a likely explanation for 169P’s being well above its observed brightness from ground-based observations” (Green 2009).

169P shortly moves into moderate forward-scattering geometry as viewed from *Earth* in mid-December. As modest as the brightness enhancement may be then (see below), it could well be enough to brighten the comet to m_1 = 7-8 for observers in the southern hemisphere. The primary purpose of this short paper is to provide a predictive ephemeris of the comet in forward-scattering geometry. A secondary purpose is to point out that after the cessation of activity, probably in January, there will be an unusually good opportunity for visual observers to glimpse the bare nucleus. The ephemeris also provides a forecast of the nuclear brightness as viewed from Earth.

2. Brightness Enhancement from Forward-Scattering

Comet 169P is now entering forward-scattering geometry, with a minimum scattering angle, θ (= 180° – β, β = phase angle = Sun-comet-Earth angle)[1], to be reached on Dec. 19.9 UT at θ_{min} = 40.5°. As the comet underwent a forward-scattering enhancement as viewed from the STEREO B satellite (see above), it should be expected to do so again as viewed from Earth. To predict the extent of this enhancement , I model the scattering function, $\Phi(\theta)$, with a modified compound Henyey-Greenstein function fashioned for comets (Marcus 2007a, b):

$$\Phi(\theta) = \frac{\delta_{90}}{1+\delta_{90}}\left[k\left(\frac{1+g_f^2}{1+g_f^2-2g_f\cos\theta}\right)^{3/2} + (1-k)\left(\frac{1+g_b^2}{1+g_b^2-2g_b\cos\theta}\right)^{3/2} + \frac{1}{\delta_{90}}\right]. \quad (1)$$

The function is normalized at 90°, i.e., $\Phi(90°) = 1$. $0 \le g_f < 1$ and $-1 \le g_b < 0$ are the forward-scattering and back-scattering asymmetry factors, $0 \le k \le 1$ is the portioning coefficient between forward and backward scattering, and δ_{90} is the dust-to-gas light ratio in the coma as viewed at 90°. As before (Marcus 2007a, b), I set $g_f = 0.9$, $g_b = -0.6$, $k = 0.95$, and $\delta_{90} = 1$ for the visual or V passbands, and $\delta_{90} = 10$ for the dust continuum as isolated by a suitable filter such as R. The magnitude of the scattering function is simply

$$m_{\Phi(\theta)} = -2.5\log\Phi(\theta). \quad (2)$$

[1] This relationship notwithstanding, I use both “θ” and “β” nomenclatures in this paper (see Sec. 3) because of the very different physics of scattering of small dispersed grains in the coma, described in the literature by θ, and reflection and shadowing on solid surfaces, described by β, as discussed in Sec. 3.3.1 of Marcus (2007a).

Note that at normalization at $\theta = 90°$, $m_{\Phi(90°)} = 0$.

3. The Baseline Nuclear Brightness of 169P

While inactive, the visual (V) magnitude of the bare nucleus is

$$V_N(\Delta, r, \beta) = V_N(1,1,0) + 5\log(\Delta r) + m_{\Psi(\beta)} \ , \quad (3)$$

where Δ and r are the Earth-comet and Sun-comet distances in AU, and $V_N(1,1,0)$ is the "absolute magnitude" of the nucleus as defined at Δ = 1 AU = r and $\beta = 0°$ (i.e., comet at opposition). $m_{\Psi(\beta)}$ is the magnitude of the nucleus phase function. From Lamy et al. (2004),

$$m_{\Psi(\beta)} = \eta\beta \ , \quad (4)$$

where $\eta = 0.04$ mag deg^{-1}. I find that both the "nuclear" and "total" magnitudes on CCD imaging in 2009, reported on Minor Planet and Ephemeris Circulars MPEC 2009-K35, K72, M10, M52, N43, O14, P18, P37, R23, and S26, are indistinguishable photometrically and behave as would a bare nucleus following the $\Delta^{-2}r^{-2}$ distance and $\eta\beta$ phase dependences of Eq. (2). These are plotted in Fig. 1. On the assumption that the CCD photometry was unfiltered, and following Sostero's argument (Marcus 2007b) that unfiltered magnitudes are generally roughly equivalent to those measured in the R (red) filter passband for many CCD chips, I applied a V−R = +0.5 magnitude correction (Lamy et al. 2004) to convert the magnitudes to the V system. From these observations I obtain $V_N(1,1,0) = 16.4$. Based on this value, I also plot in Fig. 1, as the solid curve, the heliocentric nuclear magnitude $V_N(1,r,0) = V_N(1,r,0) + 5 \log r$, the idealized magnitude of the nucleus if it were viewable at 1 AU from Earth and 0° phase angle. Note that the 2009 observations fall *below* this idealized curve as the comet moves toward perihelion. This is attributable to the increasing phase angle, from 8.4° at $t - T = -183$ days to 43.6° at $t - T = -72$ days. This behavior is consistent with the phase relation in Eq. (4) and is evidence that the bare nucleus indeed is being recorded.

