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## EXTINCTION IN THE COMA OF COMET 17P/HOLMES

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## ABSTRACT

On 2007 October 29 the outbursting comet 17P/Holmes passed within  $0.79''$  of a background star. We recorded the event using optical, narrowband photometry and detect a 3% to 4% dip in stellar brightness bracketing the time of closest approach to the comet nucleus. The detected dimming implies an optical depth  $\tau \approx 0.04$  at  $1.5''$  from the nucleus and an optical depth towards the nucleus center  $\tau_n < 13.3$ . At the time of our observations, the coma was optically thick only within  $\rho \lesssim 0.01''$  from the nucleus. By combining the measured extinction and the scattered light from the coma we estimate a dust red geometric albedo  $p_d = 0.006 \pm 0.002$  at  $\alpha = 16^\circ$  phase angle. Our measurements place the most stringent constraints on the extinction optical depth of any cometary coma.

*Keywords:* comets: individual (17P/Holmes) — methods: data analysis — techniques: photometric — opacity — occultations

## 1. INTRODUCTION

An extraordinary explosion in late 2007 brought comet 17P/Holmes (hereafter, 17P) back to the limelight of scientific interest, more than one hundred years after it was discovered by Edwin Holmes (1892). The discovery and early interest were triggered by an earlier, double outburst (Barnard 1896). Since then and until the 2007 event, 17P had received little attention due to its rather ordinary dynamical and photometric properties. 17P is a Jupiter-family comet, with an orbit between Mars (perihelion  $q = 2.1$  AU) and Jupiter (aphelion  $Q = 5.2$  AU) that has now experienced two explosive events separated by a comparatively quiet period of over 100 years. Here we report data taken shortly after the 2007 outburst to constrain the properties of the dust coma of this comet.

Like most active comets, 17P appeared optically bright owing to scattering from dust particles expelled from the nucleus by gas drag. In principle, measurements of extinction from cometary dust particles can be made by measuring the brightness of field stars when projected behind the coma of a passing comet (Combes et al. 1983). Measurements of cometary extinction are potentially important as, when combined with measurements of the scattered light, they can provide direct estimates of the ensemble dust albedo. In extreme cases, extinction effects in cometary comae might influence the radiation budget at the nucleus and so influence the mass loss rate caused by sublimation.

Several such measurements have been reported (Larson & A'Hearn 1984; Lecacheux et al. 1984; Elliot et al. 1995; Fernández et al. 1999) but the results are mostly negative or difficult to interpret, as a result of uncertainties in the photometric data. Fernández et al. (1999) reported an extinction of about 20% in bright comet C/Hale-Bopp but, unfortunately, observed through highly non-photometric skies that bring the significance of the dimming into question. Even deeper

