DETECTION OF REMNANT DUST CLOUD ASSOCIATED WITH THE 2007 OUTBURST OF 17P/HOLMES

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ABSTRACT

This article reports a new optical observation of 17P/Holmes one orbital period after the historical outburst event in 2007. We detected not only a common dust tail near the nucleus but also a long narrow structure that extended along the position angle 274°6 ± 0°1 beyond the field of view (FOV) of the Kiso Wide Field Camera, i.e., >0°2 eastward and >2°5 westward from the nuclear position. The width of the structure decreased westward with increasing distance from the nucleus. We obtained the total cross section of the long extended structure in the FOV, \( C_{\text{FOV}} = (2.3 \pm 0.5) \times 10^{10} \) m\(^2\). From the position angle, morphology, and mass, we concluded that the long narrow structure consists of materials ejected during the 2007 outburst. On the basis of the dynamical behavior of dust grains in the solar radiation field, we estimated that the long narrow structure would be composed of 1 mm–1 cm grains having an ejection velocity of >50 m s\(^{-1}\). The velocity was more than one order of magnitude faster than that of millimeter–centimeter grains from typical comets around a heliocentric distance \( r_h \) of 2.5 AU. We considered that sudden sublimation of a large amount of water-ice (\( \approx 10^{10} \) mol s\(^{-1}\)) would be responsible for the high ejection velocity. We finally estimated a total mass of \( M_{\text{TOT}} = (4–8) \times 10^{11} \) kg and a total kinetic energy of \( E_{\text{TOT}} = (1–6) \times 10^{15} \) J for the 2007 outburst ejecta, which are consistent with those of previous studies that were conducted soon after the outburst.

Key words: comets: general – comets: individual (17P/Holmes) – interplanetary medium – meteorites, meteors, meteoroids

1. INTRODUCTION

This article provides a new optical observation of 17P/Holmes in 2014 using a wide-field camera recently available at the Kiso Observatory, when it was located at the position of the 2007 outburst.

An unprecedented cometary outburst occurred at 17P/Holmes on UT 2007 October 23, brightening by about 1 million times within a day (Sekanina 2009; Hsieh et al. 2010). Soon after, the comet was enclosed by an envelope composed of high-speed dust grains. The envelope became undetectable in about a year because of solar radiation pressure, as well as its high ejection velocity, leaving behind a near-nuclear dust cloud. Afterward, the comet remained active for years, showing a minor outburst (Stevenson et al. 2010) and lingering dust ejection at 4–5 AU (Ishiguro et al. 2013). An analysis of the faint dust tail in the infrared suggested that it could contain trailing dust particles ejected during the 2007 outburst (Stevenson et al. 2014).

Big particles from comets are widely observed through telescopic observations and remote-sensing observations with spacecraft (see, e.g., Ishiguro et al. 2002; Rotundi et al. 2015). These large particles can stay close to the orbits of parent bodies for many revolutions around the Sun and form “dust tails,” which are occasionally discriminated from “dust tails” consisting of fresh dust particles ejected during current returns. The neck line is a substructure rarely detected in dust tails (and in dust trails, in principle), which is caused by a dynamical effect. Theoretically, dust particles ejected at a point (first node) converge on the orbital plane of the parent body at the opposite end viewed from the Sun (the second node, i.e., the differential true anomaly between the dust ejection point and the observed location is 180°). The accumulation of the dust particles enhances the surface brightness of the dust cloud, as first proposed by Kimura & Liu (1977); see also Fulle & Sedmak (1988). An analogous phenomenon essentially occurs when dust particles complete one orbital revolution (i.e., the third node). Taking advantage of the neck-line effect, we aimed to detect the debris cloud ejected from the 2007 outburst. We describe the observation and data reduction in Section 2 and diagnose the observed image in Section 3 on the basis of photometric and dynamical properties. As a result, we could obtain indubitable evidence for the debris cloud associated with the 2007 outburst. We derived the velocity, mass, and total kinetic energy of the outburst grains using our new observation data to deepen our understanding of the historical event.

