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Rising from Ashes or Dying Flash? The Mega Outburst of Small Comet 289P/Blanpain in 2013[*]

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Abstract

Jupiter-family comet 289P/Blanpain was first discovered in 1819 and was then lost for ∼200 years, only to be rediscovered in 2003 as a small, weakly active comet. The comet is associated with the Phoenicids, an otherwise minor meteor shower that produced significant outbursts in 1956 and 2014. The shower points to the existence of significant mass-loss events of P/Blanpain in recent history. P/Blanpain was recovered during an apparent large outburst in 2013 July at an appreciable heliocentric distance of 3.9 au, with brightness increase of 9 mag, making it one of the largest comet outbursts ever observed. Here we present an analysis of archival data taken by several telescopes. We find that the 2013 outburst has produced ∼10^8 kg of dust, which accounts for a modest fraction (∼1%) of the mass of P/Blanpain's nucleus as measured in 2004. Based on analysis of long-term light curve and modeling of coma morphology, we conclude that the 2013 outburst was most likely driven by the crystallization of amorphous water ice triggered by a spin-up disruption of the nucleus. A dust dynamical model shows that a small fraction of the dust ejecta will reach the Earth in 2036 and 2041, but are only expected to produce minor enhancements to the Phoenicid meteor shower. The 2013 outburst of P/Blanpain, though remarkable for a comet of small size, does not necessary imply a catastrophic disruption of the nucleus. The upcoming close encounter of P/Blanpain in 2020 January will provide an opportunity to examine the current state of the comet.

Key words: comets: individual (289P/Blanpain) – meteorites, meteors, meteoroids

1. Introduction

The common end states for both active and dormant comets include dynamical ejection from the solar system, solar/planetary impact, and physical disruption. For short-period comets, physical disruptions are several orders of magnitude more frequent than dynamical ejections or impacts (Jewitt 2004). Well-known examples include 3D/Biela (Jenniskens & Vaubaillon 2007; Wiegert et al. 2013), 73P/Schwassmann-Wachmann 3 (Wiegert et al. 2005; Vaubaillon & Reach 2010), and 332P/Ikeya-Murakami (Jewitt et al. 2016; Kleyna et al. 2016; Hui et al. 2017).

289P/Blanpain was first discovered by Jean-Jacques Blanpain in 1819 as a bright comet. It was last observed on 1820 January 15, and was then subsequently lost for nearly 200 years. In 2003, the Catalina Sky Survey discovered 2003 WY$_{25}$, a small asteroid whose orbit closely resembles the orbit of P/Blanpain (Ticha et al. 2003; Foglia et al. 2005). The orbits of both the 1819 object and 2003 WY$_{25}$ also match the orbit of the Phoenicid meteor shower. Without contrary evidence, it is normally assumed that 2003 WY$_{25}$ is the remnant of the original P/Blanpain, which disrupted in 1819 and supplied the Phoenicids (Jenniskens & Lyytinen 2005; Watanabe et al. 2005; Fujiwara et al. 2017).

Observations of P/Blanpain collected during the 2003/04 apparition showed that it was one-fifth the size of the 1819 object (Jenniskens & Lyytinen 2005). The object appeared point-like in nearly all observations, except for the deep integration obtained by Jewitt (2006) in 2004 March. They noted "a weak optical coma" and derived a mass loss rate of 10^{-2} kg s^{-1}, among the lowest values of known comets. With a diameter of ∼320 m, the object is also among the smallest cometary nuclei ever observed.

The cometary nature of P/Blanpain became more conclusive when it was recovered by the Panoramic Survey Telescope and Rapid Response System (Pan-STARRS) survey on 2013 July 4, with a distinct coma and a broad tail (Williams et al. 2013). The Pan-STARRS team initially reported a brightness of $V = 20.1$ but later commented that it was underestimated (R. Weryk 2016, private communication). Follow-up observations showed an evolving coma and tail, with a brightness at about $V = 17.5$ on UT 2013 July 6.55 (H. Sato, iTelescope at Siding Spring). No further observations were made after 2013 July 17, likely because the comet had faded. The comet was near the opposition at that time and should have been easily detectable.

