COMET 17P/HOLMES: CONTRAST IN ACTIVITY BETWEEN BEFORE AND AFTER THE 2007 OUTBURST

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Received 2013 July 9; accepted 2013 September 17; published 2013 October 29

ABSTRACT

A Jupiter-family comet, 17P/Holmes, underwent outbursts in 1892 and 2007. In particular, the 2007 outburst is known as the greatest outburst over the past century. However, little is known about the activity before the outburst because it was unpredicted. In addition, the time evolution of the nuclear physical status has not been systematically studied. Here, we study the activity of 17P/Holmes before and after the 2007 outburst through optical and mid-infrared observations. We found that the nucleus was highly depleted in its near-surface icy component before the outburst but that it became activated after the 2007 outburst. Assuming a conventional 1 μm sized grain model, we derived a surface fractional active area of 0.58% ± 0.14% before the outburst whereas the area was enlarged by a factor of ~50 after the 2007 outburst. We also found that large (>1 mm) particles could be dominant in the dust tail observed around aphelion. Based on the size of the particles, the dust production rate was >170 kg s⁻¹ at a heliocentric distance of rₜ₈ = 4.1 AU, suggesting that the nucleus was still active around the aphelion passage. The nucleus color was similar to that of the dust particles and average for a Jupiter-family comet but different from that of most Kuiper Belt objects, implying that color may be inherent to icy bodies in the solar system. On the basis of these results, we concluded that more than 76 m of surface material was blown off by the 2007 outburst.

Key words: comets: individual (17P/Holmes) – interplanetary medium

Online-only material: color figures

1. INTRODUCTION

17P/Holmes is a distinguished comet because of its spectacular outbursts in 1892 and 2007. There is no other known comet that has exhibited such large-scale outbursts. However, its size and orbit are typical among Jupiter-family comets: 17P has a radius of 1.62–1.71 km (Snodgrass et al. 2006; Levison & Duncan 1997). It passed through perihelion at and most probably originated from the trans-Neptunian region (e.g., a Tisserand parameter with respect to Jupiter of 2.86) (Levison & Duncan 1997).; Reach et al. 2010; Ishiguro et al. 2010; Boissier et al. 2012). Cometary fragments were also found by optical wide-field imaging. Stevenson et al. (2010) detected 16 fragments with a maximum effective size of 10–100 m. The evidence of decameter-sized fragments may suggest that >10 m of the surface layer could have been excavated by the outburst. Yang et al. (2009) detected two absorption features at 2 and 3 μm and suggested that the 17P/Holmes cloud contained a significant fraction of pure water ice.

contrast, Altenhoff et al. (2009) indicated that the nucleus was activated by the outburst and that its activity continued for over 30 days. Small grains were dominant near the nucleus after the outburst whereas large grains were dominant gradually, probably because small grains were kicked out by solar radiation pressure (Zubko et al. 2011). The mineralogical properties of the dust grains were studied by mid-infrared spectroscopy. It was found that the infrared spectrum of the diffuse emission could be explained by a mixture of amorphous and crystalline silicate materials, as observed in most comets (Watanabe et al. 2009; Reach et al. 2010). The total ejecta mass was estimated to be 10¹⁰–10¹³ kg (Montalto et al. 2008; Altenhoff et al. 2009; Reach et al. 2010; Ishiguro et al. 2010; Boissier et al. 2012). More than 2 m of the surface layer could have been blown off by the initial event although this is strongly dependent on the size distribution and maximum size of the dust particles (Ishiguro et al. 2010). Cometary fragments were also found by optical wide-field imaging. Stevenson et al. (2010) detected 16 fragments with a maximum effective size of 10–100 m. The evidence of decameter-sized fragments may suggest that >10 m of the surface layer could have been excavated by the outburst.
It is unlikely that the outburst was triggered by an impact of a small object, not only because the probability is incredibly low (Ishiguro et al. 2010) but also because of evidence that multiple outbursts occurred on the same comet in 1892 (Barnard 1896; Sekanina 2008). Several possible scenarios have been presented to explain the cause of the outburst; these include vaporization of pockets of more volatile ices such as CO2 and CO (Schleicher 2009), the phase change of water (Gronkowski & Sacharczuk 2010), or the polymerization of hydrogen cyanide from amorphous to crystalline ice (Sekanina 2009), thermal outburst when the comet was at $r_h = 2.23$ AU. A list of the observations is given in Table 1. Details of the data acquisition and reductions are given in the following subsections.

2.1. NHAO Observations in 2008 December and 2010 January

The NHAO (134° 20′ 08″ E, 35° 01′ 31″ N, 449 m) is a public astronomical observatory that conducts public relations activities. Our observations were conducted as a part of the NHAO @site program, which was contrived as a means of public outreach to introduce visitors to cutting-edge astronomy through research experiences (Sakamoto 2008). We thus made observations with the @site program participants. We employed MINT, a N$_2$-cooled optical CCD camera mounted on the f/12 Cassegrain focal plane with a focal reducer and $R_c$-band filter. In this configuration, the pixel size on the sky was 0″276, so that the field of view was 9.4 × 9.4. The observations of 17P/Holmes were made using non-sidereal tracking on 2008 December 23 and 26 and 2010 January 16 under photometric conditions. The average seeing was 1′9 on 2008 December 23, 2′0 on 2008 December 27, and 1′6 on 2010 January 16.