2. OBSERVATION AND DATA ANALYSIS

We imaged 17P/Holmes in the \( R_c \) band for four nights on UT 2014 September 18, 22–23, and 25 with the Kiso Wide Field Camera (KWFC) attached to the 105 cm Schmidt
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Figure 1. Example of an $R_C$-band (wavelength $0.64 \mu m$) full-scale ($2^\circ 2 \times 1^\circ 1$) snapshot image taken at UT 17:09, 2014 September 22. The location of the comet is indicated by the arrow. The cometary tail was unclear in the snapshot because of contamination by stars and diffuse galactic light.

telescope operated by the Kiso Observatory, University of Tokyo. The KWFC is a mosaic CCD camera consisting of eight CCD chips with a total of $8k \times 8k$ pixels (Sako et al. 2012). The combined system provides a $2^\circ 2 \times 2^\circ 2$ field of view (FOV) with a moderate pixel resolution ($0^\circ 946$ pixel$^{-1}$). We used the lower half of the KWFC for our observation to reduce the readout time (from 144 to 68 s), so the instrument covered $2^\circ 2 \times 1^\circ 1$ on the sky plane in a single snapshot with four CCD chips (see Figure 1). Because the telescope can be operated only in a sidereal tracking mode, we could not take longer exposures. We set the individual exposure time to 180 s, during which the comet moved by $1^\circ 75$, which is larger than the pixel scale but still less than half of the typical seeing disk size at the observatory (i.e., an FWHM of $3^\prime 3 \sim 5^\prime 3$; Morokuma et al. 2014). We took images of 17P/Holmes on UT 2014 September 18 and 22–23 in the range between $\sim 0^\circ 2$ eastward and $\sim 2^\circ$ westward from the nucleus position. In addition, we contrived to take images on UT 2014 September 25 with a wide coverage, within $6^\circ$ westward from the nucleus, scanning along the projected orbit of the comet.

Only the images on UT 2014 September 22 are available for study because the sky background was too high to detect the faint structure on UT 2014 September 18 owing to moonlight, the weather conditions were bad because of a typhoon (known as Tropical Storm Fung-wong) on UT September 23, and the total exposure time was insufficient to subtract the background objects on UT 2014 September 25. For these reasons, we focused on analysis of images taken on UT September 22. On that night, we took 60 snapshot images (i.e., a total exposure time of 3 hr) at UT 15:11–19:35, when the comet was at a heliocentric distance $r_h$ of 2.464 AU, an observer’s distance $\Delta$ of 2.094 AU, and a phase angle (Sun–comet–observer angle) $\alpha$ of $23^\circ 7$. The true anomaly was $\theta_{TA} = 63^\circ 1$, slightly larger than that of the 2007 outburst, $\theta_{TA} = 61^\circ 1$. In this configuration, the convergent point exists at $2^\circ 7$ westward from the nucleus.

The observed data were preprocessed using bias and dome flat images. Figure 1 shows an example snapshot image after bias and flat-field correction. There are $\sim 1^\prime$ gaps between each CCD chip. Because we employed the dithering operation mode for the telescope, the gaps are mostly (but not perfectly) eliminated by multiple exposures. In the snapshot, the comet and dust cloud are unclear because they were located in the star-crowded area near the galactic plane (galactic latitude $b \sim 2^\circ$). Accordingly, we paid close attention to elimination of background components. We thus subtracted the background stars and diffuse interstellar cirri using images taken on the next night (UT 2014 September 23) when the comet had moved northeastward by $1^\circ$. Moreover, we masked the position of stars brighter than $R_C \sim 22$ in the images after star and cirrus subtraction to eliminate the remnants caused by misalignment of the stellar positions. We then combined 60 masked images according to the motion of the comet nucleus, excluding the masked regions. The defective pixels and CCD gaps are also excluded by the image combination process. Flux calibration was conducted using field stars archived in the UCAC3 catalog, ensuring a photometric accuracy of $\sim 0.1$ mag or less (Zacharias et al. 2010). Geometrical correction was performed by comparison with the astrometric data in the USNO B1.0 catalog (Monet et al. 2003). The positional error of the USNO B1.0 catalog, $\sim 0^\prime 4$, is good enough that we can discuss the position angle and morphology of the dust structure in this study.

3. RESULTS

3.1. Appearance

Figure 2 shows a composite image taken on UT 2014 September 22 after background objects and instrumental
artifacts were subtracted. The figure shows not only a cometary tail near the nuclear position (a whitish cloud in the lower left corner) but also a long structure extending from the lower left (southeast) to the upper right (northwest). It spreads to both sides beyond the FOV of the KWFC (>2″2). We hereafter analyze these cloud morphologies as shown below.