**Table 1**  
Journal of Observations of 17P.

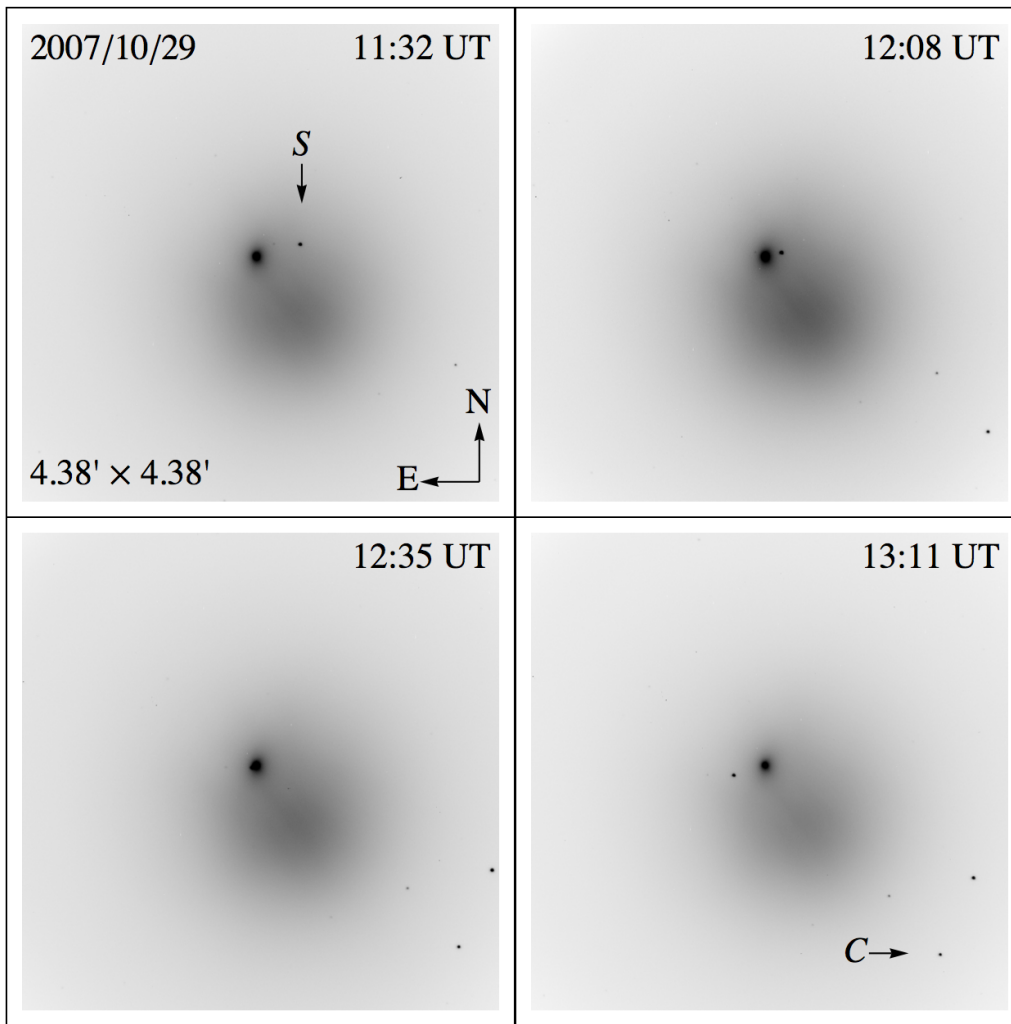
|                               |                                |
|-------------------------------|--------------------------------|
| UT Date                       | 2007 October 29                |
| Time of closest approach      | UT 12:28:42                    |
| Heliocentric distance, $R$    | 2.455 AU                       |
| Geocentric distance, $\Delta$ | 1.627 AU                       |
| Phase angle, $\alpha$         | $15.6^\circ$                   |
| Rate of motion                | $26.4'' \text{ hr}^{-1}$       |
| Weather                       | Photometric                    |
| Telescope                     | UH 2.2 m                       |
| Instrument                    | TEK                            |
| Pixel scale                   | $0.219''/\text{pixel}$         |
| Seeing                        | $0.9 \pm 0.1''$                |
| Filters (Exp. Time)           | BC (120 s), RC (25 s), R (1 s) |

events were reported in 95P/Chiron by Elliot et al. (1995) and interpreted by them as resulting from extinction in narrow, near nucleus dust jets. Extinction from the diffuse coma of Chiron was not detected.

The bright coma of exploding comet 17P provided an opportunity to search for measurable extinction of light from field stars. The comet impulsively ejected  $(2-90) \times 10^{10}$  kg of dust into the coma, with a peak production rate  $3.5 \times 10^5$  kg/s on UT 2007 Oct 24.54 $\pm$ 0.01 (Li et al. 2011). These authors inferred, from surface photometry alone, an optically thick region near the nucleus subtending 0.1 arcseconds when the comet was at peak brightness. Extinction was reported by Montalto et al. (2008) four days later and at much larger angular distances from the nucleus (25 to 180 arcsec), where surface photometry indicates immeasurably low line of sight optical depths  $< 2.5 \times 10^{-3}$  (Li et al. 2011).

