2014–2015 MULTIPLE OUTBURSTS OF 15P/FINLAY

Masateru Ishiguro, DaiSUKE KuroDA, Hidekazu HanayaM, Yuna Grace Kwon, Yoonyoung Kim, MYung Gyoon Lee, MAKoto WatAnabe, Hiroshi Akitaya, Koji Kawabata, Ryosuke Itoh, Tatsuya Nakaoka, Michtoshi Yoshida, Masataka ImA, Yuki Sarugaku, KensiYi Yanagisawa, Kouji Ohta, Nobuyuki Kawai, Takeshi Miyah, Hideo Fukushima, Satoshi Honda, Jun Takahashi, Mikiya Sato, Jerome J. VaubailIon, and Jun-ichi WatAnabe

1 Department of Physics and Astronomy, Seoul National University, Gwanak, Seoul 151-742, Korea; ishiguro@astro.snu.ac.kr
2 Okayama Astrophysical Observatory, National Astronomical Observatory of Japan, Asakuchi, Okayama 719-0232, Japan
3 Ishigakijima Astronomical Observatory, National Astronomical Observatory of Japan, 1024-1 Arakawa, Ishigaki, Okinawa 907-0024, Japan
4 Department of Applied Physics, Faculty of Science, Okayama University of Science, 1-1 Ridai-cho, Okayama-si, Okayama 700-0005, Japan
5 Hiroshima Astrophysical Science Center, Hiroshima University, Higashihiroshima, Hiroshima 739-8526, Japan
6 Department of Cosmosciences, Graduate School of Science, Hokkaido University, Kita-ku, Sapporo 060-0810, Japan
7 Kiso Observatory, Institute of Astronomy, Graduate School of Science, The University of Tokyo, Mitake, Kiso-machi, Kiso, Nagano, 397-0101, Japan
8 Department of Astronomy, Kyoto University, Kyoto 606-8502, Japan
9 Department of Physics, Tokyo Institute of Technology 2-12-1 Ookayama, Meguro-ku, Tokyo 152-8551, Japan
10 National Astronomical Observatory of Japan, Mitaka, Tokyo, 181-8588, Japan
11 Nishi-Harima Astronomical Observatory, Center for Astronomy, University of Hyogo, Sayo, Hyogo 679-5313, Japan
12 Kawasaki Municipal Science Museum, Kawasaki, Kanagawa 214-0032, Japan
13 Observatoire de Paris, I.M.C.C.E., Denfert Rochereau, Bat. A., F-75014 Paris, France

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ABSTRACT

Multiple outbursts of a Jupiter-family comet (JFC), 15P/Finlay, occurred from late 2014 to early 2015. We conducted an observation of the comet after the first outburst and subsequently witnessed another outburst on 2015 January 15.6–15.7. The gas, consisting mostly of C2 and CN, and dust particles expanded at speeds of 1110 ± 180 m s⁻¹ and 570 ± 40 m s⁻¹ at a heliocentric distance of 1.0 au. We estimated the maximum ratio of solar radiation pressure with respect to the solar gravity βmax = 1.6 ± 0.2, which is consistent with porous dust particles composed of silicates and organics. We found that 10⁶–10⁷ kg of dust particles (assumed to be 0.3 μm–1 mm) were ejected through each outburst. Although the total mass is three orders of magnitude smaller than that of the 17P/Holmes event observed in 2007, the kinetic energy per unit mass (10⁴ J kg⁻¹) is equivalent to the estimated values of 17P/Holmes and 332P/2010 V1 (Ikeya–Murakami), suggesting that the outbursts were caused by a similar physical mechanism. From a survey of cometary outbursts on the basis of voluntary reports, we conjecture that 15P/Finlay-class outbursts occur >1.5 times annually and inject dust particles from JFCs and Encke-type comets into interplanetary space at a rate of ~10 kg s⁻¹ or more.

Key words: comets: individual (15P/Finlay) – interplanetary medium – meteorites, meteors, meteoroids

1. INTRODUCTION

15P/Finlay (hereafter 15P) was an undistinguished comet discovered by William Henry Finlay at the Cape of Good Hope, South Africa, on 1886 September 26. This comet has a semimajor axis of a = 3.488 au, eccentricity of e = 0.720, inclination of i = 6°80, and Tisserand parameter with respect to Jupiter of Tj = 2.62, which are typical of Jupiter-family comets (JFCs). Since the discovery, it showed irregular magnitude light curves at different apparitions (Sekanina 1993). The effective radius of 15P is estimated to be 0.92 ± 0.05 km (Fernández et al. 2013), which is consistent with early results in Whipple (1977) and Mendis et al. (1985). It has maintained the perihelion around the Earth orbit at 0.98–1.10 au for about a century and is sometimes linked to a meteor shower (Beech et al. 1999; Terentjeva & Barabanov 2011). It is likely that the measured absolute magnitude reduced by a factor of ~10 from 7.5 mag in 1886 to 10.1 mag in 1981 (Kresak & Kresakova 1989), suggesting that 15P might have lost a fraction of volatile components near the surface while developing a dust mantle layer on the surface similar to other periodic comets (e.g., Hsieh et al. 2015; Kwon et al. 2016).

The comet exhibited two large-scale outbursts around the perihelion passage in 2014–2015, with the first outburst occurring on 2014 December 16 (Ye et al. 2015). The image showed an envelope feature and near-nuclear tail, which is reminiscent of past cometary outbursts at 17P/Holmes and 332P/2010 V1 (Ikeya–Murakami), hereafter referred to as 17P and 332P, respectively (Ishiguro et al. 2010, 2014). Soon after the report of the first outburst, we conducted an observation from 2014 December 23 to 2015 March 16 to deepen our understanding of cometary outbursts. We used six ground-based telescopes that constitute a portion of the Optical and Infrared Synergetic Telescopes for Education and Research (OISTER) inter-university observation network. As a result of frequent observation several times a week, we witnessed the second outburst on UT 2015 January 15.

Such cometary outbursts have drawn the attention of researchers because they offer insight into the physical properties of comet nuclei (Hughes 1990). The huge outburst of 17P could be explained by the crystallization of buried amorphous ice (Li et al. 2011). Although similar morphological features were found at 332P (Ishiguro et al. 2014), numerous fragments were identified on its return in 2016 (Kleya et al. 2016; Weryk et al. 2016). Motivated by a series of detections regarding cometary outbursts, we investigated the physical properties of the 15P multiple outbursts and estimated the frequency and mass production rate of outbursts on a scale
Table 1
Observation and Event Summary