3.1.1. Near-nuclear Dust Tail and Coma

Figure 3 shows a close-up of the contours of the near-nuclear dust tail. It extended between the negative heliocentric velocity vector (at a position angle, P.A. = 275°±4) and the antisolar direction (P.A. = 260°±1). In Figure 3, we show a close-up of the contours (loci of positions of particles having a wide range of sizes released at given times, Tej) and syndynes (loci of positions of particles of a given size, order, having a wide range of ejection epochs). Although these lines are not separated well, we roughly estimated the dust ejection epoch and particle size. We determined the locus of the maximum brightness of the dust tail using least-squares fitting with a Gaussian function in every 1″ bin and found that the dust tail extended to P. A. = 270° ± 0°±2, which corresponds to the synchrone of Tej ~ 180–360 days before the observation. Because the comet was observed 179 days after the perihelion passage, it is likely that the near-nuclear dust tail consisted of particles ejected during the perihelion passage in 2015. From comparison with the syndynes, we estimate an effective particle radius of 10 μm –1 mm for the near-nuclear tail.

We visually set the sunward extent of the dust coma to ~40″, which corresponds to the distance projected on the sky plane, \( l = 6 \times 10^7 \) m, at the position of the comet. Considering \( l \) as the turnaround distance of dust particles ejected toward the solar direction while being pushed by solar radiation pressure, we placed a limitation on the ejection velocity, \( V = 340\sqrt{\beta} \text{ m s}^{-1} \), where \( \beta \) denotes the ratio of the solar radiation pressure with respect to the solar gravity (Jewitt & Meech 1987). In the possible size range (10 μm–1 mm, or \( \beta = 5.7 \times 10^{-2} - 5.7 \times 10^{-5} \)), we estimated an ejection velocity \( V \) of 8 m s\(^{-1} \) for 1 mm particles and 80 m s\(^{-1} \) for 10 μm particles. Although we understand that these are very crude estimates, the derived velocity is typical of dust emission from Jupiter-family comets (JFCs) at \( r_h \sim 2.5 \) AU (Ishiguro et al. 2007; Ishiguro 2008). Thus, 17P/Holmes changed from its peculiar appearance just after the 2007 outburst to an appearance typical of JFCs in only one orbital revolution.

We measured A\( \rho \) values with differential aperture size from 5000 km (3″3, equivalent to 1×FWHM) to 50,000 km at intervals of 5000 km, and we obtained almost constant values of A\( \rho = 139-141 \) cm within 10,000 km but found significant drops due to the radiation pressure. The A\( \rho \) value is typical of general comets listed in A’Hearn et al. (1995) (~10\(^{-3} \)–10\(^{-4} \) cm around 2.5 AU).

3.1.2. Long Extended Structure

The prominent feature is the long narrow structure. There could be four possibilities to create such long extended structure: (1) dust tail (i.e., dust particles ejected during the current return), (2) ion tail, (3) dust trail, and (4) neck line. We measured a position angle of 274°6 ± 0°1, which deviates significantly from that of the antisolar direction (P.A. = 260°±1) but is very close to that of the negative heliocentric velocity vector (P.A. = 275°±4). It also coincides with the direction of the synchrone of the 2007 outburst epoch (i.e., Tej = −2526 days = 817:77...818 days). Hatched diagonal lines from upper left to lower right are loci of sizes released at given times, \( \alpha = 23°7 \). The shadowed region is caused by image subtraction using an image taken on UT 2014 September 23 (see Section 2). Hatched diagonal lines from upper left to lower right are remnants of background stars that could not be subtracted using our data reduction algorithm. Vertical lines in the center are a relic of the CCD gap. Antisolar direction and negative velocity vector are indicated by "r_0" and "−v_0," respectively. The image has a standard orientation in the sky; that is, north is up, and east is to the left. The FOV is 130″ × 25″.
days in Figure 3), although the time resolution of the synchrotron analysis is not sufficiently accurate to specify the exact ejection epoch. This fact indicates that the long narrow structure is associated with neither (1) the dust tail nor (2) the ion tail, but with either (3) the dust trail or (4) the line neck (i.e., a swarm of dust particles ejected during the last perihelion passage or even before). It is interesting to consider why the comet has this spectacular long extended structure, although the near-nuclear dust tail looks typical of JFCs, as we mentioned above (Section 3.1.1).