2.2. HCT Observations on 2011 March 29–30

The 2.0 m Ritchey–Chretien HCT is located in Hanle, India (78° 57′ 51″ E, 32° 46′ 46″ N, 4500 m), a high-altitude area in the Himalayan region. It is operated by the IIA. We made observations on 2011 March 29 with the Himalaya Faint Object Spectrograph (HFOSC) 2048×4096 pixel CCD camera at the f/9 Cassegrain focus of the telescope. The telescope was controlled via a satellite from the CREST campus near Bangalore. Half of the imaging area of the HFOSC was sampled at the $R_c$-band filter. For more details of the observations, see Table 1. Observations and data reduction are given in the following subsections.
observations were performed under photometric conditions. Point sources on the images were spread out to 2′/6 probably because of inadequate adjustment of the focus position or vibration of the telescope by strong winds.

2.3. Subaru Observations on 2011 January 7 and June 5

Subaru is an 8.2 m optical–infrared telescope at the summit of Mauna Kea, Hawaii, operated by the NAOJ and the National Institutes of Natural Sciences. We carried out observations of 17P/Holmes with the wide-field camera Suprime-Cam (Miyazaki et al. 2002) attached to the prime focus of Subaru for two nights on 2011 January 7 and 2011 June 5. The camera has a 34′ × 27′ field of view with 10 2000 × 4000 CCDs, whose pixel size is 0′′/20. Since there are gaps of a few arcseconds (over 10 arcsec between the CCD chips), we dithered the telescope to make up for the gap areas. Five dithering modes were applied for one complete set of images. We took images with an RC-band filter on 2011 January 7 and with g′-, r′-, and i′-band filters on 2011 June 9. These observations were carried out in a non-sidereal tracking mode. The seeing was 0′′/6–0′′/8.

The weather was variable during the first run on 2011 January 7 and photometric conditions prevailed during the second run on 2011 June 5.

2.4. UH2.2m Observations on 2011 February 4–5

The UH2.2m observations were made for two nights on 2011 February 4–5. We used a Tek2k and a Kron–Cousins RC-band filter. The individual frames were taken in non-sidereal tracking mode. The CCD was used in 1 × 1 binned mode on February 4 and 2 × 2 binned mode on February 5. The instrument provides a 7.5′ × 7.5′ field of view and a pixel resolution of 0′′/22 (in 1 × 1 binned mode) and 0′′/44 (in 2 × 2 binned mode). At the time of the observations, the seeing was ∼1′/0. The weather conditions for these two nights were photometric.

2.5. AKARI All-sky Survey

AKARI (originally called ASTRO-F), which launched on 2006 February 21 UT, is a Japanese infrared space telescope used to carry out an all-sky survey and pointed observations. It orbits at an altitude of ∼700 km in a Sun-synchronous polar orbit along the boundary between the night and day sides. The boresight vector of the telescope is pointed at a solar elongation angle around 90° to suppress the incident thermal flux from the Earth and the Sun. AKARI consists of a bus module and a science module. The science module consists of a cryogenically cooled telescope with a 68.5 cm diameter aperture and two focal-plane instruments, the Far-Infrared Surveyor (Kawada et al. 2007) and the Infrared Camera (IRC; Onaka et al. 2007). Detailed descriptions of the design and operation of AKARI have appeared in Murakami et al. (2007). The all-sky survey, conducted between 2006 May 8 and 2007 August 26, is the major task of the AKARI project and the first half of the mission period is dedicated to it. 17P/Holmes was serendipitously detected with the longer channel of mid-infrared (MIR) in L18W (13.9–25.3 μm) twice on 2007 August 23.

2.6. Data Reduction

The observed optical raw data were reduced in a standard manner using bias (zero exposure) frames recorded at intervals throughout the nights plus skyflat data. The data were analyzed using SDFRED2 for the Subaru data (Ouchi et al. 2004) and IRAF for the other data. Flux calibration was done using standard stars in the Landolt catalog (Landolt 1992, 2009) or field stars listed in the USNO–B1.0 catalog (Monet et al. 2003). To convert pixel coordinates into celestial coordinates, we employed the imcoords package in IRAF or WCSTools.

To find the faint dust cloud structure, star-subtracted composite images were produced by the method described in Ishiguro et al. (2007) and Ishiguro (2008). We first made images to align the stars to detect faint stars and galaxies. We masked the identified objects using ∼3× seeing-sized circular masks. We also masked pixels identified as bad in the bias (hot pixels) and flat-fielding images (pixels whose sensitivity was 5% higher or lower than the average). We combined the masked images with offsets to align 17P/Holmes, excluding the masked pixels and shifting the background intensity to zero. Since the comet moved relative to the stars, it was possible to exclude nearly all masked pixels in the resultant composite image.

The AKARI infrared images were constructed in the same manner as described in Ishihara et al. (2010). The reduction pipeline process includes a reset anomaly correction, a linearity and flat correction, and internal stray light removal. We applied the conversion factor of 4.3 MJy/sr/ADU in L18W, where ADU denotes the Arbitrary Data Unit from the detector (D. Ishihara 2012, private communication).