| Median UT        | Telescope | Filter | N°  | $T_{ex}^{b}$ | $r_{h}^{c}$ | $\Delta t^{d}$ | $\alpha^{e}$ | $f_{1}^{f}$ | Note          |
|------------------|-----------|--------|-----|--------------|-------------|----------------|--------------|--------------|---------------|
| (2014 Dec 16.0)  | ...       | ...    | ... | ...          | ...         | ...            | ...          | ...          | ...           |
| 2014 Dec 23.398  | OAO 0.5 m | $g'$,  | 58  | 58.0         | 0.977       | 1.443          | 42.8         | 355.1        | Close to Mars |
| 2014 Dec 23.402  | NHAO 2 m  | $g'$,  | 20  | 20.0         | 0.977       | 1.443          | 42.8         | 355.1        | Close to Mars |
| 2014 Dec 23.433  | IAO 1.05 m | $g'$,  | 18  | 54.0         | 0.977       | 1.442          | 42.8         | 355.1        | Close to Mars |
| 2014 Dec 25.400  | OAO 0.5 m | $g'$,  | 62  | 62.0         | 0.976       | 1.434          | 43.1         | 357.8        |                |
| 2014 Dec 25.406  | NHAO 2 m  | $R_{C}$| 17  | 17.0         | 0.976       | 1.434          | 43.2         | 357.8        |                |
| 2014 Dec 26.375  | NO 1.6 m  | $R_{C}$| 16  | 48.0         | 0.976       | 1.431          | 43.3         | 359.1        | Polarimetry   |
| 2014 Dec 26.419  | OAO 0.5 m | $g'$,  | 17  | 17.0         | 0.976       | 1.430          | 43.3         | 359.1        |                |
| (2014 Dec 27)    | ...       | ...    | ... | ...          | ...         | ...            | ...          | 0.0          | Perihelion     |
| 2014 Dec 27.369  | NHAO 2 m  | $R_{C}$| 15  | 12.5         | 0.976       | 1.427          | 43.5         | 0.4          |                |
| 2015 Jan 11.430  | IAO 1.05 m | $g'$,  | 15  | 15.0         | 0.999       | 1.394          | 44.9         | 19.0         |                |
| 2015 Jan 11.436  | IAO 1.05 m | $g'$,  | 27  | 27.0         | 1.002       | 1.393          | 44.9         | 20.2         |                |
| 2015 Jan 13.420  | OAO 0.5 m | $g'$,  | 84  | 84.0         | 1.009       | 1.392          | 44.9         | 22.8         |                |
| (2015 Jan 15.6–15.7) | ...       | ...    | ... | ...          | 1.017       | ...            | ...          | 25.5         | 2nd outburst   |
| 2015 Jan 16.448  | IAO 1.05 m | $g'$,  | 6   | 3.0          | 1.021       | 1.393          | 44.9         | 26.5         |                |
| 2015 Jan 17.434  | OAO 0.5 m | $g'$,  | 54  | 54.0         | 1.025       | 1.394          | 44.9         | 27.7         |                |
| 2015 Jan 18.400  | OAO 0.5 m | $g'$,  | 3   | 3.0          | 1.030       | 1.394          | 44.8         | 28.9         |                |
| 2015 Jan 19.411  | OAO 0.5 m | $g'$,  | 25  | 25.0         | 1.034       | 1.396          | 44.8         | 30.1         |                |
| 2015 Jan 23.458  | IAO 1.05 m | $g'$,  | 16  | 48.0         | 1.055       | 1.403          | 44.5         | 34.8         |                |
| 2015 Jan 24.424  | OAO 0.5 m | $g'$,  | 65  | 65.0         | 1.060       | 1.406          | 44.4         | 35.9         | Close to Moon |
| 2015 Jan 24.440  | IAO 1.05 m | $g'$,  | 14  | 14.0         | 1.061       | 1.406          | 44.4         | 36.0         | Close to Moon |
| 2015 Jan 25.436  | IAO 1.05 m | $g'$,  | 4   | 4.0          | 1.066       | 1.408          | 44.3         | 37.1         |                |
| 2015 Jan 30.427  | NHAO 2 m  | $R_{C}$| 30  | 25.0         | 1.097       | 1.426          | 43.6         | 42.5         |                |
| 2015 Jan 31.429  | OAO 0.5 m | $g'$,  | 29  | 29.0         | 1.103       | 1.430          | 43.4         | 43.6         |                |
| 2015 Feb 02.422  | OAO 0.5 m | $g'$,  | 47  | 47.0         | 1.117       | 1.440          | 43.1         | 45.7         |                |
| 2015 Feb 08.451  | OAO 0.5 m | $g'$,  | 113 | 113.0        | 1.160       | 1.475          | 41.9         | 51.6         |                |
| 2015 Feb 13.440  | OAO 0.5 m | $g'$,  | 45  | 90.0         | 1.198       | 1.511          | 40.7         | 56.2         |                |
| 2015 Feb 18.445  | OAO 0.5 m | $g'$,  | 43  | 86.0         | 1.239       | 1.553          | 39.5         | 60.5         |                |
| 2015 Feb 20.465  | IAO 1.05 m | $g'$,  | 13  | 39.0         | 1.256       | 1.571          | 39.0         | 62.2         |                |
| 2015 Mar 16.375  | OAO 1.88 m | $R_{C}$| 10  | 28.0         | 1.472       | 1.852          | 32.3         | 78.8         |                |

Notes.

$a$ Number of exposures.

$b$ Total exposure time [minute].

$c$ Heliocentric distance [au].

$d$ Geocentric distance [au].

$e$ Solar phase angle [degrees].

$f$ True anomaly [degrees].

$g$ Because accurate time was not known for the first outburst, we quoted $r_{h}$ and $f_{1}$ at UT 00:00 on the possible day.

similar to 15P. We describe our observations and data analysis in Section 2, and the photometric and polarimetric results in Section 3. We then discuss our findings considering the reports of recent outbursts in Section 4.

2. OBSERVATIONS AND DATA ANALYSIS

The observational journal is summarized in Table 1. Imaging observations were conducted from UT 2014 December 23 to UT 2015 March 16 using four telescopes: the Okayama Astrophysical Observatory (OAO) 0.5 m reflecting robotic telescope (OAO 0.5 m) and 1.88 m telescope (OAO 1.88 m), the Ishigakijima Astronomical Observatory (IAO) Murikabushi 1.05 m telescope (IAO 1.05 m), and the Nishihara Astronomical Observatory (NHAO) Nayuta 2 m telescope (NHAO 2 m). We employed standard charge coupled device (CCD) cameras, that is, Multicolor Imaging Telescopes for Survey and Monstrous Explosions (MITSuME) systems with Sloan Digital Sky Survey (SDSS) $g'$, Johnson–Cousins $R_{C}$, and
$I_C$-band filters attached to OAO 0.5 m and IAO 1.05 m; Kyoto Okayama Optical Low dispersion Spectrograph (KOOLS) with $R_C$-band filter attached to OAO 1.88 m; and Multiband Imager for Nayuta Telescope (MINT) with $R_C$-band filter attached to NHAO 2 m. Two sets of MITSuME systems at OAO 0.5 m and IAO 1.05 m are identically designed for monitoring transient objects such as gamma-ray burst afterglows, sharing nearly the same sky field at three wavelengths using two dichroic mirrors. The combinations of these telescopes and instruments cover a 26′ × 26′ field of view (FOV) with 1″.53 pixel resolution at OAO 0.5 m (Kotani et al. 2005), 5″.0 × 4″.4 FOV with 0″.33 pixel resolution at OAO 1.88 m (Yoshida 2005), 12″ 12′ FOV with 0″.72 pixel resolution at IAO 1.05 m, and 11″ 11′ FOV with 0″.32 pixel resolution at NHAO 2 m. In addition, we made optical and near-infrared polarimetric observations during two nights on UT 2014 December 24–27 by using the Nayoro Observatory 1.6 m Pirka telescope of the Faculty of Science, Hokkaido University (NO 1.6 m) and the Higashi–Hiroshima Observatory (HOO) Kanata 1.5 m Optical and Near-Infrared telescope of Hiroshima Astrophysical Science Center, Hiroshima University (HOO 1.5 m). We used a visible multi-spectral imager (MSI) with a polarimetric module and $R_C$-band filter at NO 1.6 m (Watanabe et al. 2012) and Hiroshima Optical and Near-Infrared camera (HONIR) with $R_C$ and $J$-band filters for HOO 1.5 m (Akitaya et al. 2014). In the imaging mode, NO 1.6 m/MSI has 3″.3 × 3″.3 FOV with 0″.39 pixel resolution, whereas HOO 1.5 m/HONIR has 10″ × 10″ FOV with 0″.29 pixel resolution. In the polarimetric mode, which is designed to use a focal mask for polarimetry, a Wollaston prism, and a half-wave plate, the NO 1.6 m/MSI FOV is subdivided into two adjacent sky areas each having 3″.3 × 0″.7 FOV, and the HOO 1.5 m/HONIR FOV is subdivided into five adjacent areas each having 9″.7 × 0″.75 FOV (Watanabe et al. 2012; Akitaya et al. 2014).