Intriguingly, P/Blanpain was at 3.9 au from the Sun at the time of the Pan-STARRS recovery, with an expected magnitude $V = 26.9$.[6] It is therefore evident that P/Blanpain was recovered during a large outburst. With a brightness increase of $\Delta m \approx 9$ mag, this is one of the largest cometary outbursts ever observed, exceeded only by the outburst of 17P/Holmes in 2007 ($\Delta m = 15$).

2. Observations

We identified images containing P/Blanpain obtained during and after its 2013 outburst, using the solar system Object Image

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[*] Data and codes that generate the figures of this work are available on Zenodo (10.5281/zenodo.3238650) and on GitHub (https://github.com/Yeqzids/blanpain-2013).

[6] Calculated using a simple *HG* model (see Li et al. 2015) taking $H_R = 21.2$ (Jewitt 2006), assuming $G = 0.15$ and a solar color.

1

Table 1
Summary of the Archival Observations

Date (UT)	Telescope	Filter	N	r_H (au)	Δ(au)	α	m_{obs}	m_{model}	Detection?
2013 July 5	CFHT	r_S	5	3.881	2.878	3°	$17.61 \pm 0.01\ r \Leftrightarrow 17.8\ V$	26.9 V	✓
2015 January 10	DECam	z	1	1.956	1.933	29°	$>22.4\ z \Leftrightarrow 22.4\ V$	25.5 V	✕
2015 February 2	DECam	$\underline{VR}$	2	2.158	1.830	27°	$>23.2\ V$	25.5 V	✕
2015 July 14	CFHT	r	1	3.342	3.206	18°	$>24.8\ r \Leftrightarrow 25.0\ V$	27.4 V	✕
2015 July 20	CFHT	r	1	3.379	3.330	17°	$>24.7\ r \Leftrightarrow 24.9\ V$	27.4 V	✕

Note. Listed are date, telescope, and filter used for the observation, number of images (N), heliocentric and geocentric distances (r_h, Δ), as well as phase angles (α) at the time of the observation, observed total brightness or 3σ upper limit of the comet (m_{obs}), the brightness of P/Blanpain predicted by a simple HG model taking $H_R = 21.2$ (Jewitt 2006) and assuming $G = 0.15$ (m_{model}), and whether P/Blanpain is visible. Magnitudes are converted to Johnson V using the relations derived by Tonry et al. (2012) assuming a solar color (Willmer 2018). For the $\underline{VR}$-band observations, we assume that their color coefficients are equal to those of V.

Search provided by the Canadian Astronomy Data Centre (Gwyn et al. 2012). A total of five nights of data, taken by the Canada–France–Hawaii Telescope (CFHT) MegaCam imager and the Dark Energy Camera (DECam) and spanning from 2013 to 2015, were found. For nights with multiple images, we stacked the images following the motion of the comet to enhance the signal of the comet. Brightnesses of P/Blanpain (or, for the case of non-detection, upper limit of the brightnesses) were calculated using the photometric zero-points and color corrections supplied with each image. Details are tabulated in Table 1.

The only set of images where P/Blanpain is clearly visible is the CFHT image set taken on 2013 July 5. The final stacked image is shown as Figure 1. The coma measures approximately 15–20″ in diameter, and is slightly shifted toward the sunward direction. By using the photometric constants provided along with the images and adopting a 20″ diameter aperture centered on the centroid of the coma, we obtain $r_{SDSS} = 17.7 \pm 0.1$, which is equivalent to Johnson $V = 17.9$ assuming a solar color. The uncertainty is estimated considering the interference from the background star at the 8 o'clock direction of the comet. Other sets of images show no trace of P/Blanpain down to the noise floor within the positional uncertainties (which are all at the order of 1″). From these non-detections, it can be derived that the diameter of the nucleus of P/Blanpain is no larger than 800 m assuming a geometric albedo of 0.04, consistent with the number directly measured by Jewitt (2006), which is 320 m.