We examined the surface brightness and width. Figure 4 shows the surface cut profiles perpendicular to the long extended structure, where we averaged the brightness along the extended direction (P.A. = 274°6) in the bin length of 6′. The structure was unclear at the distance +3′ < l < +9′ because the bright near-nuclear dust tail overlapped the faint extended structure. We fitted the background sky brightness by third-order polynomials and obtained the peak brightness and FWHM. Figure 5 shows the result. The FWHM clearly increased as the peak brightness decreased from west to east. The peak brightness is in the range of 26.2–27.0 mag arcsec−2, which is equivalent to those of some bright cometary dust trails such as 67P/Churyumov–Gerasimenko (Ishiguro 2008) and 22P/Kopff (Ishiguro et al. 2002). It is, however, important to notice that the shape and brightness distributions differ from general dust trails. As shown in some papers (see, e.g., Sykes 1990; Ishiguro et al. 2002, 2003), dust trails show narrowing toward the nucleus. In addition, the fading toward the nucleus is inconsistent with the dust trail structure of 17P/Holmes detected by Spitzer observation, where the brightness increased toward the nucleus (Reach et al. 2010). Thus, the long extended structure in our 17P/Holmes image could be unlike the typical dust trail structures seen to date.

### 3.2. Photometry of the Long Extended Structure

To determine the surface brightness profile of the long extended structure, we summed up the signal from the extended structure. We set a rectangular aperture box of 2′ × 2′2. After subtracting the sky background, which was determined at 1′–3′ from the trail center on both the north and south sides, we obtained the total Rc magnitude of mR = 12.3 ± 0.2 in the WFC3 FOV. The observed Rc magnitude was converted to the absolute magnitude (i.e., corrected to unit heliocentric and geocentric distances at zero phase angle) using

\[
H_R = m_R - 5 \log_{10} (r_h \Delta) - 2.5 \log_{10}(\Phi(\alpha)),
\]

where the term \(\log_{10}(\Phi(\alpha))\) characterizes the scattering phase function of dust grains. Using a commonly used formula, \(\log_{10}(\Phi(\alpha)) = 0.035\alpha\), and substituting \(r_h = 2.464\) AU, \(\Delta = 2.094\) AU, and \(\alpha = 23°7\), we obtained \(H_R = m_R - 4.4\) = 7.9 ± 0.2. The absolute magnitude is converted into the cross
section by the following equation (Russell 1916): 
\[
C_{\text{FOV}} = \frac{2.24\pi \times 10^{22} \times 10^{0.4(m - H_k)}}{p_R},
\]
where \(m_\odot = -27.1\) is the \(R_C\) magnitude of the Sun (Drilling & Landolt 2000, p. 381) and \(p_R\) is the geometric albedo in the \(R_C\) band. Assuming \(p_R = 0.04\), which is often used for cometary grains, we obtained \(C_{\text{FOV}} = (2.3 \pm 0.5) \times 10^{10} \text{m}^2\).

The grain mass can be derived as \(M_{\text{FOV}} = \frac{4}{3}C_{\text{FOV}} d_a\rho_a\), where \(d_a\) and \(\rho_a\) are the grain radius and mass density, respectively. From the synchronization analysis (see Figure 3), the long extended structure extended to the upper right (along the negative velocity vector, \(v\)), which is consistent with dust particles of \(d_a \gtrsim 1\) mm but inconsistent with \(d_a \lesssim 100\) \(\mu\)m. Assuming \(\rho_a = 10^3\) kg m\(^{-3}\), we obtained \(M_{\text{FOV}} = 3 \times 10^{10} \text{kg}\) (when \(d_a = 1\) mm) or \(M_{\text{FOV}} = 3 \times 10^{11} \text{kg}\) (when \(d_a = 1\) cm). It is important to note that the derived mass is the lower limit because the dust particles extended beyond the FOV. Nevertheless, we can use the \(M_{\text{FOV}}\) value to identify the origin of the long extended structure. The dust production rate of 17P/Holmes was \(\sim 3\) kg s\(^{-1}\) around its perihelion before the 2007 outburst (Ishiguro et al. 2013). Supposing that a comet loses most of its mass at a constant rate within 2.5 AU, which corresponds to a duration of about a year, 17P/Holmes was expected to lose about \(10^8\) kg in total during the last perihelion passage, except for the outburst. The mass is significantly (more than two orders of magnitude) smaller than the mass of the long extended structure in the KWFC FOV. In contrast, the total mass of the outburst ejecta was derived as \(10^{10}-10^{13}\) kg (Montalto et al. 2008; Allenhoff et al. 2009; Ishiguro et al. 2010; Reach et al. 2010; Boissier et al. 2012). The mass of the long extended structure is equivalent to or smaller than the total ejecta mass of the 2007 outburst. Together with the position angle and morphology we mentioned above, we conclude that the long extended structure is a part of the dust cloud ejected during the 2007 outburst but is tentatively detected by our observation because of the convergence effect (i.e., the neck-line effect). In Section 4, we further investigate the physical properties of the long extended structure, regarding it as a remnant dust ejecta during the 2007 outburst.