The observed data were analyzed with standard techniques for CCD images. Raw data were reduced by using flat field images taken with uniform screens on telescope domes and with dark or bias obtained before or after the comet exposures. For imaging data, we combined individual exposures into nightly composite images for each filter, excluding cosmic rays, background stars, and galaxies by using the same technique as that of Ishiguro (2008). $R_C$-band flux calibration was performed in comparison with field stars in the third U.S. Naval Observatory (USNO) CCD Astrograph Catalog (UCAC3), which ensured photometric accuracy of $\sim$0.1 mag (Zacharias et al. 2010). We measured the instrumental magnitudes of all stars in the FOV and compared them with the catalog magnitudes to determine the zero magnitudes of each $R_C$-band image.

For analysis of the polarimetric data, we followed the technique written in Kuroda et al. (2015). Because of a low signal-to-noise ratio (S/N), we did not analyze near-infrared polarimetric data. Raw data were preprocessed by using flat and dark frames in the same manner as that for the imaging data. We extracted source fluxes on ordinary and extraordinary parts of images by applying an aperture photometry technique. The obtained fluxes were used for deriving the Stokes parameters normalized by the intensity, $Q/I$ and $U/I$. The linear polarization degree ($P$) and the position angle of polarization ($\theta_p$) were derived by the following equations (Tinbergen 1996, p. 174):

$$ P = \sqrt{\left(\frac{Q}{I}\right)^2 + \left(\frac{U}{I}\right)^2}, $$

and

$$ \theta_p = \frac{1}{2} \tan^{-1}\left(\frac{U}{Q}\right). $$

We then derived the linear polarization degree commonly used for solar system objects ($P_i$) and the position angle of the polarization plane ($\theta_i$) referred to the scattering plane, which are given by

$$ P_i = P \cos (2\phi), $$

and

$$ \theta_i = \theta_p - (\phi \pm 90^\circ), $$

where $\phi$ denotes the position angle of the scattering plane projected on the sky. The sign in the parentheses was chosen to meet the condition $0 \leq (\phi \pm 90^\circ) \leq 180^\circ$. The position angle of the polarized light from comets is generally perpendicular to the scattering plane at the solar phase angle (Sun–observer’s angle) $\alpha \gtrsim 30^\circ$; thus, as expected, $\theta_i$ was $\sim 0^\circ$.

3. RESULTS

3.1. Overall Appearance

Figure 1 shows time-series false-color composite images at the $R_C$-band. We chose these images because the $R_C$-band is the most sensitive to cometary dust among the available filters. In fact, we examined the contribution of the spherical gas component by using the same technique as that described in Section 3.1 of Ishiguro et al. (2014). We found that gas intensity took up only $10 \pm 2\%$ (within an aperture at $\rho = 10^4$ km from the nucleus) of $R_C$-band total intensity on UT 2014 December 26, which supports the weak gas flux contribution shown in Figure 1. Some images taken in close time intervals are similar and are thus not shown separately. In the first image captured on UT 2014 December 23 (Figure 1(a)), an envelope structure extends approximately toward the anti-solar direction. It is likely that the envelope is related to the first outburst around UT 2014 December 16. The surface brightness of the envelope reduced quickly and became undetectable after around UT 2014 December 29 (Figure 1(c)). After that time, a near nuclear dust coma and dust tail remained. The coma and tail are attributed to steady activity of the comet because both the shape and magnitude were almost constant over several months. A dramatic change was observed in images after UT 2015 January 16. The inner coma brightened on UT 2015 January 16 (Figure 1(j)), and dust ejecta appearing soon afterward were stretched toward the anti-solar direction (Figures 1(k)–(n)). The appearance of the dust cloud on UT 2015 January 23 (Figure 1(m)) is similar to the image taken on UT 2014 December 23 (Figure 1(a)), in which the comet was enclosed by a widely expanded envelope. The envelope dimmed quickly, leaving behind a near-nuclear dust cloud similar to that from the pre-second outburst. In summary, we observed at least two outburst ejecta superposed on the continuous activity of the comet during its perihelion passage.
All images have standard orientation in the sky, that is, north is up and east is to the left. The anti-solar vectors \( \mathbf{r}_{-\odot} \) and the negative heliocentric velocity vectors \( \mathbf{v} \) are indicated by arrows. A dozen point-like sources appearing in (p) were not erased by a star subtraction technique because of the short duration of exposures.

### 3.2. Photometric Results

To clarify the time variation of the activity in a more quantitative manner, we conducted aperture photometry of the dust particles in the inner coma. We set a constant physical aperture distance from the nucleus at \( \rho = 10^4 \text{ km} \) and integrated the signal within \( \rho \) by using the IRAF/APPHOT package. The aperture distances correspond to \( 7''-9'' \) on the sky plane, which is large enough to enclose the seeing disk sizes of these data (typically \( 2''-3'' \)) but small enough to detect daily changes in dust production (an ejection speed of \( \sim 100 \text{ m s}^{-1} \) was assumed). In general, the measured magnitudes are determined not only by the time-variable activity of comets but also by the observing geometry (i.e., distances and viewing angles). To correct the latter effect, we converted the observed magnitudes into absolute values, which are magnitudes at a unit heliocentric distance \( r_h = 1 \text{ au} \), observer’s distance \( \Delta = 1 \text{ au} \), and solar phase angle \( \alpha = 0^\circ \). These values were determined by

\[
m_R(1, 1, 0) = m_R - 5 \log_{10}(r_h\Delta) - 2.5 \log_{10} \Phi(\alpha),
\]

where \( m_R \) and \( m_R(1, 1, 0) \) denote the observed and absolute magnitudes in the \( R_C \)-band. The third term on the right-hand side is given to correct phase darkening, which is given by

\[
2.5 \log_{10} \Phi(\alpha) = b\alpha,
\]

where the constant \( b \) was assumed to be a generally quoted value for cometary dust particles, \( 0.035 \text{ mag deg}^{-1} \) (Lamy et al. 2004, p. 223). Over our observation period, the observed magnitudes were subtracted by 2.2–3.3 mag by Equations (5)–(6) to convert the absolute magnitudes.

Figure 2 shows the absolute magnitudes with respect to (a) the observed time and (b) the true anomaly \( f \); by definition, the perihelion and aphelion occur at \( f = 0^\circ \) and \( 180^\circ \), respectively. The magnitude was almost constant or slightly decreased by 0.03 mag day\(^{-1} \) until the day of the second outburst. A minor eruption appears to have occurred on UT 2015 January 7 with a true anomaly of \( f = 154^\circ \), brightening the comet by \( 0.46 \pm 0.14 \text{ mag} \). A careful review of the above time-sequence images revealed a sharp tail on UT 2015 January 7 with a true anomaly of \( f = 151^\circ \), which matches to anti-solar direction on that day (158°9), we considered that a sudden ejection of fresh, small grains or ionized particles might have been stretched in that direction soon after the minor eruption on UT 2015 January 7.