3. Onset of the Outburst

To better constrain the onset time of the outburst, we searched the image catalogs of a variety of surveys including Pan-STARRS, CFHT, the Catalina Sky Survey, and all contributions to the Minor Planet Center's Sky Coverage Database, over the time window of 2013 May 1 to September 30, using the image search facility of the Fireball Retrieval on Survey Telescopic Image (FROSTI) software (Clark 2014). Our 10,000,000+ image borehole database contains 116,984 images for the above time window, of which only a small number of Pan-STARRS exposure sets potentially contain the comet (in addition to the CFHT images mentioned previously). Table 2 list these exposure sets. Upon our request, Robert Weryk from the Pan-STARRS team kindly examined the images and provided comments on the visibility of the comet, which are also tabulated in Table 2. Based on the result of the search, as well as Weryk's comments, we conclude that P/Blanpain was already in outburst at least 1 day before the official rediscovery on 2013 July 4, but the 49-day gap between
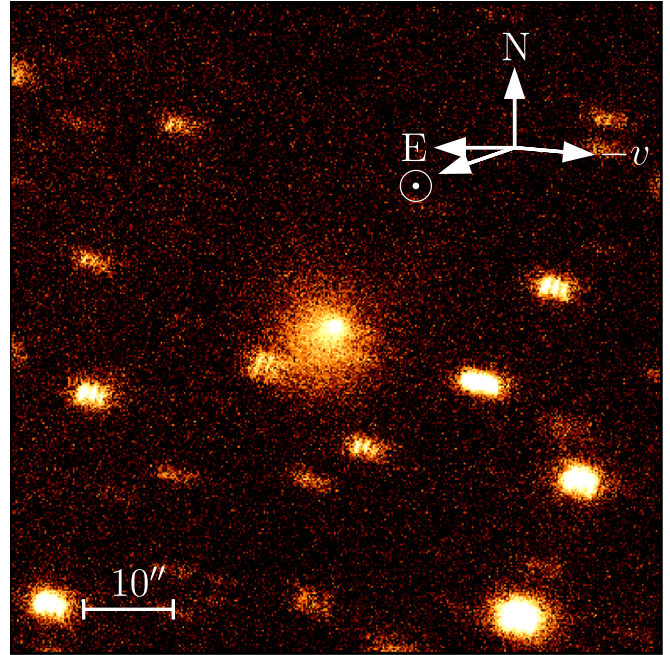

Figure 1. Stacked CFHT image of P/Blanpain taken on 2013 July 5 (center). The arrows on the upper-right corner mark the celestial north, celestial east, direction to the Sun (⊙), and the minus heliocentric velocity motion ($-v$). Notebook is available here:https://github.com/Yeqzids/blanpain-2013/blob/master/cfht_stack.ipynb.

Table 2
Results of the FROSTI Search of Possible Detections of P/Blanpain between 2013 May 1 and September 30

Date (UT)	Survey	Comment
2013 May 15	Pan-STARRS	Object not visible
2013 Jun 18	Pan-STARRS	Object in a chip gap
2013 Jul 3	Pan-STARRS	Object visible but was not initially picked up by Pan-STARRS software
2013 Jul 4	Pan-STARRS	Date of rediscovery
2013 Jul 9	Pan-STARRS	Object visible but was not initially picked up by Pan-STARRS software
2013 Jul 17	Pan-STARRS	Detector issue
2013 Jul 19	Pan-STARRS	Detector issue
2013 Aug 24	Pan-STARRS	Object not visible
2013 Sep 9	Pan-STARRS	Object not visible

Note. The comments are quoted from Robert Weryk through private communication (with bracketed clarifications).

the 2013 July 3 detection and the last image that covers the predicted position of P/Blanpain (2013 May 15) makes it difficult to pinpoint the exact onset time of the outburst. The non-detections on 2013 May 15, August 24, and September 9 set an upper limit of $V \approx 22.5$ of the comet, based on the typical survey depth of Pan-STARRS (Denneau et al. 2013).

4. Coma Morphology and Properties

To understand the driving mechanism of the outburst, we first need to probe the properties of the coma. We use the dust dynamics code originally developed by Ye et al. (2016) to model the coma morphology. To probe different ejection mechanisms, we test two ejection models: the classic Whipple (1951) model and the gravitational escape model.

The Whipple model is devised from the assumption that gas drag from water ice sublimation lifts dust from the sunward-side of the nucleus, a process that happens on most comets. However, we note that the result produced by the Whipple model is also numerically compatible with the ejection caused by amorphous-crystalline transition of water ice (Prialnik et al. 2004). Therefore, this model can be used to describe the dust ejected by either regime.