3. RESULTS AND DISCUSSION

Figure 1 shows the pre-outburst, mid-infrared image of 17P/Holmes taken with AKARI on 2007 August 23. It consists of a near-nuclear dust coma and a faint tail extended toward the southwest. Figure 2 shows the time-series, post-outburst optical images of 17P/Holmes between 2007 October 30 and 2011 February 5. For reference, images taken soon after the initial outburst are shown in Figures 2(a) and (b); these were acquired with the Kiso observatory 1.05 m Schmidt telescope and archived at SMOKA. The dust cloud was initially observed as nearly spherical with respect to the position of the nucleus (Figure 2(a) and gradually it stretched toward the southwest (Figure 2(b)). As it expanded, the inner coma became faint and pointlike (Figures 2(c)–(f)). Among these images, Figure 2(e) is the most sensitive among all of our data. Using the composite images with offsets to align stars, we estimated a detection limit of 26.7 mag in Figure 2(e). Because there is no detectable
fragment in the image, we put the upper limit of the fragment radius at 400 m. It is important to note that all images in Figure 2 show the dust tail. Obviously, 17P/Holmes possessed a dust tail even when it was located around aphelion at 5.2 AU (Figures 2(e)–(f)). However, a pre-outburst observation on 2005 May 3 and June 3 revealed no comet-like coma at a heliocentric distance of \( r_h = 4.66 \) AU (Snodgrass et al. 2006). This fact may suggest that an inactive dust layer was excavated by the outburst and fresh icy materials were exposed on the surface at the time of our observations. In the following subsections, we provide a quantitative analysis of the activities.

3.1. Radial Profiles

We examined radial brightness profiles of the near-nuclear light source to confirm the activity. We prepared these profiles using \textit{AKARI} data on 2007 August 23, NHAO data on 2008 December 23, UH2.2m data in 2011 February, and Subaru data in 2011 January; we compared these data with the point spread function (PSF) determined by stars and asteroids (Figure 3).

Because the image was taken in non-sidereal tracking mode in the optical, field stars were usually stretched out in the comet’s images. Infrared data were taken with short exposure times (<1 s), so both the comet and background stellar objects remained stationary in the observed data. Among the profiles in Figure 3, the Subaru data on 2011 January 7 are the best for the comparison because we set the individual exposure time to 40 s, which is too short for the field stars to be elongated in the non-sidereal tracking mode. In fact, the stars can be extended no longer than \( 0'1 \) in the Subaru data on 2011 January 7. For the \textit{AKARI} data, we used the PSF of the average profiles of stars and asteroids in the same scan pass. We determined the PSF of the other data using images before or after the comet observations. They were usually taken with short exposure times to confirm the position of 17P/Holmes after the pointing of the telescopes. Therefore, there may be uncertainty in the time variation of the PSFs in the NHAO data on 2008 December 23 and the UH2.2m data in 2011 February (Figures 3(b) and (d)), but probably the variations were \( \lesssim 0'3 \), which is typical at these observational sites.

Figure 2. Composite optical images of 17P/Holmes taken after the 2007 outburst. These images have the standard orientation on the sky, that is, celestial north is up and east is to the left. For reference, we show two images soon after the outburst from the SMOKA data archive (top two images).
In Figure 3, one can see that the surface brightness profiles of 17P/Holmes were broader than those of point sources at $\gtrsim 0\farcs2−1\arcsec$ from the photometric center. Hence, we consider the epoch of the dust emission that is responsible for the broadening of the radial brightness profiles. The expansion dust speed has been studied in much of the literature. It depends on how dust particles are coupled with the expanding gas molecules, the expansion velocity of the gas molecules, the gas-to-dust mass ratio, and so on. Surface orography and its inhomogeneities also play a significant role in the terminal velocity of the grains (Crifo & Rodionov 1997). Although there are many factors that determine the expansion dust speed, it can be approximated by a simple power-law function of size and heliocentric distance, that is, $v_{ej} = K / \sqrt{r_{hd}}$, where $a_d$ denotes the radius of the dust particles in microns. $K$ is a constant, typically in the range of $100 < K < 1000$ m s$^{-1}$ based on theoretical studies (Whipple 1951; Ip & Mendis 1974), past observations of normal comet activities (Lisse et al. 1998; Ishiguro et al. 2007; Sarugaku et al. 2007; Snodgrass et al. 2008; Ishiguro 2008), and cometary outbursts including the 17P/Holmes event in 2007 (Sekanina 2008; Montalto et al. 2008; Moreno et al. 2008; Hsieh et al. 2010; Sarugaku et al. 2010; Reach et al. 2010; Stevenson & Jewitt 2012). From the equation for the expansion speed, dust particles could escape from a region of a $1\arcsec$ aperture in 1.4–22 hr for $a_d = 1 \mu$m and 6–94 days for $a_d = 1$ cm particles. Since our postburst data were taken $>342$ days after the outburst, we can conjecture that the near-nuclear dust particles were not remnants of the particles ejected by the 2007 outburst. We investigated the staying time of the dust particles in a $0\farcs2−1\arcsec$ aperture using a sophisticated dynamical model (Appendix), but both model results are consistent with each other in that the near-nuclear dust particles were not the remnants of the 2007 outburst.