A more outstanding brightening was observed on UT 2015 January 16 (\( f = 26^\circ5 \)). The near-nuclear absolute magnitude was \( m_R(1, 1, 0) = 6.37 \pm 0.10 \). After the brightening, the magnitudes remained smaller than the pre-outburst magnitudes over three days and returned to a normal magnitude within about one week. Although the image on UT 2015 January 23 (Figure 1(n)) showed the widespread envelope, it is likely that a large part of the dust grains expanded beyond the aperture size of our photometry (i.e., \( \rho > 10^4 \text{ km} \)) and became obscured by a steady stream of ejecta from the nucleus. To eliminate the magnitude excess on UT 2015 January 23, the outburst ejecta should have an ejection speed able to reach the aperture (i.e., \( \rho > 10^4 \text{ km} \)). We determined that a large fraction of outburst
indicated by downward arrows. The brightening events on UT 2015 January 7 and January 15 are distances are shown at the top of each graph. Thin vertical lines denote the UT 2015 January 01 and the corresponding heliocentric distances are shown at the top of each graph. Thin vertical lines denote the perihelion. The brightening events on UT 2015 January 7 and January 15 are indicated by downward arrows.

ejecta should have an effective speed of \( \gtrsim 15 \text{ m s}^{-1} \) to reach the aperture radius within one week.

3.3. Polarimetric Results

Polarimetric observation was conducted to find the optical similarities and differences between normal cometary dust and the outburst ejecta. The polarimetric data were acquired about 10 days after the first outburst by using NO 1.6 m and HHO 1.5 m telescopes. \( R_C \)-band filters were employed for our observations because the band is less contaminated by gaseous components and is sensitive to the solar-like dust spectrum, as mentioned above (Section 3.2). We integrated the signals of the observed data within apertures of \( \rho = 8000 \text{ km} \) and \( 12,000 \text{ km} \), and derived the polarization degree \( (P) \) and the position angle of the polarization vector \( (\theta_P) \). We obtained \( P_1 = 6.5 \pm 0.3\% \) on UT 2014 December 26 and \( P_1 = 7.0 \pm 0.5\% \) on UT 2014 December 27. The position angle was aligned to the normal vector of the scattering plane, that is, \( \theta_P = 1^\circ \pm 4^\circ \). No significant difference was noted within the errors in \( P_1 \) between measurements with the large and small apertures (i.e., \( \rho = 8000 \text{ km} \) and \( 12,000 \text{ km} \)). Figure 3 compares the polarimetric results with those of other comets. The phase angle dependence of the polarization degree is known to be classified into two groups: dust-rich comets with high polarization degrees and gas-rich comets with low polarization degrees (Levasseur-Regourd et al. 1996). Comet C/1995 O1 (Hale-Bopp) did not match these two categories and showed a very high polarization degree (Hadamcik et al. 1997). The polarization degree of 15P fell into common values of comets between gas-rich and dust-rich groups. As described above, the surface brightness of the outburst ejecta faded out within \( \sim \) seven days from the near-nuclear region in the case of the second outburst, which is similar to the case of the first outburst, and was indistinguishable from the background dust particles produced by continuous activity. Therefore, the similarity in polarization degree does not mean that the optical properties of outburst ejecta are the same as those in normal comets. As a result of the data analysis, we learned that earlier follow-up observations within \( \sim \) three days are required to determine the characteristics of such fresh particles during outbursts, such as fluffy or compact optical properties. This topic should be covered in future observation planning.

3.4. Order-of-magnitude Estimates for the Outburst Ejecta Mass

In this section, we provide an approximate but straightforward estimate of outburst ejecta mass to compare with previous outbursts, and subsequently present a more sophisticated estimate by conducting a dynamical analysis of dust particles in Section 3.6. We measured the total \( R_C \)-band magnitudes with apertures large enough to enclose the entire visible dust cloud for obtaining the total mass of the outburst materials. We set aperture radii of \( \rho = 4.5' \) (UT 2014 December 23) and 1' (UT 2015 January 16), and obtained \( m_R = 9.44 \pm 0.10 \) (UT 2014 December 23) and \( m_R = 7.95 \pm 0.10 \) (UT 2015 January 16). The magnitude was \( m_R = 11.12 \pm 0.12 \) on UT 2015 January...
11–13, which was obtained just prior to the second outburst and well after the first outburst, when little outburst material was present as a result of radiation pressure sweeping. By using Equations (5)–(6), we derived the absolute magnitudes of \( m_{\text{R}}(1, 1, 0) = 7.20 \pm 0.10 \) (UT 2014 December 23), \( 8.82 \pm 0.12 \) (UT 2015 January 11–13), and \( 5.61 \pm 0.10 \) (UT 2015 January 16). With these magnitudes, the optical cross-sections of the dust cloud \( (\sigma_c) \) were calculated by

\[
p_R C_c = 2.24 \times 10^{22} \pi 10^{0.4(m_{\text{V}} - m_{\text{R}}(1, 1, 0))},
\]

where \( p_R \) is the geometric albedo (\( p_R = 0.04 \) was assumed), and \( m_{\text{C}} = -27.11 \) is the \( \text{C-band} \) magnitude of the Sun at \( r_b = 1 \text{ au} \) (Drilling & Landolt 2000).

By substituting \( m_{\text{R}}(1, 1, 0) \) in Equation (7), we obtained \( C_c = 3.32 \times 10^{10} \text{ m}^2 \) (UT 2014 December 23), \( 7.47 \times 10^{9} \text{ m}^2 \) (UT 2015 January 11–13), and \( 1.44 \times 10^{11} \text{ m}^2 \) (UT 2015 January 16). We attributed the cross-section on UT 2015 January 11–13 to dust grains ejected via continual activity, which is irrelevant to these outbursts. We subtracted this value from the other two values and obtained the cross-section associated with the first outburst, \( C_c = 2.56 \times 10^{10} \text{ m}^2 \), and the second outburst \( C_c = 1.36 \times 10^{11} \text{ m}^2 \). There is a possibility that we missed some fraction of the cross-section from the first outburst because our data might not cover its entire dust cloud on UT 2014 December 23. We thus considered the total cross-section of the first outburst ejecta as the lower limit (i.e., \( C_c \geq 2.56 \times 10^{10} \text{ m}^2 \) for the first outburst ejecta).

The ejecta masses of the outbursts can be given by

\[
M_d = \frac{4}{3} \rho_d a_{\text{eff}} C_c,
\]

where \( a_{\text{eff}} \) and \( \rho_d \) are the effective dust grain radius and mass density, respectively. The effective radius is given by

\[
a_{\text{eff}} = \frac{\int_{a_{\text{min}}}^{a_{\text{max}}} a^3 \rho_d \, da}{\int_{a_{\text{min}}}^{a_{\text{max}}} a^2 \, da},
\]

where \( q \) denotes the power index of the size distribution in the range of \( a_{\text{min}} \leq a \leq a_{\text{max}} \).