## 2. OBSERVATIONS

Observations of 17P were obtained using the University of Hawaii 2.2-m telescope situated atop Mauna Kea. The telescope was equipped with a Tektronix TEK charged coupled device (CCD), which holds  $2048 \times 2048$  pixels each  $0.219'' \times 0.219''$  on the sky, and is read out in  $\sim 35$



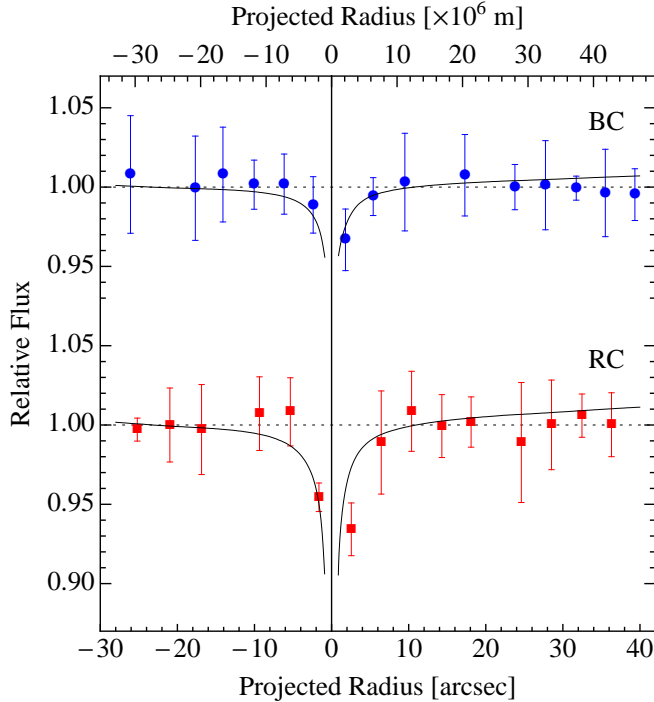
**Figure 1.** RC-band snapshots of the stellar appulse of 17P and star S. Differential photometry between stars S and C revealed dimming of the former as it passed behind the central coma of 17P. These are sub-frame sections of the TEK 2k CCD.

s. Our measurements were obtained through the Hale-Bopp narrowband blue continuum (BC;  $\lambda = 4453 \text{ \AA}$ ,  $\Delta\lambda = 61 \text{ \AA}$  FWHM) and red continuum (RC;  $\lambda = 7133 \text{ \AA}$ ,  $\Delta\lambda = 58 \text{ \AA}$  FWHM) filters (Farnham et al. 2000; Jewitt 2004). For absolute calibration purposes we obtained a number of broadband  $R$  (Kron-Cousins-type filter) images of 17P and Landolt standard stars throughout the night. To avoid saturation of the bright central region we were forced to use an integration time of 1 s, shorter than the minimum advised 5 s for the TEK camera. Integrations shorter than  $\sim 5$  s suffer from a systematic spatial pattern due to the finite shutter time that is more noticeable towards the edges of the CCD. Using 1 s dome flatfield images we found that within our region of interest (near the center of the CCD as we tried to image the full circular coma) the shutter pattern uncertainty amounts to  $< 1\%$ . The data were calibrated using bias frames and flatfield images obtained from dithered, median-combined images of the twilight sky. The night was photometric with very stable seeing,  $0.9 \pm 0.1''$ . We set the telescope to track the non-sidereal rate ( $26'' \text{ hr}^{-1}$ ) of 17P and, as a result, stellar trailing in the longer BC exposures is comparable to the seeing. A journal of the observations can be found in Table 1.