### 3.2. Photometry of the Inner Dust Coma

We next deduced the dust coma magnitude as use a different font of time and heliocentric distance. Photometry was performed using the APPHOT package in IRAF, which provides the magnitude within synthetic circular apertures projected onto the sky. Since the seeing disk sizes were different each night at each observatory, we set a flexible aperture radius between 1.75–6.50, which corresponds to 2.5 times the FWHM. The sky background was determined within a concentric annulus with projected inner and outer radii of $2.5 \times$ FWHM of point sources and $3.0 \times$ FWHM of point sources, respectively. The observed $R_c$-band magnitudes, $m_{R_c}$, are summarized in Table 2. The absolute magnitude, the magnitude at a hypothetical point at unit heliocentric distance and observer distance, at zero solar phase angle (Sun–object–observer angle), is given by

$$m_{R_c}(1, 1, 0) = m_R - 5 \log(r_h \Delta) - 2.5 \log \Phi(\alpha),$$  

(1)
where $\Delta$ is the observer’s distance in AU and $\alpha$ is the solar phase angle in degrees. The empirical scattering phase function, $\Phi(\alpha)$, is given by the following equation (Lamy et al. 2004):

$$2.5 \log \Phi(\alpha) = \beta \alpha,$$

(2)

where $\beta$ characterizes the phase slope, $\beta = 0.035 \text{ mag deg}^{-1}$ has been commonly assumed for cometary nuclei (Lamy et al. 2004; Snodgrass et al. 2006). Alternatively, the phase function of active comets is given based on observations of 1P/Halley by Schleicher et al. (1998), Li et al. (2011), and Stevenson & Jewitt (2012):

$$2.5 \log \Phi(\alpha) = -0.045\alpha + 0.0004\alpha^2.$$

(3)

We found that these different phase functions result in only less than a 1%–2% inconsistency at $\alpha = 0^\circ$ in the range of our observations, i.e., $\alpha = 3^\circ$–13$^\circ$. For this reason, we corrected the phase angle dependence of the observed magnitudes using Equation (2) with $\beta = 0.035 \text{ mag deg}^{-1}$.

Figure 4 shows the absolute $R_C$-band magnitude of the dust coma as a function of heliocentric distance. In the figure, we subtracted the nuclear magnitude, assuming 1.71 km spherical bodies and a geometric albedo of 0.04 (Lamy et al. 2004).

For comparison, we plot the mean magnitude (the average of maximum and minimum magnitudes caused by the rotating nucleus) obtained before the 2007 outburst (Snodgrass et al. 2006), where the authors could not find the detectable coma. Figure 4 clearly shows that the photometric magnitudes after the outburst were significantly brighter than the nuclear magnitude. This result is consistent with the fact that the radial profiles of the near-nuclear light source were brightness than the stellar profiles (Section 3.1). In addition, there is a trend of decreasing with increasing heliocentric distance. This trend can be attributed to the fact that the sublimation rate of ice, which is responsible for the dust emission from the nucleus, could decrease because of the low solar flux. Accordingly, we can conclude that 17P/Holmes was active and had a faint coma during the time of our observations.

### 3.5. Dust Mass-loss Rate

Note that the absolute magnitude of active comets depends on the aperture size of the photometry. A larger physical aperture encloses more dust particles and accordingly the total cross section increases. Stevenson & Jewitt (2012) used apertures of fixed physical radius at the position of the comet to eliminate this effect. It is, however, difficult to fix the physical aperture size for our data because the seeing differed at different sites from night to night. We adopted a method in Luu & Jewitt (1992) to correct for the aperture size effect. We converted the magnitude into the cross section and then a mass-loss rate, by assuming that spherical dust grains with a certain radius and mass density. In addition, we utilized the infrared data from AKARI to derive the dust mass-loss rate before the outburst in the manner described below.

We first calculated the cross section of coma dust particles, $C_c$, and compared it with the area of the comet nucleus, $C_n$. We assumed the 17P/Holmes nucleus to be spherical with a radius of 1.71 km (Lamy et al. 2004). We supposed that the scattering properties of the dust particles are the same as those of the nucleus because of the small phase angles in our dataset. We thus assumed a geometric albedo of 0.04 and a scattering phase function given in Equation (2) for the dust particles. Second,
we derived a parameter \( \eta \) defined as the ratio of the coma cross section \( C_c \) to the nucleus cross section \( C_n \). At optical wavelengths, \( \eta \) is proportional to the ratio of the flux density scattered by the coma, \( I_c \), to the flux density scattered by the nucleus cross section, \( I_n \), which enables us to characterize the contribution of dust particles in the coma (Luu & Jewitt 1992; Hsieh & Jewitt 2005; Kasuga & Jewitt 2008), that is,

\[
\eta = \frac{C_c}{C_n} \approx \frac{I_c}{I_n} \quad \text{(optical).} \tag{4}
\]

For the mid-infrared data, it is improper to use Equation (4) for the derivation of \( \eta \) because the thermal properties of dust particles are significantly different from those of cometary nuclei. We modified Equation (4) into

\[
\eta = \frac{C_c}{C_n} = \frac{I_c}{I_n} \left( \frac{i_c}{i_n} \right)^{-1} \quad \text{(infrared),} \tag{5}
\]