With assumptions of \( \rho_d = 1000 \text{ kg m}^{-3} \) and \( a_{\text{eff}} = 1 \times 10^{-6} \text{ m} \) (i.e., \( 1 \mu\text{m} \)), \( C_c \) gives \( M_d > 3.41 \times 10^7 \text{ kg} \) for the first outburst and \( M_d = 1.81 \times 10^5 \text{ kg} \) for the second outburst. These values are equivalent to masses of \( R_c > 20 \text{ m} \) and \( 35 \text{ m} \) bodies. It should be noted, however, that this simple assumption likely underestimates the dust mass. Although the small particle \( (a_{\text{eff}} = 1 \mu\text{m}) \) assumption is occasionally quoted in previous research, abundant evidence exists for large particles from comets, which is subsequently discussed. Thus, it is better to consider that the masses should be the lowest limits. Ye et al. (2015) derived \( C_c = 7 \times 10^5 \text{ m}^2 \) for the first outburst and \( C_c = 2 \times 10^{10} \text{ m}^2 \) for the second outburst, which are smaller than our estimates. In addition, they reported \( M_d = (2–3) \times 10^5 \text{ kg} \) for the first outburst and \( M_d = (4–5) \times 10^5 \text{ kg} \) for the second outburst, which are more than two orders of magnitude less than our estimates. Although we were unable to verify their results with the information available in their paper, we found that these orders-of-magnitude estimates reveal that the ejecta masses of 1SP outbursts are equivalent to those of the 332P event \( (10^8–10^9 \text{ kg}) \) (Ishiguro et al. 2014).

![Figure 4](https://example.com/figure4.png)

**Figure 4.** Selected images after the second outburst. We allocated \( g' \) images as blue, \( R_c \)-band images as green, and \( I_c \)-band images as red to create these color images. These images are rotated to align the anti-solar vector \( (r_{\odot,c}) \) to the horizontal direction of each image. The FOV of each panel is \( 13' \times 7' \).

### 3.5. Motion of Dust and Gas Ejecta in the Second Outburst Images

We further investigated the images soon after the second outburst. Figure 4 shows images taken after UT 2015 January 16.4 on the day in which brightening in Figure 2 was detected. We do not show the image taken on UT 2015 January 18 because of its bad quality (the total exposure time was only 3 minute due to unstable weather). To clarify the movement of dust grains via solar radiation pressure, we rotated these images...
to match the Sun–comet’s direction to the horizontal direction. We produced color images, assigning $g'$-band images (the effective wavelength and the full width at half-maximum of $\lambda_e = 483$ nm and $\Delta \lambda = 134$ nm) to blue; $R_C$-band images ($\lambda_e = 655$ nm and $\Delta \lambda = 121$ nm) to green; and $I_C$-band images ($\lambda_e = 799$ nm and $\Delta \lambda = 157$ nm) to red colors. In these images, a whitish component expanded in space and simultaneously stretched toward the anti-solar direction. On the other hand, a bluish component expanded spherically with respect to the nuclear position. In general, prominent emissions associated with C2 and CN appear in the $g'$-band, weak emissions with NH$_2$ in the $R_C$-band, and negligibly faint signals with NH$_2$ and CN in the $I_C$-band (Brown et al. 1996; Meech & Svoren 2004, p. 317). In theory, dust particles are accelerated by solar radiation pressure, whereas neutral gas molecules are less sensitive to the radiation pressure and expand almost spherically. Thus, it is reasonable to consider that the whitish elongated structure originated from scattered sunlight from dust particles and that the bluish structure originated from CN and C$_2$ emissions.

We attempted to extract the signals from the second outburst and to discriminate the gas flux from the scattered light by dust grains. The observed angles rotated very little over 2015 January 11–23 (that is, 0$^\circ$.4 for the phase angle, 2$^\circ$.4 for the position angles of the anti-solar vector, and 1$^\circ$.4 for the position angle of negative orbital velocity). Therefore, we subtracted the pre-outburst signals by using images observed on 2015 January 11 (IAO 1.05 m) and 2015 January 13 (OAO 0.5 m) from post-outburst images to adjust the apparent sizes of the comet based on the geocentric distances without rotating these images. Next, assuming that $I_C$-band images have little gas contamination, we subtracted them from $g'$-band images by adjusting the $I_C$-band intensity scales to minimize the extended dust structure (i.e., dust tail) in the residual images to produce gas intensity maps. Specifically, we detected a very weak spherical component in the $I_C$-band images that likely originated from weak CN emissions at 790–820 nm, which were noticeable until UT 2015 January 17 but were unclear after January 19. We subtracted the faint spherical component in the $I_C$-band images by using the above gas intensity maps, scaling the gas intensities to obscure the spherical components in the residuals to produce new dust intensity maps assuming that the intensity distributions of the gas components are the same in $g'$ and $I_C$-bands.

The resultant images are shown in Figure 5. As expected, we extracted a spherical structure centered on the nucleus for the gas component associated with the second outburst (Figure 5 right). The surface brightness reduced rapidly in a few days not only because the gas diffused out in space, but also because the molecules had lifetimes equivalent to the observed period, i.e., two days for CN and five days for C$_2$ during the active solar phase (Huebner et al. 1992). We then examined the radius of the gas component from the images. Figure 6 shows the radial profile of the gaseous coma. Considering the sky background noise, we derived radii of $89 \pm 5^\circ$ on UT 2015 January 16.4 and $182 \pm 10^\circ$ on UT 2015 January 17.4. Assuming that the gas expanded at a constant speed since its ejection, we derived the onset time and expansion speed of the gas component as UT 2015 January $15.5 \pm 0.2$ and $v_g = 1.110 \pm 0.180$ m s$^{-1}$ (Figure 7). We quoted the maximum ranges of these parameters as the errors in consideration of the margin of measurement because we had only two data points, which is insufficient for deriving the errors by using the least squares method. We found that the derived gas speed was slightly faster than the observed values of CN emission at other comets around 1 au, probably because we derived the speed at a very large distance from the nucleus ($\approx 10^8$ km), where the gas flow velocity continued to increase (Krankowsky et al. 1986; Ip 1989).

In the left-hand column of Figure 5, we show the dust component images. A short tail was visible on the first night (a), and an irregular cloud appeared on the second night (b) that extended toward the anti-solar direction via the radiation pressure. From the apparent cloud size, we derived the ejection onset time. We focused on the widths of the dust cloud perpendicular to the Sun–comet direction because dust particles were not accelerated by radiation pressure along that direction. Figure 7 shows the time evolution of the dust cloud width. The width increased linearly with the progression of time. By using a linear least squares method, we obtained the onset time on UT 2015 January $15.7 \pm 0.1$ for dust particles. Although this result agrees with the onset time of gas within the accuracy of our measurements, the trivial lag may suggest that the dust required more time to reach terminal velocity, which should be accelerated by the gas outflow. We conclude that the second outburst occurred on UT 2015 January 15.6–15.7 from gas and dust components. In addition, we derived the dust speed perpendicular to the Sun–comet direction as $v_{dl} = 280 \pm 20$ m s$^{-1}$. Here, we should note that this speed might be misleading. Because we measured the speed perpendicular to the Sun–comet direction, we must underestimate the ejection speed for dust particles in $v_{dl}$.