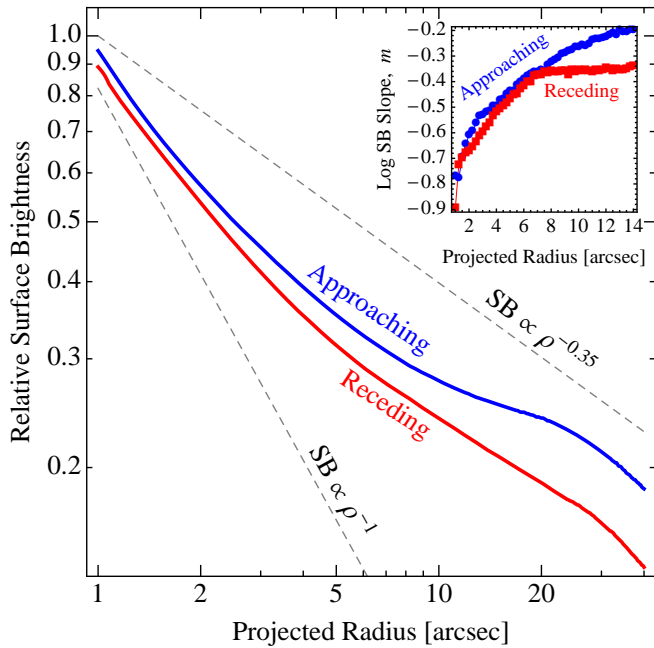
### 3. PHOTOMETRY

We identified several field stars in the projected path of the comet and selected the one (TYC 3334-166-1) having the highest brightness ( $R = 11.0 \pm 0.1 \text{ mag}$ ) and minimum impact parameter ( $\rho = 0.79''$ ) for this study; we refer to this as star S. Figure 1 shows some representative images in RC band. By 2007 October 29, the coma of 17P had expanded to fill the entire  $7.5'$  field of view of the TEK detector (Hsieh et al. 2010). Consequently, each CCD pixel included contributions from the background sky and from the 17P coma. To measure small changes in the flux from star S it was necessary to subtract the contribution from the sky and the coma of 17P. We attempted this subtraction in two different ways.

Firstly, we employed pair-wise subtraction of near-consecutive frames aligned on the comet nucleus. Before subtraction, the frames were scaled by dividing each by the median pixel value measured in a  $0.7' \times 0.7'$  square region centered on the comet nucleus. The point spread function (PSF) of the star overlapped slightly in consecutive frames (17P moved  $\sim 3.9''$  between frames) so we used every second frame for pair subtraction. A second method consisted of constructing “starless” frames by median-combining sets of three near-consecutive expo-



**Figure 2.** Lightcurve of star S versus projected radius from the nucleus of 17P through filters BC (blue circles) and RC (red squares). Negative projected radii indicate approach. The flux of star S was measured relative to that of star C. Overplotted as a solid black line is the inverted coma brightness profile, vertically shifted and scaled to fit the lightcurve of star S.



**Figure 3.** Surface brightness of the coma of 17P versus projected distance from the nucleus along the path of star S. Overplotted as dashed lines are slopes proportional to  $\rho^m$ , for  $m = -0.35$  and  $m = -1$ . The inset shows the slope of the profile as a function of projected distance.

**Table 2**  
Model Optical Depths for 17P.

| $n(r)$ model       | $q$      | $q(\rho < 1'')$ | $\tau(1.5'')$ | $\tau_n$ |
|--------------------|----------|-----------------|---------------|----------|
| $n(r) \propto r^q$ | -2       | -2              | 0.04          | 13.3     |
| $n(r) \propto r^q$ | -1.35    | -1.35           | 0.04          | 0.19     |
| from SB            | variable | $q(1'')$        | 0.04          | 3.46     |
| from SB            | variable | -2              | 0.04          | 8.28     |

**Note.** — Columns are (1) model for  $n(r)$  where “from SB” indicates that  $n(r)$  is inferred from coma surface brightness profile, (2) assumed  $q$  if constant, (3) assumed  $q$  for coma inner to  $1''$ , not resolved by our photometry, (4) measured optical depth at  $1.5''$  impact parameter, (6) model optical depth towards nucleus.

tures. Each median frame was then subtracted from the central of the medianed exposures. As before, the median of three consecutive exposures retained artifacts due to the star, so we used sequences 1-3-5 to construct the median to be subtracted from frame 3. Medians of 5 frames (median of frames 1-3-5-7-9 subtracted from frame 5) produced similar results to 3-frame medians. Neither of the methods was ideal due to the fast-expanding coma, to slight changes in the seeing, and to imperfect alignment of the nucleus in different frames. Both methods left traces of the coma that were strongest near the nucleus, but that amounted to at most, 1% of the flux from star S. The following results are based on the pair-wise subtraction method which we found to produce slightly better (less noisy) results.