Under the Whipple model, the speed of the ejected dust follows the relation

$$v_{\mathrm{ej}} = 0.8 r_{\mathrm{H}}^{-9/8} \left(\frac{R_{\mathrm{N}}}{\rho_{\mathrm{d}} r_{\mathrm{d}}} \right)^{1/2} \qquad (1)$$

where r_{H} is the heliocentric distance, R_{N} is the radius of the cometary nucleus, and ρ_{d}, r_{d} are the bulk density and radius of the dust, respectively. The inputs are all in SI units except r_{H}, which is in au. In our simulation, we take $R_{\mathrm{N}} = 160$ m as measured by Jewitt (2006) and assume $\rho_{\mathrm{d}} = 2000 \, \mathrm{kg \, m^{-3}}$ (Rotundi et al. 2015).

Previous studies (see Jewitt et al. 2015, their Figure 18) suggested that impulsive ejections tend to have constant ejection speeds. Therefore, we assume in our gravitational escape model that all particles are ejected isotropically at gravitational escape speed, which is defined by

$$v_{\mathrm{esc}} = \left(\frac{2 G M_{\mathrm{N}}}{R_{\mathrm{N}}} \right)^{1/2} \qquad (2)$$

where G is the gravitational constant, and M_{N} and R_{N} are the mass and radius of the cometary nucleus, respectively. For P/Blanpain, we derive $v_{\mathrm{esc}} \approx 0.1$ m/s. We also simplistically assume that for both models, the dust size r_{d} follows a simple power law, with $dN(r_{\mathrm{d}})/dr_{\mathrm{d}} \propto r_{\mathrm{d}}^{-3.6}$ (see Fulle 2004), and the dust size ranges from $10 \, \mu$m to 0.1 m, following the results of in situ measurements of other comets (e.g., Rotundi et al. 2015).

We test four different dates of which particles are impulsively ejected from the nucleus: 2013 May 16 (i.e., the last pre-outburst observation from Pan-STARRS), June 1, June 16, and July 1, with the model images for each onset date and ejection model shown in Figure 2. The model most compatible with the observation shown in Figure 1 is the Whipple model with ejection date of 2013 July 1, suggesting that the dust were being launched by a sublimation/crystallization-driven activity just a few days before the comet was rediscovered.

While the best-match model reproduces the size and the general shape of the observed coma, we note that it does not reproduce the asymmetry of the coma. This cannot be due to the sunward-only ejection, as this is already accounted for in the assumption of the Whipple model. We suspect that the asymmetry may be due to ejections within a much narrower cone angle near the sub-solar point of the nucleus.

Except for large and very active comets, the brightness of the comet is dominated by the reflected light from the nucleus and the emitted dust. The total mass loss can be calculated by

$$M_{\mathrm{d}} = \frac{4}{3} \rho_{\mathrm{d}} \bar{a} C_{\mathrm{e}} \qquad (3)$$

where $\bar{a} = 10 \, \mu$m is the characteristic grain size (see Jewitt 2006), and C_{e} is the effective scattering cross-section of the ejecta:

$$C_{\mathrm{e}} = \frac{\pi r_{\mathrm{H}}^2 \Delta^2}{p_V \Phi(\alpha) a_{\oplus}^2} (10^{0.4 \Delta m_V} - 1) 10^{0.4(m_{\odot,V} - m_V)} \qquad (4)$$

where $p_V = 0.04$ is the assumed geometric albedo of the dust, $\Phi(\alpha) = 0.035\alpha$ is the simple phase function of the target with a phase angle of α (see Li et al. 2015), $a_{\oplus} = 1.5 \times 10^{11}$ m is the mean heliocentric distance of the Earth, $\Delta m_V = 9$ is the brightness excess in V (as discussed in Section 1), $m_{\odot,V} = -26.8$ is the apparent V magnitude of the Sun (Willmer 2018), and m_V is the nuclear brightness of P/Blanpain. By substituting corresponding numbers, we obtain $M_{\mathrm{d}} = 1 \times 10^8$ kg. The uncertainty in this estimate is within a factor of several, mainly contributed by the uncertainty in $\bar{a}$. The mass loss accounts for $\sim 1\%$ of the mass of the pre-outburst nucleus ($\sim 9 \times 10^9$ kg assuming a nuclear density of $500 \, \mathrm{kg \, m^{-3}}$).

5. Meteor Prospects

The disintegration of comets whose orbits pass near the Earth's orbit is a source of meteor activities at the Earth (Jenniskens 2008; Ye 2018). P/Blanpain is associated with the Phoenicid meteor shower (Jenniskens & Lyytinen 2005; Sato & Watanabe 2010; Fujiwara et al. 2017), and it has been shown that the 1819/20 breakup event has produced a short but intense meteor outburst in 1956 (Weiss 1958; McBeath 2003; Watanabe et al. 2005).