3.6. Ejecta Dynamical Model

To derive the ejection speed, mass, and kinetic energy of the dust cloud in a comprehensive manner, we conducted a model simulation to reproduce the observed morphologies of dust ejecta from the second outburst by following the scheme in Ishiguro et al. (2013). The morphologies of dust clouds are generally determined by the ejection speeds and the effects of solar radiation pressure, which can be approximately given by a function of grain size. Therefore, the sizes and ejection speeds of the dust particles can be determined essentially through an investigation of dust cloud morphologies. For a spherical particle, the ratio of the radiation pressure with respect to the solar gravity ($\beta$) is given as $\beta = 5.75 \times 10^{-4} Q_{pr}/\rho a$, where $a$ and $\rho a$ are dust radius (m) and mass density (kg m$^{-3}$), and $Q_{pr}$ is a radiation pressure coefficient (Finson & Probstien 1968; Burns et al. 1979). Here, we assumed $\rho = 1 \times 10^3$ kg m$^{-3}$ and $Q_{pr} = 1$. For convenience of fitting, we assumed that the dust ejecta consisted of two components, a high-speed envelope and a low-speed tail. We set the ejection epoch of UT 2015 January 15.5, which has negligible influence on the result within the error range (i.e., 0.1 day). For simplicity, we assumed that dust particles were ejected symmetrically with respect to the solar direction within a cone of a half opening angle of $w$. We employed a size-dependent ejection speed of $V_{ej} = V_{ej0}a^{-u}$ and power-law size frequency distribution given by $N(a) = N_0a^{-q}$ in the range between $a_{min}$ and $a_{max}$. Because the ranges of these parameters and fitting scheme are the same as those given in Ishiguro et al. (2013), we do not describe the details here.

Through the fitting, we derived the best-fit parameters as shown in Table 2. Because large particles are not sensitive to solar radiation pressure and still reside near the nucleus, we found it impossible to derive the maximum size of particles.
We fixed the minimum value for $\beta$ to $6 \times 10^{-4}$ (i.e., $a = 1$ mm) on the grounds that large cometary boulders may not be ejected efficiently through outbursts (Bertini et al. 2015). Figure 8 shows a comparison of the observed dust cloud morphology and our best-fit model, which broadly match. However, the entire morphology was not perfectly reconstructed by our model, probably because the dust ejection was not symmetric with respect to the solar direction. Although we do not intend to upgrade the model fitting by fine tuning the central axis of the dust emission here, we would insist that the outburst location might deviate slightly from the sub-solar point because of this asymmetry. The maximum $\beta$ was determined well to be $\beta_{\text{max}} = 1.6 \pm 0.2$ because our observation data covered the faint end of the dust cloud, where particles with $\beta_{\text{max}}$ were dominant. To fit the width and sunward extension of the cloud, we obtained the best fit parameters $V_0 = 450 \pm 30$ m s$^{-1}$ for the envelope particles and $V_0 = 330^{+40}_{-30}$ m s$^{-1}$ for the tail. These parameters resulted in a maximum speed for the smallest particles of $V_{\text{max}} = 570 \pm 40$ m s$^{-1}$. For confirmation, we calculated the speed perpendicular to the Sun–comet direction with these simulation results, $V_{\perp} = V_{\text{max}} \sin(w) = 285 \pm 40$ m s$^{-1}$, which is consistent with the value given in Section 3.5 (i.e., $V_{\perp} = 280 \pm 20$ m s$^{-1}$). From the model fitting, we

Figure 5. (a)–(d) Dust and (e)–(h) gas distributions derived by using the same images as those in Figure 4. To view faint diffuse structures, we applied $3 \times 3$ pixel boxcar smoothing to these images. The physical scale at the position of the comet, $10^5$ km, is indicated by horizontal lines. Remnants of star subtraction and CCD artifacts associated with the edges of frames are shown by “S” and “E.” The FOV of each panel is $13' \times 7'$ for dust images and $7' \times 7'$ for gas images.
cometary dust particles have been investigated theoretically considering fluffy dust particles (Mukai et al. 1992) and a variety of compositions (Burns et al. 1979). In Section 3.6, we adopted a simple model in which $\beta$ is inversely proportional to size under an assumption of a radiation pressure coefficient of $Q_{pr} = 1$. However, this assumption holds only when the particle size is larger than the optical wavelength ($\lambda = 0.5 \mu m$). $Q_{pr}$ has almost constant value for $a > 0.1–0.3 \mu m$ and significantly drops as the size of dust grains decreases (Ishiguro et al. 2007). For fluffy dust particles, $\beta$ is less dependent on the aggregate size but similar to that of each constituent (Mukai et al. 1992). Wilck & Mann (1996) calculated the $\beta$ values of dust particles by using a core–mantle spherical particle model composed of silicate and amorphous carbon with different porosities, and suggested that cometary dust particles have $\beta_{max} = 1–1.8$. Transparent materials such as silicates and water ice tend to have small $\beta$ maximum values (i.e., $\beta_{max} < 1$), whereas that of absorbing particles such as carbon is $\beta_{max} > 1$ (see e.g., Kimura et al. 2016). The $\beta_{max}$ value determined in our measurement, $1.6 \pm 0.2$, is consistent with that in the porous absorbing particles model (Wilck & Mann 1996) and silicate-core, organic-coated grains model for dust aggregates (Kimura et al. 2003). However, our value is inconsistent with those of silicate spheres ($\beta_{max} < 1$) and organic spheres ($\beta_{max} > 3$).

4.2. Outburst Frequency

Cometary outbursts have been observed in a wide variety of comets. There are some references that analyzed historical observations of cometary outbursts (e.g., Hughes 1990). However, the occurrence frequency and mass production rate have not been studied well because there is no coordinated observation system for monitoring comet magnitude. Some outbursts could have been missed because the magnitude...
contrast was too weak before and after to be noticed as an outburst or because the observation condition was not suitable for detection (i.e., too close to the Sun or Moon). Nevertheless, some outburst events have been reported in a voluntary manner by amateur observers. For example, the 17P event was first reported by A. Henriquez Santana (Spain), who noted sudden brightening to 8.4 mag by using a 0.2 m reflector (Buzzi et al. 2007). 332P was discovered in Japan during its outburst by S. Murakami and K. Ikeya. They observed this event by looking into the eyepieces of 0.46 and 0.25 m telescopes when it reached ~9 mag (Murakami 2010). Moreover, 15P double outbursts with brightening to 8–9.4 mag were also reported by amateurs through a mailing list of comet observers (Ye et al. 2015).

It has been suggested that 17P and 332P events were caused by a phase change of amorphous water ice (Li et al. 2011; Ishiguro et al. 2013), although other mechanisms such as rotational breakup of brittle cometary nuclei cannot be ruled out (Li & Jewitt 2015). Excavations via impacts might create environments favorable to outbursts, as suggested in Beech & Gauer (2002). Because the energy per unit mass is similar to both events, we conjecture that 15P events were also caused by a phase change of amorphous water ice. Here, we consider the frequency of such outbursts in the inner ($r < 5$ au) solar system, where the physical mechanism of general cometary activity is confined to sublimation of water ice rather than that of super volatiles such as CO (Jewitt 2009). For this reason, we excluded frequent outbursts at 29P/Schwassmann-Wachmann 1 beyond the Jupiter orbit. Moreover, we restricted our discussion to JFCs and Encke-type comets (ETCs) because significant observation samples are not available for Halley-type comets (HTCs) and long-period comets. We applied a sample cut of the perihelion distance $q \lesssim 5$ au to the JPL Small-Body Database Search Engine14 and retrieved 505 JFCs and ETCs in the list of known comets as of the end of 2015. We regarded disintegrated comets as a single object (e.g., 73P/Schwassmann-Wachmann 3 B, C, G... constituted a united body). Moreover, we excluded disappeared or dead comets (3D/Biela and 5D/Borresen), designated as “D/,” and main-belt comets, which are unlikely to contain amorphous ice (Prialnik & Rosenberg 2009). Among JFCs and ETCs, 357 objects passed their perihelion at least once between 2007 October and 2015 December, which make up ~70% of the entire population. This means that ~70% of JFCs and ETCs might have a chance of displaying outburst activities owing to the additional heat from the Sun near their perihelia.