We performed circular aperture photometry centered on star S in each of the sky- and coma-subtracted images. Tests with increasing apertures indicated that an aperture radius of  $3.3''$  produced the most stable photometry when star S projected far from the nucleus. Because of the subtraction, the flux surrounding the star should be zero, with a combined uncertainty that is approximately Gaussian. However, we chose to subtract the sky measured in an annulus surrounding the star to remove local residual subtraction offset. To estimate the uncertainty in the flux from star S at position  $i$  we used the standard deviation of the fluxes measured at that same position  $i$  in the  $N - 1$  frames ( $N = 15$ ) for which the star is not present in the aperture. In addition, to confer protection against small seeing variations and other time-dependent variations we employed relative photometry. For this, we used another star (C, see Fig. 1) that lies further ( $>2.3'$ ) from the nucleus, which we measured in the same way as star S. Star C ( $R \sim 13$  mag) lies distant enough from the bright central region of the coma that it should suffer much smaller extinction than star S (Li et al. 2011). We computed the ratio of the fluxes of stars S and C as a function of time.

Figure 2 shows the relative flux of stars S and C versus projected radius from the nucleus through the BC and RC filters. We divided the curve by its median dimming so that it explicitly represents the fractional dimming of star S. Near closest approach to the nucleus of 17P, the star dims by about 3% in BC (at  $1.7''$  from the nucleus) and about 4% in RC (at  $1.5''$ ). The nearest BC and RC measurements occur on opposite sides of the nucleus and, for both bands, the brightness dip is visible in two separate measurements bracketing the nearest projected distance from 17P. The two BC points are  $0.6\sigma$

and  $1.7\sigma$  below the median, while the two RC points are  $5.1\sigma$  and  $4.0\sigma$  below the median. Assuming that each pair of measurements is uncorrelated (i.e., their probabilities can be multiplied) the combined significance of the two dips is  $2.0\sigma$  in BC and  $6.6\sigma$  in RC. We note that both bands show a consistent trend of stronger dimming on the post-appulse side of the nucleus. This is true even though for RC the closest post-appulse measurement lies slightly farther from the nucleus (at  $\sim 2.5''$ ) than the nearest pre-appulse point.

The observed dimming can be converted to an optical depth  $\tau$  using

$$\tau(\rho) = -\ln[F(\rho)/F_0] \quad (1)$$

where  $\rho$  is the impact parameter at which the dimming is detected,  $F(\rho)$  is the star S flux at  $\rho$  and  $F_0$  is the unimpeded star S flux. Substituting 0.97 and 0.96 into equation (1) we obtain optical depths  $\tau(1.7'') = 0.03$  in BC and  $\tau(1.5'') = 0.04$  in RC. In the remainder of the paper we use the higher significance RC optical depth.

#### 4. DISCUSSION

##### 4.1. The optical depth to the nucleus

Assuming a spherically symmetric coma composed of dust particles of radius  $a$  with a radial number density dependence  $n(r)$ , the optical depth along a line-of-sight to the center of the nucleus,  $\tau_n$ , can be related to the optical depth at a projected distance  $\rho$  by

$$\frac{\tau_n}{\tau(\rho)} = \frac{(1/2) \int_{r_n}^{\infty} \pi a^2 n(r) dr}{\int_0^{\infty} \pi a^2 n(r') dl} \quad (2)$$

where  $r' = \sqrt{l^2 + \rho^2}$ ,  $l$  is measured along the line-of-sight to projected radius  $\rho$ ,  $r_n$  is the radius of the nucleus, and the  $(1/2)$  factor accounts for the opaqueness of the nucleus. We can use the observed coma surface brightness profile (surface brightness versus projected radius from the nucleus,  $\rho$ ) to infer the dust number density profile,  $n(r)$ . If we assume the latter varies proportionally to  $r^q$  then by integration the former will vary proportionally to  $\rho^m$ , where  $m = q + 1$ . Figure 3 shows the near-nucleus surface brightness profile from our RC data measured on a  $3''$ -wide band centered on the path of star S across the coma. The profile is steepest near the nucleus, where it approaches the canonical slope  $\rho^{-1}$  of a spherically symmetric, steady state coma, and is on average  $\propto \rho^{-0.35}$  in the inner  $30''$  of the coma. Using  $n(r) \propto r^q$  with the maximum slope  $q = -2$  (from  $m = -1$ ), and replacing  $\tau(1.5'') = 0.04$  and  $r_n = 1.7$  km (Lamy et al. 2009) into equation (2) we obtain  $\tau_n = 13.3$ . If, instead, we use the average inner coma slope  $q = -1.35$  we obtain  $\tau_n = 0.19$  (Table 2). The former, larger estimate can be regarded as an upper limit to the optical depth towards the nucleus. Steeper slopes than  $m = -1$  are generally due to solar radiation pressure which has insufficient time to act in the inner  $1''$  ( $\sim 1000$  km) of the coma (Jewitt & Meech 1987).