To investigate future encounters between the Earth and the 2013 ejecta, we simulated the dynamical evolution of the ejecta following the same numerical procedure in Ye et al. (2016). In brief, we simulated a set of particles between $10 \, \mu$m and 10 cm in diameter, using the RADAU numerical integrator (Everhart 1985), and followed their positions until 2300 January 1. This size range is chosen as it corresponds to size of meteors detectable by modern techniques (Ye et al. 2016). Ejection vectors of the particles are generated following the Whipple model assuming an ejection time of 2013 July 1, as found in Section 4, based on the orbit solution #7 from the JPL Small-Body Database (https://ssd.jpl.nasa.gov/sbdb.cgi). Effects considered are the radiation pressure on the particles, as well as the gravitational influences from the Sun and the eight major planets, with the Earth–Moon system represented as a single perturber at the barycenter of the two bodies.

We have identified two encounters between the Earth and the ejecta, as tabulated in Table 3. Neither encounters are expected to produce particularly strong meteor activities, as only a small fraction of dust will reach Earth's vicinity. Meteors in both
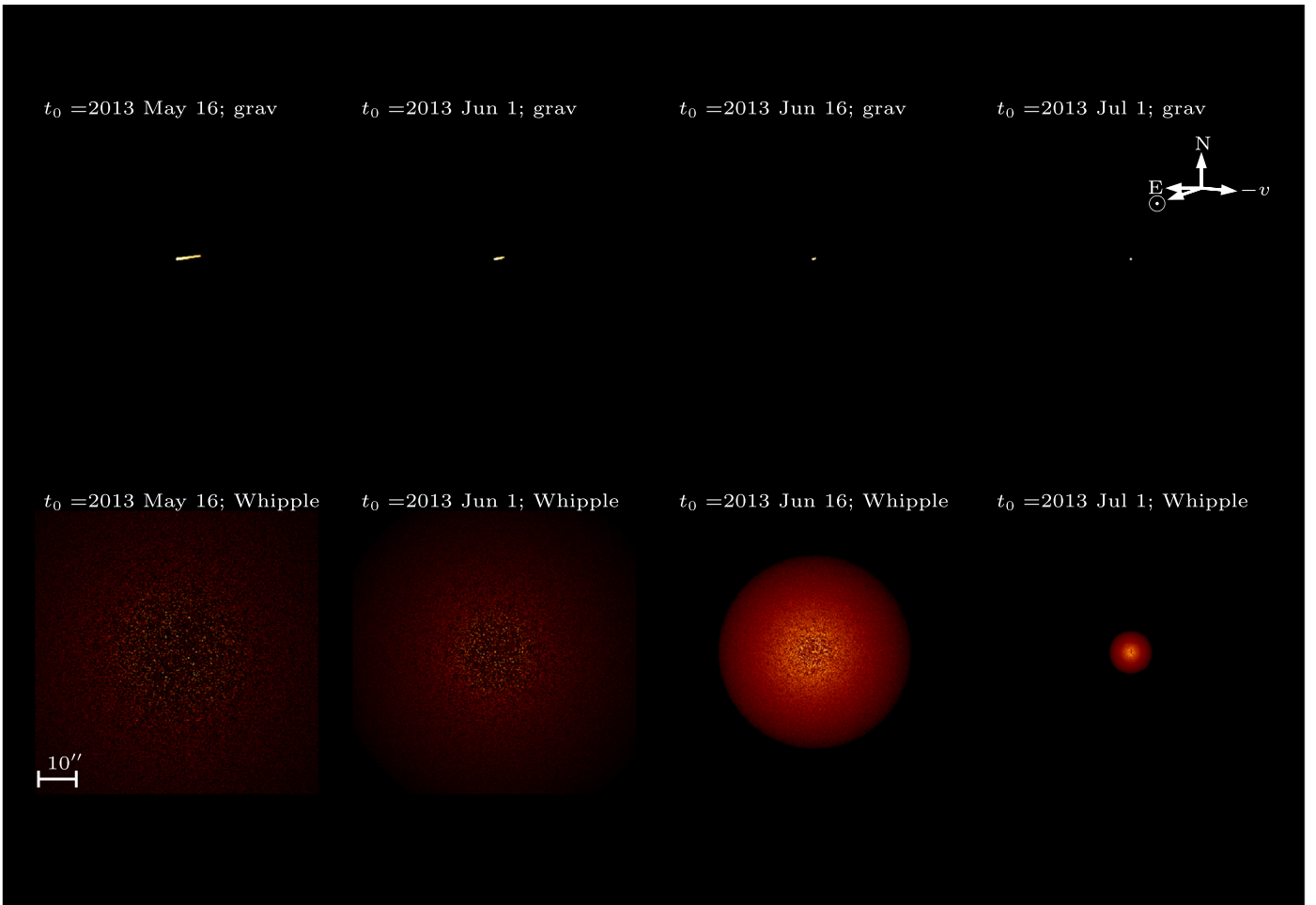
Figure 2. Model images of P/Blanpain on 2013 July 5 under different assumptions: ejection dates (t_0) of 2013 May 16, June 1, June 16 and July 1, as well as ejections following Whipple model or gravitational escape model. The model most compatible with the observation is the Whipple model with ejection date of 2013 July 1 (lower right). Notebook is available here:https://github.com/Yeqzids/blanpain-2013/blob/master/coma_sim.ipynb.