4. The Baseline Total Brightness of 169P

4.1. Observations

Table 1 shows visual m_1 and coma diameter estimates in arcminutes from the 2005-06 and current 2009 apparitions. The observers and their *International Comet Quarterly* (ICQ) observer codes are Alan Hale (HAL), New Mexico; Edwin van Dijk (DIJ) and Reinder J. Bouma (BOU), near Groningen, The Netherlands; Juan J. Gonzalez (GON05), Asturias, Spain; and Werner Hasubick (HAS02), Germany. In the telescope aperture column, the telescope types are reflector (L), Jones-Bird (J), and catadioptric (T). Several of the observers describe the coma appearance on a "degree of condensation" (DC) scale, where DC = 1 is completely diffuse and DC = 9 is completely condensed, i.e., stellar. Note first that the four 2005 August estimates all report the comet as "essentially stellar" (Aug. 2.17), "stellar", or degree of condensation (DC) 9, which is equivalent to stellar. Indeed, van Dijk and Bouma specify that they used the "in-in" method for their estimates, as would be done for a star. These August estimates therefore likely represent the bare nucleus without coma. For them, I therefore make no corrections for "magnification artifact," in which the faint outer reaches of the (in this case non-existent) coma are lost to human vision as the surface brightness contrast gradient falls below the gradient contrast threshold with increasing magnification. For all of the other visual estimates for which an extended coma is present, I apply a correction to a standard 10x magnification as $m_{1,cor} = -1.25 \log (M\Delta^{-1}/10)$, where M is the telescope magnification. In Fig. 1 I plot the observations, with or without corrections per above, as heliocentric magnitude, $H_1 = m_{1,cor} - 5 \log \Delta$ (the magnitude of the comet at $\Delta = 1$ AU), against the time from perihelion, t − T in days. The Bouma and van Dijk estimates are shown by the same partly overlapping symbols, with Bouma's being the 0.1-magnitude fainter value.