Shown as an inset in Fig. 3 is the measured surface brightness profile slope as a function of projected radius  $\rho$ , which varies from  $m \sim -0.8$  at  $\rho < 3''$  to  $m \sim -0.3$  at  $\rho \sim 12''$ . These slopes match the  $m \sim -0.3$  to  $-0.2$  found by Stevenson & Jewitt (2012) at distances 10000 to 20000 km ( $8''$  to  $16''$  in our data) from the nucleus in

data obtained a few days to a few weeks after our own observations. We can use the measured radial dependence of  $m$  to solve numerically the integrals in equation (2) and improve our estimate of the optical depth to the nucleus,  $\tau_n$ . Table 2 summarizes our results where, again, we used  $\tau(1.5'') = 0.04$  and  $r_n = 1.7$  km. Because we only measure  $m$  to within approximately  $1''$  of the nucleus we need to assume the value of  $q$  in the innermost  $1''$  of the coma. We consider two possibilities: the limiting case  $q(\rho < 1'') = -2$ , and a constant  $q(\rho < 1'') = q(1'')$ . In both cases we obtain optical depths to the nucleus only slightly larger than unity, falling off to  $\tau = 1$  at  $\rho \sim 0.01''$ .

Our measurement is consistent with the findings of Li et al. (2011) who used coarser spatial resolution photometry on data taken around 2012 October 24.5 to conclude that the coma of 17P was optically thick only within a tiny central region,  $\sim 0.1''$ . They find a peak optical depth towards the nucleus  $\tau_n \sim 65$  on October 24.8. Another detection of extinction by the coma of 17P was reported by Montalto et al. (2008), using an ensemble of 20 stars located between  $25''$  and  $180''$  from the nucleus of the comet. They infer optical depths  $0.3 < \tau < 0.5$ , two to three orders of magnitude larger than the  $1 \times 10^{-4} < \tau < 4 \times 10^{-3}$  implied by our measurements in the region  $25'' < \rho < 180''$ .

##### 4.2. The coma dust albedo

The extinction obtained in §4.1 can be combined with the measured scattered light, to provide a direct estimate of the coma dust albedo. We here use the  $R$  band images mentioned in §2. Assuming that the inner coma of 17P is spherically symmetric then the optical depth at projected radius  $\rho$  from the nucleus can be written

$$\tau(\rho) \approx \frac{A_d}{\pi (2\rho\delta\rho)\Delta^2} \quad (3)$$

where  $\pi (2\rho\delta\rho)\Delta^2$  is the projected area of the annulus centered on the nucleus with inner radius  $\rho - \delta\rho/2$  and outer radius  $\rho + \delta\rho/2$ , and  $A_d$  is the total effective scattering cross-section of the dust grains within the annulus. The latter can be calculated from (Russell 1916)

$$p_d A_d = 2.24 \times 10^{22} \pi 10^{0.4[m_\odot - m_d(\rho)]} \quad (4)$$

where  $p_d$  is the red albedo of the dust grains,  $m_\odot = -27.11$  is the apparent red magnitude of the Sun, and  $m_d(\rho)$  is the absolute red magnitude<sup>1</sup> of the dust contained within the annulus defined above. Equations (3) and (4) can be combined to yield

$$p_d = \frac{2.24 \times 10^{22} 10^{0.4[m_\odot - m_d(\rho)]}}{2\rho\delta\rho\Delta^2\tau(\rho)}. \quad (5)$$

We take  $\rho = 1.5''$ ,  $\delta\rho/2 = 0.219''$  (1 pixel),  $\tau(1.5'') = 0.04$  and calculate the magnitude of the coma in the annulus using

$$m_d(1.5'') = -2.5 \log_{10} (10^{-0.4m_{\text{out}}} - 10^{-0.4m_{\text{in}}}) \quad (6) \\ = 7.17 \pm 0.47 \text{ mag}$$

<sup>1</sup> The absolute magnitude is the apparent magnitude reduced to unit heliocentric and geocentric distances and to zero degrees phase angle.

where  $m_{\text{out}} = 6.04 \pm 0.11$  mag and  $m_{\text{in}} = 6.51 \pm 0.11$  mag are the absolute red magnitudes measured within the outer and inner radii of the annulus. Replacing those quantities into equation 5 we obtain  $p_d = (6 \pm 2) \times 10^{-3}$ .