4. THE DYNAMICAL MODEL

We conducted a model simulation of dust particles ejected during the 2007 outburst to derive the size and ejection velocity of the 2007 outburst ejecta. The basic theory is essentially the same as that described in Ishiguro et al. (2014). In the model, the motion of dust particles is governed by the ejection velocity \((V)\) and the solar radiation pressure (parameterized by \(\beta\), the ratio of the radiation pressure acceleration to solar gravity, which is the same as \(\beta\) in Section 3.1.1). For spherical compact particles with a mass density of \(\rho_a\) (kg m\(^{-3}\)) and a radius of \(d_a\) (m), it is written as \(\beta = 5.7 \times 10^{-4} \rho_a^{-1} d_a^{-1}\) (Finson & Probstin 1968; Burns et al. 1979). The modeled images were generated by the Monte Carlo approach assuming the velocity and size distribution. Positions of dust particles at the observed epoch were calculated semianalytically by solving the Kepler equations rigorously.

4.1. Size Estimate

As a first step, we considered a simple impulsive dust ejection model in which the dust cloud consists of dust particles with a uniform size and ejection velocity. Assuming \(\rho_a = 10^3\) kg m\(^{-3}\) and isotropic dust ejection (i.e., particles are ejected equally in all directions), we simulated \(a_d = 100\) \(\mu\)m particles and \(a_d = 1\) cm particles in a possible velocity range of \(V = 5-500\) m s\(^{-1}\). The upper limit of \(V\) is comparable to the highest dust velocity in the outburst envelope (i.e., 554 m s\(^{-1}\), Lin et al. 2009), whereas the lower limit is close to the escape velocity \((V_{\text{esc}} = 1.5\) m s\(^{-1}\)) from the nucleus with \(R_N = 2080\) m (Stevenson et al. 2014) and a bulk density of 1000 kg m\(^{-3}\). Figures 6 and 7 show the resultant simulated images. In Figure 6, the width and length of the neck-line structure increase as \(V\) increases. The convergent point appears about 25°7 rightward of the nucleus, showing the strongest intensity enhancement (i.e., neck-line structure). These models qualitatively reproduce the observed narrowing and brightening from east to west. A visual comparison yielded an order-of-magnitude estimate of the ejection velocity of \(V \approx 50\) m s\(^{-1}\) for 1 cm particles. For 100 \(\mu\)m particles with low \(V < 50\) m s\(^{-1}\), the dust cloud was blown off westward beyond the FOV, because such small dust particles are susceptible to solar radiation pressure and are strongly accelerated toward the negative velocity vector (i.e., western direction) (Figures 7(a) and (b)). The increase in ejection velocity would enlarge the dust cloud in every direction, having the cloud appear in the FOV of the KWFC. However, we noticed that 100 \(\mu\)m is too small to be detected in the KWFC FOV. If we increase \(V\) to be observable in the FOV, it should have a width much wider than what we observed (e.g., Figure 7(c)). To summarize the uniform size model, we applied constraints of \(a_d \gtrsim 100\) \(\mu\)m and \(V \approx 50\) m s\(^{-1}\).