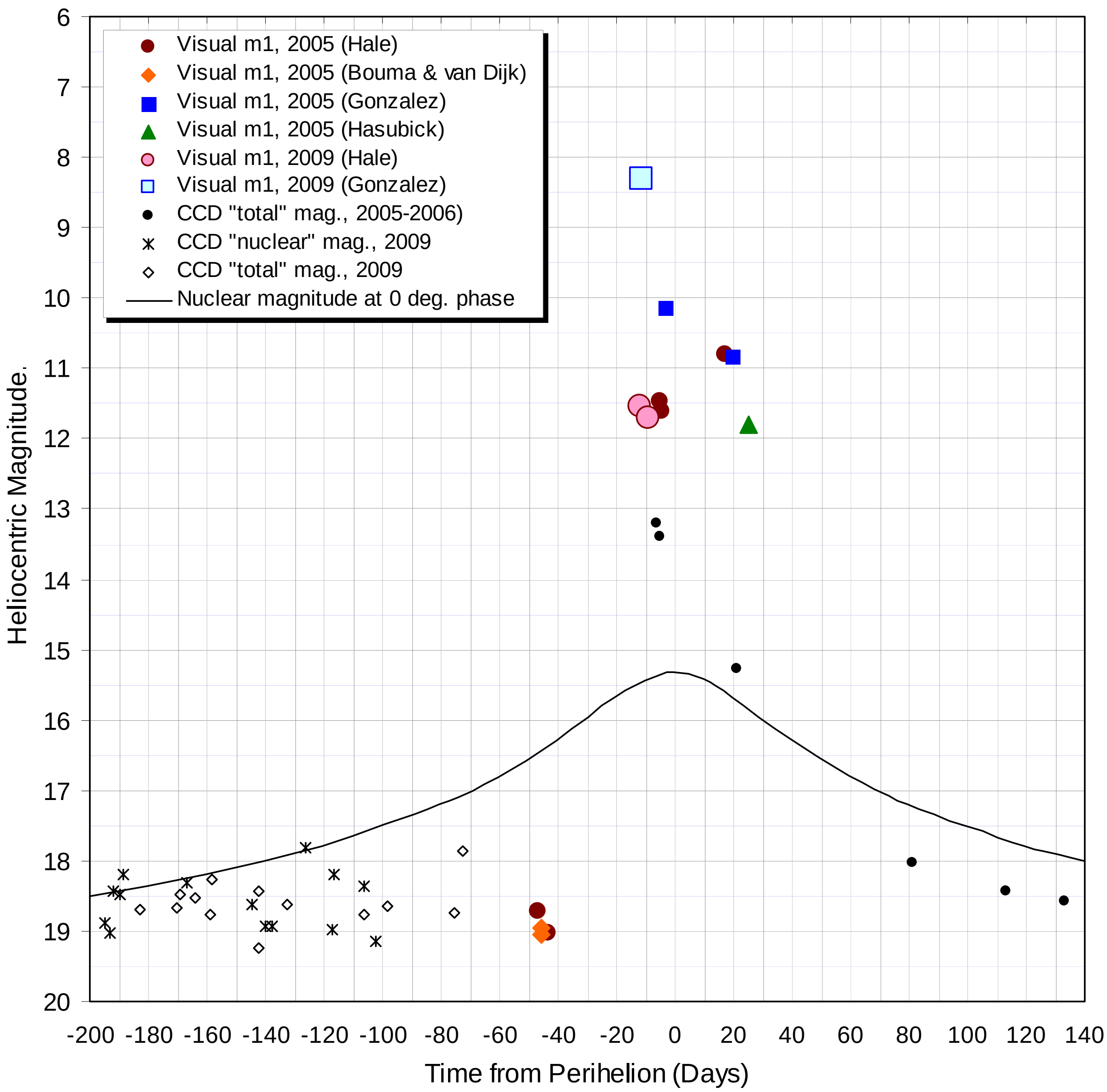

Figure 1

Table 1. Visual Brightness Estimates of Comet 169P/NEAT

Date (UT)	t–T (days)	Observer	Ap (cm) & type	Pwr	m_1	Coma (′)	Condensation	Source
05 Aug 02.17	–46.69	HAL	41 L	183	14.7	–	≈ stellar	Personal communication
05 Aug 02.95	–45.90	DIJ	44 J	155	14.9	–	DC 9	ICQ 27:269
05 Aug 02.95	–45.90	BOU	44 J	155	15.0	–	DC 9	ICQ 27:269
05 Aug 05.17	–43.69	HAL	41 L	183	14.9	–	Stellar	Personal communication
05 Sep 12.48	–05.38	HAL	20 L	110	11.5	1.5	Diffuse	Personal communication
05 Sep 13.47	–04.39	HAL	41 L	70	11.5	1.5	Diffuse	Personal communication
05 Sep 14.19	–03.67	GON05	20.3 T	100	10.3	3	DC 2.5	ICQ 27:269
05 Oct 05.49	+17.31	HAL	41 L	183	12.4	–	Diffuse	Personal communication
05 Oct 07.20	+19.34	GON05	20.3 T	133	12.3	1.5	DC 2	ICQ 27:269
05 Oct 13.15	+25.29	HAS02	44 L	156	13.5:	0.5	DC 3	ICQ 28:24
09 Nov 18.06	–12.24	HAL	41 L	229	12.9	–	Diffuse	Personal communication
09 Nov 18.77	–11.53	GON05	20.3 T	100	9.2	4	DC 2	m1-list #16134
09 Nov 21.06	–09.24	HAL	41 L	70	12.3	–	Diffuse	Personal communication

I also plot the several "total" magnitude measured from unfiltered CCD photometry from the 2005-06 apparition. These were published in the ICQ (27:277, 2005; 28:82, 2006) but are not listed in the Table. The measured coma sizes range from 2.4′ at the beginning of the period ($t - T = -6$ days) to 0.2′ to 0.5′ at the end ($t - T = +132$ days). Through the positions of their observations on the $t - T$ (days) axis, the photometrists can be identified in the Figure as Ken-ichi Koaota, Saitama, Japan (–6, –5), Katsumi Yoshimoto, Hirao, Japan (+21), Mitsunori Tsumara, Japan (+81, +113), and Yuuji Oshima, Nagano, Japan (+133). Again following Sostero's suggestion that unfiltered photometry is roughly equivalent to R photometry, I have applied a slightly lesser $V - R = +0.4$ coma magnitude correction (see Marcus 2007b) to transform these CCD observations to the V system.