where \( i_n \) is the flux from a big spherical body like a comet nucleus of unit cross-sectional area. We calculated the flux using the standard thermal model (STM; Lebofsky & Spencer 1989). In the model, it is assumed that the nucleus is a non-rotating spherical body. We thus considered that each element of the surface is in instantaneous equilibrium with the solar influx. In situ observations with the Deep Impact spacecraft revealed that the STM was a good approximation for characterizing the thermal balance of a comet nucleus whose surface consists of dry materials without icy components (A’Hearn et al. 2005). Standard thermal parameters are assumed, i.e., emissivity \( \epsilon_E = 0.90-0.95 \), beaming parameter \( \eta_E = 0.756-0.850 \), phase integral \( q_E = 0.28-0.75 \), and thermal phase coefficient \( \beta_E = 0.01 \) mag deg \(^{-1} \). In the range, we obtained \( i_n = (5.3-6.0) \times 10^{-10} \) Jy m \(^{-2} \). In contrast, the flux from the dust coma, \( i_c \), that has an equivalent total cross-sectional area was derived in the manner described in Ishiguro et al. (2010). We calculated the equilibrium temperature of a \( 1 \mu m \) sized particles at \( r_h = 2.23 \) AU using the optical constants of astronomical silicate (217 K), magnetite (229 K), and graphite (235 K) and derived a thermal flux at the 18 \( \mu m \) wavelength of \( i_c = 2.0 \times 10^{-9} \) Jy m \(^{-2} \) for astronomical silicate, \( i_c = 2.4 \times 10^{-9} \) Jy m \(^{-2} \) for magnetite, and \( i_c = 2.6 \times 10^{-9} \) Jy m \(^{-2} \) for graphite. We obtained the observed flux \( I_c + I_n = 0.39 \pm 0.04 \) Jy. Using the STM, we estimated the flux from the nucleus to be \( I_n = (4.8-5.5) \times 10^{-2} \) Jy. Substituting these values into Equation (5), we obtained \( \eta = 17 \pm 4 \) for the pre-outburst data. The derived \( \eta \) values are summarized in Table 2.

The dust mass-loss rate can be derived from \( \eta \) in the manner of Luu & Jewitt (1992) as

\[
M_d = \frac{1.1 \times 10^{-3} \pi \rho_d \bar{a} \eta R_{obj,0}^2}{\phi \bar{a}^{1/2} \Delta}, \tag{6}
\]

where \( \rho_d \) is the mass density of the dust particles, \( \bar{a} \) is the grain radius in meters, \( R_{obj} \) is the radius of the 17P/Holmes nucleus, and \( \phi \) is the reference photometry aperture radius in arcsec. We assumed that 17P/Holmes emitted small dust grains, that is, \( \bar{a} = 1.0 \times 10^{-6} \) m. We supposed the mass density of dust particles to be \( \rho_d = 1000 \) kg m \(^{-3} \). The derived dust mass-loss rates are listed in Table 2. Note here that the dust mass-loss rate is a crude estimate. In fact, there is a large uncertainty in the dust mass-loss rate because the mass-loss rate is proportional to the grain size.

Figure 5 shows the dust mass-loss rate as a function of heliocentric distance \( r_h \). In addition to our data, we compared the dust mass-loss rate with data from previous research. As we previously mentioned, Snodgrass et al. (2006) could not detect any coma at 4.66 AU before the outburst and put an upper limit on an unresolved coma of 24.6 mag. We converted the magnitude into the mass-loss rate in the figure. Miles (2010) monitored the near-nuclear magnitude over 5 months using 2.0 m telescopes, the Faulkes Telescope North and the Liverpool Telescope, with an Sloan Digital Sky Survey \( r' \) filter and derived the magnitude. Since the aperture size for photometry and the bandpass filter of...
their observations were different from ours, we scaled their data to match our data at the NHAO run in 2008 December. Owing to frequent observations as well as to good photometric stability, Miles (2010) succeeded in detecting a minor burst possibly occurring on 4.7 ± 0.5 2009 January and attaining a peak magnitude enhancement of 0.85 ± 0.1 mag. Moreover, we refer to the dust mass-loss rate derived in Stevenson & Jewitt (2012). The observation covered when the comet was at 2.49–2.50 AU. They derived the mass-loss rate in a manner similar to ours. The observation was different from ours, we scaled their data to match our data at the NHAO run in 2008 December. Owing to their observations were different from ours, we scaled their data to match our data at the NHAO run in 2008 December. Owing to frequent observations as well as to good photometric stability, Miles (2010) succeeded in detecting a minor burst possibly occurring on 4.7 ± 0.5 2009 January and attaining a peak magnitude enhancement of 0.85 ± 0.1 mag. Moreover, we refer to the dust mass-loss rate derived in Stevenson & Jewitt (2012). The observation covered when the comet was at 2.49–2.50 AU. They derived the mass-loss rate in a manner similar to ours. They thus obtained the mass-loss rate by assuming spherical dust grains with radii of 1 μm and a bulk density of 1000 kg m⁻³.

In Figure 5, it is clear that the mass-loss rate significantly increased after the 2007 outburst. In addition, it decreased with increasing heliocentric distance most likely because of a weaker solar influx. There are two minor peaks on 2007 November 12 and 2009 January 5, indicating that minibursts occurred at those epochs (Stevenson & Jewitt 2012; Miles 2010).