4.2. Model with Arbitrary Size and Velocity

Second, we employed a more realistic model having a power-law size distribution and velocity distribution for the neck-line structure. We assumed that the number of dust particles was

\[
N(a_d) da_d = N_0 \left(\frac{a_d}{a_0}\right)^q da_d
\]

in the size range \(a_{\text{min}} \leq a_d \leq a_{\text{max}}\), where \(a_{\text{min}}\) and \(a_{\text{max}}\) are the minimum and maximum particle sizes detectable in the KWFC FOV, respectively. Further, \(a_0\) is the reference size of dust particles (we set \(a_0 = 1\) cm and \(a_{\text{min}} = 100\) \(\mu\)m following the result of the uniform size model above). We use the following function for the ejection terminal velocity of dust particles:

\[
V = V_0 \left(\frac{a_d}{a_0}\right)^v, \quad v,
\]

where \(v\) is a random variable having an average of 1 and a standard deviation \(\sigma_v\) (see, e.g., Ishiguro et al. 2014). We set \(\sigma_v = 0.1\), which was the value obtained from a similar outburst at P/2010 V1. Note that \(v\) makes a minor contribution to the spatial distribution of dust particles when \(\sigma_v \ll 1\). Now we have five variables \((N_0, a_{\text{max}}, q, V_0, \sigma_v)\). Among them, \(N_0\) can be determined by scaling the simulation intensity to the observed one once the other four parameters are fixed. We thus created a number of simulation images to find the best-fit parameter set assuming \(a_{\text{max}} = 1\) cm, 10 cm, and 1 m in \(-4.5 \leq q \leq -3.0\) at the interval of \(\Delta q = 0.1\),
The simulation revealed several trends. The width of the neck-line structure increases as $V_0$ increases. Further, $q$ is also sensitive to the width. The width increases when $q$ is small, because small particles with higher velocity are efficient scatterers for smaller $q$. We compared the width and intensity distribution with respect to the distance from the nucleus with those of the model simulation. We found that the leftmost data point does not match any model probably because the data were contaminated by an unconsidered error source (such as the remnant of background stars or imperfect flat-fielding), and thus we ignored it. We obtained the best-fit parameters via the $\chi^2$ test, $q = -3.4 \pm 0.1$, $V_0 = 50 \pm 10$ m s$^{-1}$, and $u = 0.3 \pm 0.1$. We appended the errors of these parameters when simulation results matched the observed results to an accuracy of the measurement. In the parameter range above, $a_{\text{max}}$ is less determined (although we got the constraint of $a_{\text{max}} > 1$ cm) because such large particles are supposed to stay near the comet nucleus while such a signature from the biggest particles was obscured by the bright dust tail and coma.
5. DISCUSSION

5.1. Velocity

An unexpected result is the high ejection velocity for 1 mm–1 cm particles in the neck-line structure. Before this observation, we predicted an ejection velocity of several meters per second for various reasons. First, we predicted the low ejection velocity as an analog of cometary dust trails. They consist of 1 mm–1 cm particles with an ejection velocity of several meters per second, which is marginally larger than that of the escape velocities from kilometer-sized bodies (Sykes & Walker 1992; Ishiguro et al. 2002). In addition, the velocity of the smallest (probably 0.1–1 μm) particles for the 2007 outburst was estimated to be 554 m s\(^{-1}\) (Lin et al. 2009). If we extrapolate the velocity of 1 cm particles using the inverse square law of the grain size, we would have 2–6 m s\(^{-1}\). Figure 8 shows the velocity of the dust particles with respect to the grain size. For comparison, we show the velocity predicted using the classical model developed by Whipple (1951). The model has been widely applied to characterize the velocity–size law. The velocity in the classical model is found to be in good agreement with that of fresh dust particles in the coma (see Section 3.1.1) but more than one order of magnitude smaller than those of dust particles in the neck-line structure. The discrepancy may suggest that dust ejection in the 17P/Holmes outburst differed from ejection due to normal sublimation by solar heating.