Analysis

There is little doubt that as late as $t - T = -45$ days, when $r = 1$ AU, only the bare nucleus is being observed. At that point in 2005, Hale, Bouma and van Dijk had the comet under visual observation, thanks to its very close approach to Earth ($\Delta = 0.152$ AU then). The mean heliocentric magnitude of their tightly clustered observations is 18.9 at a mean $\beta = 83.4°$. The phase correction (Eq. 2) for that angle is $m_{\Psi(\beta)} = 0.04$ mag/° × 83.4° = 3.3 magnitudes, roughly consistent with their estimates, which lie 2.6 magnitudes under the heliocentric nuclear magnitude curve in the Figure for $\beta = 0°$. By Nov. 12.9 UT in the 2009 apparition ($t - T = -17$ days, $r = 0.69$ AU), there is unequivocal activity, witnessed by the enhanced brightness of coma dust through forward-scattering in the STEREO B satellite view noted in Sec. 1. By the next week, Gonzalez and Hale had the comet in view in moderate-aperture instruments (Table 1), clearly much brighter than the nuclear magnitude, but there is a ~3 magnitude difference in their estimates. This disparity may relate to the difficulty of estimating a very faint, extended coma at high magnifications. After Hasubick's observation at $t - T = +25$ days, there is a large gap until Tsumara's CCD magnitude estimate at $t - T = +81$ days, at which time the brightness has returned to near the nuclear magnitude. In this gap, the total brightness must be declining very rapidly, but exactly when and how fast is poorly known. Note that the 2005-06 CCD total magnitude estimates fall well under those made visually. This is a well-known and poorly explained artifact in cometary photometry, perhaps due in part to incomplete integration of the coma (Ferrin 2005).

Because the high dispersion in the total magnitude estimates and the large data gaps, the total magnitude m_1 light curve on both sides of perihelion must be considered as very uncertain, and a formal least-squares regression solution is not really warranted. I apply the standard power law formula

$$m_1(\Delta,r,\theta) = m_0 + 5 \log \Delta + 2.5 n \log r + m_{\Phi(\theta)}, \qquad (5)$$

where $m_0 = m_1(1,1,90)$ is the "absolute total magnitude" defined at $\Delta = 1$ AU = r and $\theta = 90°$, more familiarly known as "m_0", and $m_{\Phi(\theta)}$ is the magnitude of the scattering function (Eqs. 1 and 2). Because none of observations in the Table were made in significant forward-scattering geometry ($\theta > 60°$), any $m_{\Phi(\theta)}$ correction would be minimal, less than the dispersion in the observations, and so none is made here. A graphical solution to heliocentric magnitude plotted against log r (not shown here), normalized to 10x magnification and scattering angle $\theta = 90°$, gives $m_0 = 16$ and n = 12, applicable for $r \leq 1$ AU. However, with the nature of these data, other solutions would also certainly fit. With any solution, the m_0 value would be among the faintest for any comet. n = 12 is very high and bespeaks an unusually steep heliocentric brightness dependence ($\sim r^{-12}$), reflecting a rapid "turn on" and "turn off," amounting essentially to a short-duration spike. This, too, would be a feature of any solution. The exact times of onset of "turn on" and "turn off" are poorly constrained by the present data. My model solution puts these at about r = 1 AU, corresponding to $t - T = \pm \approx 45$ days, but these points need to be better determined by additional observations.

5. Predictive Ephemeris for Forward-Scattering Brightness Enhancement and Nuclear Brightness

Table 2 gives provides forecasted total and nuclear magnitudes taking into account forward-scattering by coma dust and the nuclear phase. The columns give the date (UT), comet-Earth (Δ) and comet Sun (r) distances in AU, the elongation ($\varepsilon°$), the comet's position angle offset ($\rho°$) from the sun (measured counterclockwise from north on the sky), the scattering angle ($\theta°$), the nuclear magnitude (V_N), and forward-scattering magnitude enhancement $m_{\Phi(\theta)}$ for δ_{90} = 1 (the visual passband) and 10 (for continuum filters such as R), and the total magnitude, $m_1 = 16 + 5 \log \Delta + 30 \log r + m_{\Phi(\theta)}$ for the visual scotopic passband.