3.4. Fractional Active Area of the Nucleus

We now consider a model to predict the dust mass-loss rate based on a thermal balance on the surface. We assume that this element of the surface is in instantaneous equilibrium with solar radiation and the latent heat of sublimation of ice. We thus consider the energy balance on the surface of the icy body to be given by

\[
S_0 \frac{(1 - A_p)}{r_h^2} \cos z = \epsilon_E \sigma T^4 + L_w(T) \frac{dZ}{dt} \quad (7)
\]

(Desvoivres et al. 1999, 2000), where \(S_0\) is the solar flux at 1 AU, \(z\) is the zenith distance of the Sun, \(\epsilon_E\) is the emissivity, \(\sigma\) is the Stefan–Boltzmann constant, \(A_p\) is the geometric albedo, and \(T\) is the surface temperature. The latent heat of sublimation of water, \(L_w\), is given by

\[
L_w = 2.886 \times 10^6 - 1116 T \text{ J kg}^{-1} \quad (8)
\]

The sublimation rate of the water ice is given by

\[
\frac{dZ}{dt} = \frac{1}{1 + 1/k} \gamma(T)P_w(T) \sqrt{\frac{m_w}{2\pi kT}} \text{kg s}^{-1}, \quad (9)
\]

where \(\kappa\) is the water ice-to-dust mass ratio, defined as \(\kappa = \rho_w/\rho_d\) (where \(\rho_w\) and \(\rho_d\) are the masses of water ice and dust particles per unit volume, respectively), \(m_w\) is the molecular mass of water, and \(k\) is the Boltzmann constant. \(\gamma\) denotes the sticking coefficient (Haynes et al. 1992; Enzian et al. 1997), given by

\[
\gamma(T) = -2.1 \times 10^{-3} T + 1.042 (T > 20 \text{ K}) \quad (10)
\]

In Equation (9), the saturated vapor pressure of water, \(P_w(T)\), is given by the Clausius–Clapeyron equation. The mass-loss rate of the dust particles, \(\dot{M}_d\), is therefore given by an integral over the sunlit hemisphere of the spherical body:

\[
\dot{M}_d = \frac{2\pi r^2_{obj} f}{\kappa} \int_0^{\pi/2} \left( \frac{dZ}{dt} \right) \sin z \, dz \, \text{kg}, \quad (11)
\]

where \(f\) is the fractional active area. We used \(\epsilon_E = 0.9\). In this model, there is a large uncertainty in \(\kappa\). It is conventionally assumed to be unity in the literature. Once we fix \(\kappa\), it is possible to determine \(f\) by a comparison with the observed mass-loss rate. We considered five different cases in the range of \(0.1 \leq \kappa \leq 10\) and fit the model results to the observed data at 4.1 AU, adjusting \(f\). Figure 6 shows the heliocentric distance dependence of the dust mass-loss rate. In the figure, we compared the observed dust mass-loss rate with those calculated from the models. Our models reproduce the trend that the dust mass-loss rate decreases with increasing heliocentric distance. However, there are large differences at <3 AU and at the time of the miniburst on 2009 January 5. We infer that there could be remnants of large dust particles in the physical aperture (Stevenson & Jewitt 2012) or that the nucleus was still in an extraordinarily excited state in the aftermath of the 2007 outburst. Infrared space observations of periodic comets suggest that the mass-loss rates of dust trail particles are comparable with those inferred from OH production rates or larger than those inferred from visible-light scattering in comae (Sykes & Walker 1992; Reach et al. 2007; Lisse et al. 2006). A theoretical model to simulate the recurrent outburst nature of 17P/Holmes shows favorable results when \(\kappa = 0.4–0.6\) (Hillman & Prialnik 2012).
MODEL 2 ($\kappa = 0.32$) and MODEL 3 ($\kappa = 1.00$) are therefore reasonable models among these five. When we adopt these models, we can derive the fractional active area, as shown in Figure 7. The fractional active area was 0.20–0.38 over the time of our observations but increased to 0.64 when the miniburst occurred. The $f$ values are larger than the average for short-period comets (<0.2 on average; see, e.g., Tancredi et al. 2006). Note again that the dust mass-loss rate derived from the observation strongly depends on the particle size. If we assume 10 $\mu$m sized particles, the fractional active area is saturated to be unity. Therefore, we conclude that a significant fraction of the surface of 17P/Holmes was still active.

### 3.5. Dust Tail Morphology

So far, we derived the dust mass-loss rate under the assumption of small particles (i.e., $a_d = 1 \mu$m). The model has been widely used in previous research (see, e.g., Luu & Jewitt 1992). It also permits a direct comparison with the previous study of the 17P/Holmes dust mass-loss rate given in Stevenson & Jewitt (2012). However, the existence of large particles as well as micrometer-sized particles is widely confirmed based on telescopic observations (Watanabe et al. 1990; Ishiguro et al. 2002; Sykes & Walker 1992; Fulle 2004; Reach et al. 2007), remote-sensing observations with cameras onboard spacecraft (Sekanina et al. 2004), and in situ measurements of cometary dust particles (McDonnell et al. 1986; Tuzzolino et al. 2003; A’Hearn et al. 2011). The detection of a cometary dust trail associated with 17P/Holmes with Spitzer is definitive evidence that 17P/Holmes had ejected large dust particles (Reach et al. 2010). Furthermore, Moreno et al. (2008) suggested that >600 $\mu$m particles could be ejected by the 2007 outburst. Millimeter-wavelength continuum observations also suggested the existence of submillimeter particles (Altenhoff et al. 2009). We hence examined the dust particle size using our observed composite images.