To compensate for the large discrepancy in the ejection velocity, we reviewed the formula in the Whipple model. In the generalized formula of the Whipple theory, it is written as

\[
\frac{\text{d} M}{\text{d} t} = \frac{2GM_\text{N}}{R_\text{N}^2} \sqrt{\frac{k_{\text{drag}} \Delta M \sigma g}{2\pi R_\text{N}^2 m}} - \frac{2GM_\text{N}}{R_\text{N}},
\]

where \(k_{\text{drag}}\) is a drag coefficient, usually assumed to be \(k_{\text{drag}} = 26/9\), and \(m\) and \(A\) are the mass and cross-sectional area, respectively, of the dust particles. For spherical particles, they are written as \(m = 4/3\pi R_\text{N}^3\) and \(A = \pi R_\text{N}^2\). \(M_\text{N}\) is the mass of a nucleus having a radius \(R_\text{N}\). Assuming a spherical body with a mass density \(\rho_\text{N}\), it is written as \(M_\text{N} = 4\pi R_\text{N}^3\rho_\text{N}/3\). Note that the second term in the square root makes a minor contribution when \(V\) is significantly larger than the escape velocity \(V_{\text{esc}}\) where \(V_{\text{esc}} = 1.5\text{ m s}^{-1}\) for 17P/Holmes (\(R_\text{N} = 2080\text{ m}\) and \(\rho_\text{N} = 10^3\text{ kg m}^{-3}\) are assumed). \(\Delta M\) is the mass-loss rate of the gas. Assuming that dust particles are accelerated by water molecules, we can write \(\Delta M = \mu_{\text{H}_2\text{O}} Q_{\text{H}_2\text{O}}\). \(\bar{v}_g\) is the velocity of the water vapor outflow.

In this model, there are several unknown parameters. We adopted \(\bar{v}_g = 550\text{ m s}^{-1}\), which corresponds to the maximum velocity of dust particles in the outburst envelope (Lin et al. 2009) and is also equivalent to the assumed gas velocity in Dello Russo et al. (2008). The water production rate, \(Q_{\text{H}_2\text{O}}\), was determined by several authors; the obtained values include \(Q_{\text{H}_2\text{O}} = (1.2–1.4) \times 10^{27}\text{ mol s}^{-1}\) on UT 2007 October 25–27 (Combi et al. 2007), \(Q_{\text{H}_2\text{O}} = 4.5 \times 10^{29}\text{ mol s}^{-1}\) on UT 2007 October 27.6 (Dello Russo et al. 2008), and \(Q_{\text{H}_2\text{O}} = 5 \times 10^{29}\text{ mol s}^{-1}\) on UT 2007 November 01.2 (Schleicher 2009). We adopted \(Q_{\text{H}_2\text{O}} = 1 \times 10^{30}\text{ mol s}^{-1}\). Assuming the mass densities of the dust particles \(\rho_\text{A} = 10^3\text{ kg m}^{-3}\), we obtained the size–velocity law (thick dashed line in Figure 8). Although there are uncertainties in \(Q_{\text{H}_2\text{O}}\) and \(\bar{v}_g\), the model velocity coincides with the observed velocity to within a factor of \(\leq 2\). We guess that this trivial difference can be explained by the simplifications in the model. For example, the term \(2\pi\bar{v}_g\) in the denominator of Equation (5) was obtained assuming hemispherical dust emission. It can be \(< 2\pi\bar{v}_g\) in a realistic case when the dust particles were ejected from limited active areas on the surface, increasing the ejection velocity (also described in Hughes 2000). In addition, the gas velocity would be increased via adiabatic expansion into space. These effects may result in a dust velocity higher than that in the generalized Whipple model. We thus conclude that a sudden sublimation of a large amount of water-ice (\(\approx 10^{30}\text{ mol s}^{-1}\)) would be responsible for the high ejection velocity of the remnant dust debris in our observed image.

5.2. Mass and Total Kinetic Energy of the Outburst Grains

The total mass of the outburst ejecta has been derived by many researchers using different techniques. It differs substantially depending on the author, i.e., \(10^{10}–10^{14}\text{ kg}\) (Montalto et al. 2008; Altenhoff et al. 2009; Ishiguro et al. 2010; Reach et al. 2010; Li et al. 2011; Boissier et al. 2012; Ishiguro et al. 2013). As discussed in many papers, there is an intrinsic problem in the determination of the mass of cometary dust because the scattering cross section is dominated by the smallest particles, whereas the mass of the largest particles in the differential size frequency distribution has a power index of \(-3 < q < -4\). The dust cloud of 17P/Holmes may be no exception. Zubko et al. (2011) studied the polarimetric property of
of 17P/Holmes outburst ejecta and found that the size distribution has the power index $q \sim -3.5$.