We attempted to find outburst events through the Smithsonian Astrophysical Observatory/National Aeronautics and Space Administration (SAO/NASA) Astrophysics Data System (ADS) Astronomy Query Form by inputting “comet” and “outburst” as abstract terms and manually plumbing the results by reading the abstracts. In addition, we added one event at 205P which had an outburst showing similar appearance to 15P (S. Yoshida 2016, private communication). We found that 15 outburst events occurred at 11 comets since 2007 (Table 4). We chose the arbitrary period beginning in 2007 because researchers have increased their consciousness toward outbursts since then, as motivated by the 17P event.

Table 4 shows some minor outbursts detected by observers with larger telescopes because these comets drew their attention due to space mission targets (81P/Wild 2 and 103P/Hartley 2) and repeated outbursts at 17P and 15P. Figure 9 shows the cumulative mass distribution of the outburst ejecta. We note that six outburst events, including 17P, 168P/Hergenrother, 332P, 217P/LINEAR, and two events at 15P, were brightened down to 10 mag. Such events would be detectable with observation through inexpensive equipment such as ~10 cm class telescopes. Thus, we conjecture that outbursts $\lesssim 10$ mag would be detected almost completely if observed conditions allowed ground-based observers to make observations.

We fitted the ejecta mass distribution with a power-law function for five objects (i.e., $\lesssim 10$ mag events except 17P) and obtained a power index of $\gamma = 0.45 \pm 0.09$. Although there might be no physical basis to support the power-law function in Figure 9, it is likely that the 17P outburst in 2007 was a very rare phenomenon to be detected within ~eight years because the occurrence is one order of magnitude higher than that expected by the power function. In fact, the large discrepancy for 17P must be a bias of our analysis in which we counted the number of outbursts since the epoch-making event. In addition,  

\[ \text{Table 2} \]

Dust Model Parameters

| Parameter | Input Values | Best-fit (Envelope) | Best-fit (Tail + Coma) | Unit |
|-----------|--------------|---------------------|------------------------|------|
| $u_1$     | 0.1–0.9 with 0.1 interval | 0.4 ± 0.3          | 0.55 ± 0.1             |      |
| $q$       | 3.0–4.5 with 0.1 interval | 3.8 ± 0.1          | 3.8 ± 0.1              |      |
| $\beta_\text{max}$ | 1.0–2.5 with 0.1 interval | 1.6                |                        |      |
| $\beta_\text{max}$ | 0.5, 0.3, 0.1, 0.01, 0.001 | 0.3                | $6 \times 10^{-3}$ (fixed) |      |
| $V_0$     | 150–600 with 30 interval | 450 ± 30           | 330 $\pm 60$           | m s$^{-1}$ |
| $\sigma_0$ | 0–0.5 with 0.1 interval | 0.2 ± 0.1          | 0.4 ± 0.1              |      |
| $\omega$  | 5–60 with 5 interval | 35 ± 10            | 30 ± 10                | degree |

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14 http://ssd.jpl.nasa.gov/sbdb_query.cgi
the power-law function fits well in the mass range of \(6 \times 10^7 - 1 \times 10^9\) kg but deviates from the observed values in the mass range of \(\lesssim 6 \times 10^7\) kg. Some outbursts might not be noticed because of the faintness or weak contrast before and after outbursts. For these reasons, we consider that the unbiased outbursts rate in which the ejecta mass corresponds to \(6 \times 10^7 - 1 \times 10^9\) kg, (hereafter referred to as “15P-class” outbursts).

We applied the Poisson distribution following Sonnett et al. (2011):

\[ P(n) = \frac{(fCN)^n \exp(-fCN)}{n!}, \]

where \(n\) and \(f\) denote the number of outburst detections and incidence of outbursts, \(N\) is the number of observed samples, and \(C \in [0, 1]\) is the completeness of the survey. The 90% upper confidence limit on the incidence, \(f_{90\%}\), is given by

\[ 0.9 = \int_{f_{90\%}} P(n) df. \]

Assuming that observers could detect 15P-class outbursts completely at the solar elongation of \(\alpha_s > 60^\circ\), we have \(C = 0.67\). Over eight years since October 2007, there were \(n = 7\) 15P-class outbursts out of \(N = 357\) comets that passed their perihelion. By solving the implicit Equation (11), we obtained \(f_{90\%} = 0.05\), which suggests an expected number \(\langle n \rangle = f_{90\%} CN \sim 12\) in eight years, or 1.5 times per year. Therefore, we can express the unbiased cumulative and differential frequency of 15P-class outbursts \(f_{ub}\) and \(f_{ub}\) as

\[ f_{ub}(> M) = \int_M^\infty f_{ub}(m) dm = A\left(\frac{M}{M_0}\right)^{-\gamma}, \]

where \(A = 1.5\) yr\(^{-1}\) and \(M_0 = 6 \times 10^7\) kg are constants. We obtained an effective mass production rate of 15P-class outbursts of \(\sim 3 \times 10^8\) kg year\(^{-1}\) or \(\sim 10^8\) kg s\(^{-1}\), from (see Appendix)

\[ \langle m \rangle = \int_{M_1}^{M_2} m f_{ub}(m) dm, \]

where \(M_1 = 6 \times 10^7\) kg and \(M_2 = 1 \times 10^9\) kg are lower and upper bounds on the power-law behavior of 15P-class outbursts, respectively. We consider that the incidence would be underestimated because we optimistically assumed \(C = 0.67\). Some of the outbursts were missed owing to the crowded region of stars or the full lunar phase. Even considering these factors, which may decrease \(C\) by several factors, our result would obtain one order-of-magnitude
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Table 4
List of Outbursts at JFCs and ETCs since 2007 October