Orbits of dust grains are, in principle, determined by size and ejection speed. The size of the particle can be parameterized by $\beta_p$, the ratio of the solar radiation pressure to the gravitational attraction. Assuming a spherical particle, we can define $\beta_p$ as

$$\beta_p = \frac{K Q_{pr}}{\rho_d a_d^2},$$

where $a_d$ and $\rho_d$ are the particle radius in meters and the mass density in kg m$^{-3}$, respectively. $K = 5.7 \times 10^{-5}$ g cm$^{-2}$ is a constant, and $Q_{pr}$ is the radiation pressure coefficient averaged over the solar spectrum (Burns et al. 1979). Supposing that particles are compact in shape and large compared with optical wavelengths, we considered $Q_{pr}$ as unity.

As an initial guess, we drew the syndyne and synchrone curves. Syndynes are curves representing a constant value of $\beta_p$ when the ejection velocity is assumed to be zero. Synchrones are curves representing the positions of particles of different sizes (i.e., different $\beta_p$) ejected at the same time with zero velocity. Figure 8 left shows a comparison between the observed contour maps and the syndyne curves of $a_d = 1 \mu$m, 10 $\mu$m, 100 $\mu$m, 1 mm, and 1 cm. We selected two composite images on 2008 December 23 and 2011 January 7 because synchrones and syndynes are well separated in these images. From the syndyne curves, the loci of larger particles, $a_d = 0.1–1$ cm, match the center of the dust tail. This suggests that big particles are dominant in the cross-sectional area in the dust tail. From the synchrone curves, particles ejected more than 1 yr before the observation match the position of the dust tail (Figure 8, right). It is likely that the dust particles ejected soon after the outburst were responsible for the dust tail. Synchrone–syndyne analysis, however, tends to lead to a misleading value of dust sizes (Ishiguro et al. 2007; Fulle 2004). A three-dimensional analysis, which allows nonzero ejection velocities to be considered, is appropriate to estimate the particle sizes and mass-loss rate. Here, we applied a three-dimensional analysis to match the observed images, following the model in Ishiguro et al. (2007), Sarugaku et al. (2007), Ishiguro (2008), and Hanayama et al. (2012).

We assumed that the dust particles were ejected symmetrically with respect to the Sun–comet axis in a cone-shape jet with half-opening angle $w$, implying that the active regions are

![Figure 7. Fraction of active area of the 17P/Holmes nucleus as a function of heliocentric distance. In this figure, we assumed a water ice-to-dust mass ratio of $\kappa = 1$. (A color version of this figure is available in the online journal.)](image-url)
distributed ubiquitously over the surface of the nucleus and therefore that the dust emission occurred homogeneously around the subsolar point. The model also suggests that the dust particles were ejected independently of the rotation of the nucleus. Given that the ejection speed was a power-law function of heliocentric distance, we adopted an empirical function for the ejection terminal velocity of dust particles:

$$V_{ej} = V_0 \left( \frac{\beta_{rp}}{\beta_{rp,0}} \right)^{u_1} \left( \frac{r_h}{r_0} \right)^{-u_2} v,$$  

where $V_0$ is the reference ejection velocity of the particles at $r_h = r_0$. We set $\beta_{rp,0} = 1$ and $r_0 = 1$ AU, respectively. $u_1$ and $u_2$ are the power indices of $\beta_{rp}$ and the heliocentric distance $r_h$ dependence of the ejection velocity. A random variable $v$ follows the Gaussian probability density function, $P(v)$, which is given by the following formula:

$$P(v) = \frac{1}{\sqrt{2\pi}\sigma_v} \exp \left( -\frac{(v - 1)^2}{2\sigma_v^2} \right),$$  

where $\sigma_v$ is standard deviation of $v$. We set $\sigma_v = 0.25$. From this method, most $v$ values (68%) are between $1-\sigma_v$ to $1+\sigma_v$.

A power-law size distribution with index $q$ was used, i.e.,

$$N(a; t)da dt = N_0 \left( \frac{r_h}{r_0} \right)^{-k} \left( \frac{a}{a_0} \right)^{-q} da dt,$$  

in the size range of $a_{min} \leq a \leq a_{max}$.

We derived the above parameters to fit the morphology of the dust cloud. We focused on the positions of the extended dust tail and the flux ratio between the coma and the extended structures. The input and best parameter sets are summarized in Table 3. Figure 9 shows an example simulation image to compare with the observational data on 2008 December 23. From the fitting, we derived a mass-loss rate at 4.1 AU of $>170$ kg s$^{-1}$. Although there are large uncertainties in these best-fit values, it is clear that the resultant mass-loss rate is significantly larger than the rate we derived based on the small-grain model in Section 3.3.