From our dynamical model, we found that the total cross section of the dust grains in the KWFC FOV is about 5%–10% of the total dust cloud in the size range of $a_d = 100 \mu m$–1 cm. Considering the size distribution with an index of $q = -3.4 \pm 0.1$ in the size range $a_d = 100 \mu m$–1 cm, which were obtained by the dynamical model in Section 4, we obtained a mass of $M_{100 \mu m} = (3.6-7.2) \times 10^{11}$ kg for the neck-line particles (i.e., big remnant particles). If we integrate down to submicron particles (i.e., $a_{\min} = 0.6 \mu m$; Zubko et al. 2011), we derive a total mass of $M_{TOT} = (3.8-7.7) \times 10^{11}$ kg for the 2007 outburst ejecta, which is almost the same as $M_{100 \mu m}$ because largest grains make up most of the mass. The mass also shows good consistency with several previous studies, such as a radio continuum observation by Boissier et al. (2012), and is consistent with the upper limit in Li et al. (2011). The kinetic energy of large dust particles ($a_d = 100 \mu m$–1 cm) is estimated to be $E_{100 \mu m} = (7-14) \times 10^{14}$J. Similarly, if we integrate down to 0.6 $\mu m$-sized particles, we get $E_{TOT} = (1-6) \times 10^{15}$J. The energy per unit mass is less than 20% of the energy released during the crystallization of amorphous water-ice. As already described in Li et al. (2011), our results may imply that the outburst can be caused by the crystallization of buried amorphous ice.

It is interesting to notice that a large amount of big dust particles was injected into the interplanetary space by a single outburst event and survived for $>7$ yr without melting or disintegrating the structure and observed as the neck-line structure. The cometary dust particles will probably disperse in the interplanetary field via planetary perturbations and constitute a portion of the zodiacal cloud (Vaubillon et al. 2004). There is a long-standing question about the origin of the zodiacal dust cloud because it erodes by the Poynting–Robertson effect and mutual collision among particles. We estimated the contribution of cometary dust particles via 17P-like outbursts. It is not clear how often such big cometary outbursts occurred. We assumed the frequency of 0.1–1 per century because the comet exhibited similar (but slightly weaker) outburst in the nineteenth century (Reach et al. 2010). Multiplying the frequency by $M_{TOT}$, we obtained a crude estimate of 12–240 kg s$^{-1}$. Although there should be a large uncertainty in the rate, ejecta by 17P-like outburst would account for (0.1%–2.4%) of the required mass to sustain the zodiacal cloud (i.e., $10^4$ kg s$^{-1}$; Mann et al. 2006). Therefore, we speculate that some fraction of zodiacal dust might be generated by 17P-like outbursts and remain in the interplanetary space for a long time to be observable as zodiacal light.

6. SUMMARY

We observed 17P/Holmes in 2014 September using a wide-field imaging camera, the KWFC attached to the Kiso 105 cm Schmidt Telescope. We found the following:

1. 17P/Holmes consisted of two components: a near-nuclear fresh dust tail and a long extended structure.
2. The long structure extended along the position angle of 274$^{\circ}$6 $\pm$ 0$^{\circ}$1 on UT 2014 September 22 and showed westward brightening and narrowing, confirming that it was composed of dust grains ejected during the 2007 outburst.
3. The FWHM and intensity are in the range of 30$^{\circ}$–70$^{\circ}$ and $(1.5–3.1) \times 10^{-8}$ W m$^{-2}$ sr$^{-1}$ $\mu$m$^{-1}$ in the R$_C$ band.
4. The typical size of the particles is 1 mm–1 cm on the basis of a comparison with a dynamical model.
5. The ejection speed is around 50 m s$^{-1}$ or even more, which is faster than the values of submicron grains extrapolated using a simple −1/2 law. We conjecture that the high velocity would result from the sudden sublimation of the icy component.
6. The total mass and kinetic energy of the 2007 outburst ejecta were $(4–8) \times 10^{11}$ kg and $(1–6) \times 10^{15}$ J. These are consistent with but more accurate than previous studies.

This observation was conducted until 1 day before a terrible volcanic eruption occurred at Mt. Ontake, which is located about 15 km from the observatory. We offer our sincere sympathy to the victims and hope for a rapid recovery for both the people and areas affected by the disaster.

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