Our estimated dust albedo is significantly lower than an earlier, independent measurement using a different technique by Ishiguro et al. (2010). Those authors used combined optical and infrared observations of 17P taken on 2010 October 25-28 to find an albedo  $0.03 \leq p_d \leq 0.12$ . Both estimates were obtained at similar phase angle,  $\alpha = 16^\circ$ . Interestingly, Ishiguro et al. (2010) report a decrease in albedo with time, from  $p_d = 0.12 \pm 0.04$  on October 25 to  $p_d = 0.03 \pm 0.01$  on October 28. Our estimate follows the trend but we find a  $5\times$  lower albedo just a day later, on October 29.

Earlier attempts to estimate the reflectivity of cometary dust grains using stellar appulses have also found surprisingly low albedos. Larson & A'Hearn (1984) observed comet Bowell (1980b) and found a dust albedo of  $p_d \sim 1.5 \times 10^{-3}$ . They suggested that photons might go through two reflections ( $0.0015 \approx 0.04^2$ ) before escaping the dust grain to reconcile their findings with the typical 4% albedo of cometary surfaces. Fernández et al. (1999) reported an albedo  $p_d \approx 0.01$  for the coma dust of comet Hale Bopp.

Such low albedos are not unprecedented. Spacecraft imaging of comet Borrelly revealed very dark regions with geometric albedos  $p < 0.01$  at wavelengths  $0.5 \mu\text{m} < \lambda < 1.0 \mu\text{m}$  (Soderblom et al. 2002; Nelson et al. 2004). High-porosity carbon-based aerogels are also known to have very low albedos over a broad range of wavelengths (Merzbacher 2001). The least reflective carbon aerogels (reflectivities as low as 0.003) are made of  $\sim 1$  nm amorphous carbon particles and  $\sim 10$  nm voids resulting in bulk porosities larger than 90%. Indeed, theoretical studies predict that the albedo of porous grain aggregates of small particles should decrease with increasing bulk porosity (Hage & Greenberg 1990), reaching sub-1% reflectivities at void volume fraction of about 70% (Napier et al. 2004). The low reflectivity of carbon aerogels is due in part to strong absorption from amorphous carbon but results mostly from the rough, highly porous physical structure of the material (silica aerogels are also highly porous but are smoother on  $1 \mu\text{m}$  scales). Our observations and those of others may be suggesting that comet dust is highly porous and, in the case of 17P, possibly carbon-rich. We note that a significant amount of amorphous carbon is required to explain Spitzer spectra of 17P taken on 2007 November 10, only a few days after our observations (Reach et al. 2010).

## 5. CONCLUSIONS

We used narrowband photometry of a background star that passed within  $< 1''$  of the nucleus of outbursting comet 17P/Holmes to constrain the extinction optical depth of the cometary dust coma. Our conclusions are as follows:

- We detect a 3 to 4% dimming of the background

star depending on wavelength that coincides with the nearest projected distance to the cometary nucleus. If caused by extinction due to coma dust, this dimming implies an optical depth  $\tau = 0.03$  to  $0.04$  at projected radius  $1.5''$  from the comet nucleus. We infer that the coma was optically thick only in a tiny region,  $\sim 0.01''$  in radius, surrounding the nucleus. Our measurements are compatible with those by Li et al. (2011) but difficult to reconcile with those by Montalto et al. (2008).

- We combine the measured extinction with photometry of the coma to estimate a dust albedo of  $(0.6 \pm 0.2)\%$ . Our albedo estimate is  $5\times$  lower than an independent measurement using optical and thermal observations of light scattered by the dust (Ishiguro et al. 2010), but it is consistent with the darkest regions on comet Borrelly, and with the dust being composed of very small, highly porous grains of carbonaceous composition.

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