### 3.6. Total Mass and Depth Excavated by the Outburst

We hereby consider the total mass of the ejecta and the depth excavated by the 2007 outburst. There is a large uncertainty in the total mass in the range of $10^{10}$–$10^{13}$ kg (Montalto et al. 2008; Altenhoff et al. 2009; Reach et al. 2010; Ishiguro et al. 2010; Boissier et al. 2012). In addition, little is known about the...
depth excavated by the initial outburst. As discussed in Ishiguro et al. (2010), the power index of the size distribution and the maximum size of the particles are critical factors to derive the total mass. The fraction of the active area is a crucial factor in determining the depth. In the previous subsection, we confirmed that 1 mm–1 cm particles were ejected into the nucleus. The power index of the size distribution was derived to be 3.4–3.6, which is consistent with previous studies (Zubko et al. 2011; Boissier et al. 2012). Moreover, we deduced the fractional active area of 0.20–0.38. It is reasonable to think that 20%–38% of the surface materials were blown out by the initial outburst if the surface conditions remained constant after the outburst. Using these parameters and assuming the mass density of the particles and the nucleus are $\rho_d = 1 \text{ g cm}^{-3}$ and $\rho_n = 0.5 \text{ g cm}^{-3}$, respectively, we could update the total mass and newly derive the depth excavated by the 2007 outburst in the same manner as Ishiguro et al. (2010). We found that the total mass of the ejecta was in the range of $5.3 \times 10^{11} - 6.1 \times 10^{12} \text{ kg}$. The derived mass is consistent with Boissier et al. (2012). In addition, we found that 76–1600 m of surface materials were excavated by the initial outburst. Since the upper limit of the depth, 1600 m, is equivalent to the nuclear radius, our upper limit may not be a realistic estimate. Therefore, we can safely conclude that more than 76 m of surface materials were blown off by the 2007 outburst.

### 3.7. Dust Color

We measured the color of the dust within an aperture radius of 1.0′ plus the nucleus using Subaru data on 2011 June 6. The observed magnitudes are $23.63 \pm 0.10$ (g′ band), $23.15 \pm 0.09$ (r′ band), and $22.64 \pm 0.08$ (z′ band). The photometric magnitudes were converted into VRI magnitudes using the transformation equations from Smith et al. (2002). We derived the color indices $V - R = 0.39 \pm 0.08$ and $R - I = 0.54 \pm 0.07$. These color indices are consistent with those of the nucleus before the outburst, that is, $V - R = 0.41 \pm 0.07$ and $R - I = 0.44 \pm 0.08$ (Snodgrass et al. 2006). They are also similar to the average of Jupiter-family comets but different from most Kuiper Belt objects (Jewitt 2002; Meech et al. 2004). Because the old surface was excavated and the fresh surface was exposed in our data, the color may be inherent to fresh comets, that is, icy bodies in the solar system.

### 4. SUMMARY

We have outlined the observational evidence of 17P/Holmes activity before and after the 2007 outburst and found the followings.

1. The nucleus was highly depleted in its near-surface icy component before the 2007 outburst.

2. It had been active even near its aphelion passage in 2010.

3. The surface fractional active area was 0.58% ± 0.14% before the outburst, whereas it enlarged by a factor of ∼50 after the 2007 outburst under the assumption of a small dust grain model.

4. The nucleus color was similar to that of the dust particles and to the pre-outburst color of the nucleus.

5. More than 76 m of surface materials were blown off by the 2007 outburst.

We expect that long-term monitoring observations during the 2014 perihelion passage and even later will give important information about how the active nucleus depletes its near-surface ice.

We express our gratitude to the participants of the @site program for helping with our observations. We shared a joyful occasion with the public visitors at NHAO. The use of the UH2.2m telescope was supported by NAOJ. HCT observations were assisted by the observatory staff at the IIA. Subaru data were obtained with the support of the National Astronomical Observatory. We particularly thank Dr. Fumiaki Nakata and Dr. Miki Ishii for their observational support and technical advice. The infrared data were acquired with AKARI, a JAXA project with the participation of ESA. A portion of the data were collected with the Subaru Telescope and obtained from SMOKA, which is operated by the Astronomy Data Center, National Astronomical Observatory of Japan. We thank the referee for his/her careful reading and valuable comments. S.H. is supported by the Space Plasma Laboratory, ISAS/JAXA. This work at Seoul National University was supported by a National Research Foundation of Korea (NRF) grant funded by the Korean government (MEST, No. 2012R1A4A1028713).

### APPENDIX

**CONTRIBUTION OF DUST PARTICLES EJECTED THROUGH THE 2007 OUTBURST**

In the second paragraph of Section 3.1, we provided a simple theory to explain the cause of broadening in Figure 3, which helps us to understand the broadening in a straightforward manner. A similar theory was given in Stevenson & Jewitt (2012). It is important to check the consistency of the discussion with the three-dimensional model we provided in Section 3.5. We examined whether the outburst dust particles contributed to the broadening in our images using our three-dimensional model. The motion of the dust particles is more complicated than we discussed in Section 3.2. Dust particles expand because of their initial velocity, but at the same time, some dust particles ejected sunward are affected by solar radiation pressure. Figure 10 shows time-series simulation images of dust particles ejected on 2007 October 23 based on the three-dimensional model. There is no circular envelope as observed in Figures 2(a) and (b), most likely because the model simulates the low-velocity component. In Figure 10, two circles denote aperture radii of 0.2′ and 1′, respectively. Within the aperture, we observed the broadening in all datasets. We found that the brightest part of the cloud, which could contribute to the broadening of the radial profiles, was detached ∼10 months after the outburst. Since our postburst data were taken >11 months after the outburst, dust particles ejected by the outburst could not contribute to the broadening of the radial profiles. It is natural to believe that 17P/Holmes showed a broadened brightness profile because it was active when we made the observations.

![Image](image-url)
Figure 10. Motion of the dust particles ejected by the 2007 outburst based on the model in Section 3.5. Each panel shows the simulation image with a contour map on day $\Delta T$ after the outburst. The two circles correspond to apparent angular distances of 0.2 and 1$. These images have the standard orientation on the sky, that is, celestial north is up and east is to the left. The field of view is 7$''$ × 7$''$.

(A color version of this figure is available in the online journal.)

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