| Name          | Date          | $n_b$ | $\Delta$ | $\alpha$ | $m_a$  | $m_a(1, 1, 0)$ | $m_a(1, 1, 0)$ | $C_v$ | References |
|---------------|---------------|-------|----------|----------|--------|----------------|----------------|-------|------------|
| 205P/Giacobini| 2015 Sep 26   | 1.92  | 1.57     | 32       | $\sim$20 | $\sim$14       | 16.5           | 10.5  | $1.6 \times 10^9$ (1) |
| 17P/Holmes    | 2015 Jan 26   | 2.99  | 2.38     | 26       | 19.2   | 16.8           | 14.0           | 11.6  | $5.1 \times 10^8$ (2) |
| 15P/Finlay    | 2015 Jan 15   | 1.02  | 1.39     | 45       | 11.1   | 8.0            | 11.1           | 5.6   | $1.4 \times 10^{11}$ (3) |
|               | 2015 Jan 7    | 0.99  | 1.40     | 45       | 13.2   | 12.7           | 10.9           | 10.4  | $6.8 \times 10^8$ (3) |
|               | 2014 Dec      | 0.99  | 1.48     | 41       | 9.4    |                |                | 7.2   | $2 \times 10^{10}$ (3) |
| 63P/Wild 1    | 2013 May 16   | 1.98  | 1.58     | 30       | 15.6   | 13.5           | 12.0           | 10.0  | $2.2 \times 10^9$ (4) |
| 168P/Hergenrother | 2012 Aug-Dec | 1.42  | 0.43     | 13       | 15.2   | 8.0            | 15.8           | 8.6   | $9.1 \times 10^9$ (5) |
| P/2010 V1     | 2010 Nov 2    | 1.59  | 2.34     | 19       | 9.5    |                |                | 6.0   | $1.0 \times 10^{11}$ (6) |
| 103P/Hartley 2| 2010 Aug-Nov  | 1.06–1.56 | 0.12–0.70 | 29–59 |        |                |                |       | $2.2 \times 10^8$ (7) |
| 81P/Wild 2    | 2010 Apr–Aug  | 1.70–2.21 | 0.70–1.85 | 4.5–27.1 |        |                |                |       | $1.0 \times 10^{10}$ (8) |
| P/2010 H2     | 2010 Apr      | 3.11  | 2.13     | 5        | $>20$  | 12.6           | 15.7           | 8.3   | $1.2 \times 10^{10}$ (9) |
| 217P/LINEAR   | 2009 Oct      | 1.31  | 0.61     | 47       | 11.3   | 9.3            | 10.1           | 8.1   | $1.2 \times 10^{10}$ (10) |
| 199P/Shoemaker 4 | 2008 Aug     | 3.41  | 3.35     | 17       | 17.8   | 14.5           | 14.1           | 8.6   | $8.9 \times 10^9$ (11) |
| 6P/d’Arrest   | 2008 Aug      | ...   | ...      | ...      | ...    | ...            | ...            | ...   | ...        (11) |
| 17P/Holmes    | 2008 Jan 5    | 4.18  | 3.28     | 6        | 19.8   | 19.3           | 13.9           | 13.4  | $4.5 \times 10^9$ (12) |
|               | 2007 Nov 12   | 2.51  | 1.62     | 13       | 12.8   | 12.6           | 9.2            | 9.0   | $1.1 \times 10^9$ (13) |
|               | 2007 Oct 23   | 2.44  | 1.64     | 17       | 17     | 2.5            | 13.4           | $–1.1$| $7.1 \times 10^{13}$ (14) |

Notes.

\(a\) Pre-outburst apparent magnitudes.
\(b\) Post-outburst apparent magnitudes.
\(c\) Pre-outburst absolute magnitudes calculated with Equation (5).
\(d\) Post-outburst absolute magnitudes calculated with Equation (5).
\(e\) Cross-section calculated with Equation (7) assuming the geometric albedo \(p_R = 0.04\).

References: (1) S. Yoshida (2016, private communication), (2) Kwon et al. (2016), (3) This work, (4) Opitom et al. (2013), (5) Sekanina (2014), (6) Ishiguro et al. (2013), (7) Milani et al. (2013), (8) Bertini et al. (2012), (9) Vales et al. (2010), (10) Sarugaku et al. (2010), (11) Miles 2009, (12) Miles (2010), (13) Stevenson & Jewitt (2012), (14) Li et al. (2011).

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Figure 9. Cumulative distribution of outburst ejecta mass observed since 2007.

We assumed that outburst ejecta of these comets (except 17P, 332P, and 217P) have the same size distribution as 15P.

The mass is \(\sim 2\) orders of magnitude less than the mass required to sustain the interplanetary dust cloud. This implies that 15P-class outburst events may not compensate the mass eroded by Poynting–Robertson drag and other dynamical mechanisms onto the interplanetary dust. However, if we integrate \(m^2 \mu (m) dm\) up to the 17P-class ejecta mass (i.e., \(M_2 = 1 \times 10^{12} \text{ kg}\)), the mass production rate from 15P–17P class events would be \(\sim 500 \text{ kg s}^{-1}\), although we are not sure whether the frequency follows a simple power-law function up to the 17P class. These results suggest that large-scale cometary outbursts might contribute a significant fraction of the interplanetary dust source.

5. SUMMARY

We made an observation of 15P during the perihelion passage in 2015–2016, following a report of an outburst in the middle of 2015 December and detected the second outburst on UT 2015 January 15.6–15.7, which was equivalent to the first outburst. The results of our analysis are summarized in the following points.

1. Gas consisting mostly of C\(_2\) and CN expanded at a speed of \(1110 \pm 180 \text{ km s}^{-1}\), which is slightly faster than the speeds for other comets around 1 au. The excess in speed can be explained by the large distance from the nucleus (\(\sim 10^8\) km), where the gas flow velocity continues to increase.

2. The dust ejecta accelerated up to a speed of \(570 \pm 40 \text{ km s}^{-1}\), which is comparable to the ejection speeds of 17P and 332P ejecta. These consistent speeds would have resulted in the similar appearances of these outburst ejecta.

3. We derived the total mass of dust ejecta as \(10^6–10^9\) kg (\(a = 0.3 \mu m–1\) mm was assumed). This mass is
equivalent to that of the 2010 event at 332P but is three orders of magnitude smaller than the 2007 event at 17P.

4. The polarization degree was measured to 6.8 ± 0.2% at the phase angle \( \alpha = 43^\circ \), which fell into the common values of other comets. This similarity does not mean that outburst ejecta have similar polarimetric properties because it was diffused out at the time of our polarimetric measurement.

5. Based on the immediate observation of dust ejecta for the second outburst, we derived a reliable estimate of \( \beta_{\text{max}} = 1.6 \pm 0.2 \). This value is consistent with the theoretical prediction for porous absorbing particles, suggesting that such porous dust particles could remain inside the cometary nucleus and are released during the outburst.

6. The kinetic energy per unit mass (10^4 J kg^{-1}) is close to estimated values of 17P and 332P. In addition, the dust mass, speed, and kinetic energy are broadly comparable to the measured values of the 2010 outburst at 332P. This may suggest that these three outbursts occurred by a similar mechanism.

7. From a survey of cometary outbursts in publications in the SAO/NASA ADS, we estimated that 15P/Finlay-class outbursts occur annually, injecting cometary materials into interplanetary space at a rate of \( \geq 10 \) kg s^{-1} or more.

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**APPENDIX STATISTICS**

In this section, we prove the equations used in Section 4.2. Following Newman (2005), we consider a probability distribution of the form

\[
p(x) = Pr(X = x) = Cx^{-\alpha}.
\]

The cumulative distribution function of a power-law distributed variable is given by

\[
F(x) = Pr(X \geq x) = \int_{x_{\text{min}}}^{\infty} p(x') dx' = \left( \frac{x}{x_{\text{min}}} \right)^{-\alpha+1},
\]

where \( x_{\text{min}} \) is a lower bound on the power-law behavior. It’s an identical form of Equation (12), that is,

\[
f_{ab} (\geq M) = \int_{M}^{\infty} f_{ab} (m) dm = A \left( \frac{M}{M_0} \right)^{-\gamma},
\]

where we consider \( x \) and \( x' \) correspond to \( M \) and \( m \), respectively. Now we consider the mean value of our power-law distributed quantity \( x \), given by

\[
\langle x \rangle = \int_{x_{\text{min}}}^{\infty} xp(x) dx = C \int_{x_{\text{min}}}^{\infty} x^{-\alpha+1} dx = \frac{C}{\alpha-1} \left[ x^{-\alpha+2} \right]_{x_{\text{min}}}^{\infty}.
\]

It also corresponds that we integrate \( mf_{ab}(m) dm \) to obtain the mean mass production rate of 15P class outbursts at a given mass range. We can write the equation:

\[
\langle m \rangle = \int_{M_0}^{M} mf_{ab}(m) dm,
\]

where \( M_0 \) and \( M_1 \) are lower and upper bounds on the power-law behavior, respectively.

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