Having passed perihelion on Nov. 30.30 UT, the comet is now rapidly approaching the Earth in forward-scattering geometry (in a direction between the Earth and Sun). Minimum scattering angle is reached on Dec. 19.9 UT at $\theta_{min} = 40.5°$, at which time $\Delta = 0.326$ AU and r = 0.713. At that time, the model predicts brightness enhancements of $m_{\Phi(\theta)} = -1.6$ and -2.2 for δ_{90} = 1 and 10, respectively. Table 2 shows that the comet could reach m_1 = 7-8 throughout all but the last days of the month of December. Although the elongations during this period are small in this period, observations nevertheless should be possible in the southern hemisphere, and any attempts to sight the object could well be productive. The optimum latitude (ϕ) for observation at small elongations is $\phi_{opt} \approx 90° - \rho \pm \approx 15°$ for evening observations (when $90° \leq \rho + \phi \leq 270°$) and $\phi_{opt} \approx \rho - 270° \pm \approx 15°$ (at which time generally $270° \leq \rho + \phi \leq 360°$, $0° \leq \rho + \phi \leq 90°$). For example, on Dec. 15, $\rho = 138.3°$, so $\phi_{opt} \approx 90° - 138.3° \pm 15° = -48.3° \pm 15°$, i.e., the comet is viewable only from mid-southern latitudes. Because we are near the solstice in southern hemisphere summer, midnight twilight will interfere with observations south of $\phi \approx -52°$. The small elongations notwithstanding, the comet will still be at as much as 10° or greater altitudes at the end of astronomical twilight. Moonlight from the waxing crescent Moon will begin interfering after Dec. 20.

Table 2. Nuclear and Total Magnitude Forecasts for Comet 169P/NEAT, with Nuclear Phase and Coma Dust Forward-Scattering Taken Into Account

2009-10 (0^h UT)	Δ (AU)	r (AU)	ε°	ρ°	θ°	V_N	$m_{\Phi(\theta)}$ δ_{90}=1	$m_{\Phi(\theta)}$ δ_{90}=10	m_1
Nov. 20	0.771	0.639	40.3	105.7	91.6	**18.4**	0.0	0.0	**9.6**
Nov. 25	0.689	0.616	38.2	107.7	81.9	**18.5**	-0.1	-0.2	**8.8**
Nov. 30	0.606	0.608	35.7	111.0	71.3	**18.6**	-0.3	-0.5	**8.1**
Dec. 05	0.526	0.614	32.9	116.4	60.6	**18.7**	-0.6	-1.0	**7.6**
Dec. 10	0.451	0.636	30.0	125.0	50.7	**18.9**	-1.0	-1.5	**7.4**
Dec. 15	0.384	0.669	27.8	138.3	43.4	**18.9**	-1.4	-1.9	**7.3**
Dec. 20	0.326	0.713	28.1	156.2	40.5	**18.8**	-1.6	-2.2	**7.6**
Dec. 25	0.277	0.764	32.5	174.7	43.8	**18.5**	-1.4	-1.9	**8.3**
Dec. 30	0.239	0.821	41.8	188.8	53.0	**17.9**	-0.9	-1.4	**9.4**
Jan. 04	0.212	0.880	55.4	197.3	66.9	**17.3**	-0.4	-0.7	**10.6**
Jan. 09	0.197	0.942	72.3	201.4	83.8	**16.6**	-0.1	-0.2	**11.6**
Jan. 14	0.195	1.005	90.7	202.3	101.9	**16.0**	0.1	0.2	**12.6**
Jan. 19	0.207	1.069	108.8	200.6	119.4	**15.5**	0.2	0.4	**13.6**
Jan. 24	0.232	1.132	124.7	196.2	134.4	**15.3**	0.2	0.4	**14.6**
Feb. 03	0.310	1.259	147.5	177.2	155.1	**15.4**	–	–	–
Feb. 13	0.419	1.382	156.6	140.1	163.5	**15.9**	–	–	–
Feb. 23	0.551	1.502	153.2	105.3	162.7	**16.7**	–	–	–
Mar. 05	0.702	1.618	145.1	87.6	159.4	**17.5**	–	–	–
Mar. 15	0.870	1.731	136.2	79.0	156.6	**18.2**	–	–	–
Mar. 25	1.053	1.839	127.6	74.8	154.6	**18.9**	–	–	–

The waning moon will interfere with morning observations in the first week of January, although sightings in the evening from low southern hemisphere latitudes will be possible with the comets's increasing elongation (Table 2). Activity will probably cease sometime in January. The closest approach to Earth occurs on 2010 Jan 12.1 UT at $\Delta_{min} = 0.194$ AU. At that time, the comet nucleus is near "quarter phase" ($\theta \approx 90°$, Table 2), and so its brightness is relative to full phase is significantly depressed (by 3.6 magnitudes if Eq. 2 is accurate). However, as the comet moves increasingly toward opposition in later January with increasing θ (decreasing β), the nucleus brightens significantly despite increasing Δ and r (Table 2). In late January and

February, still close to the Earth (Table 2), the bare nucleus should be visible in modest telescope apertures, just as it was in 2005 August. Some scatter in magnitude estimates, whether made visually or by CCD photometry, should be expected, as the nucleus exhibits a rotational magnitude variation of 0.6 magnitude (Warner 2006).

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