encounters will be dominated by dust of 10 μm in sizes and can only be detected by certain radio techniques (e.g., head-echos).

6. Mechanism

Sub-km comets are more prone to rotational excitation, which may ultimately lead to their disruption. Following (Jewitt 2004, Equation (12)), the excitation timescale of cometary nuclei is

$$\tau_{ex} = \frac{2\pi \rho_N r_N^4}{P_N V_{th} k_T \dot{M}} \qquad (5)$$

where $\rho_N = 500 \, \mathrm{kg \, m^{-3}}$ is the density of the nucleus (Pätzold et al. 2016), $r_N = 160$ m is the radius of the nucleus (Jewitt 2006), $P_N = 5$ hr is the assumed rotational period of the nucleus, $V_{th} = 500 \, \mathrm{m \, s^{-1}}$ is the thermal speed of the sublimating gas, $0.005 < k_T < 0.04$ is the moment-arm of the torque (Belton et al. 2011), and $\dot{M} = 0.01 \, \mathrm{kg \, s^{-1}}$ is the mass-loss rate measured in 2004 (Jewitt 2006). We derive $\tau_{ex} = 20–140$ yr, which is in line with the time elapsed since the last observed disruption of P/Blanpain ($\sim$200 yr ago). We acknowledge that time-domain surveys only began after the 1990s, meaning that any outburst before the 1990s would likely

have been missed. However, an outburst rate of once every several decades is still compatible with the derived τ_{ex}.

In Section 4 we showed that the morphology of the coma is best explained by a sublimation and/or crystallization regime. The impulsive nature of the outburst, coupled with a heliocentric distance marginally beyond the water ice sublimation line, seems to disfavor the sublimation-driven scenario. The molecule production rate of the sublimation of pure water ice at 3.9 au is $\sim 4 \times 10^{20}$ molecule $\mathrm{m^{-2} \, s^{-1}}$ (Cowan & Ahearn 1979). Assuming an event duration of a few days (inferred from the rapid fading of the comet, see Section 1) and taking the previously derived dust production of 1×10^8 kg (equal to a dust production rate at the order of $\sim$0.001 kg $\mathrm{m^{-2} \, s^{-1}}$), a sublimation-driven regime will lead to an unrealistic dust-to-ice ratio ($\sim 10^3$). The amorphous-crystalline transition of water ice, on the other hand, has been proposed to explain large-scale cometary outbursts as well as the activity of comets beyond the ice line (see Prialnik et al. 2004). Such a process, probably triggered by a rotational breakup of the nucleus, provides a consistent picture of the 2013 outburst of P/Blanpain.

The amorphous-crystalline transition can also be triggered by thermal shocks induced by the rotation and orbital motion of the comet. By using dimensional analysis, we derive a skin depth of $(\kappa P)^{1/2} \sim 4$ m (where $\kappa \sim 10^{-7} \, \mathrm{m^2 \, s^{-1}}$ is the thermal

Table 3
Predicted Encounters of the 2013 Ejecta until 2100

Peak Time	Duration	Radiant (J2000)	Geocentric Speed (km s^{-1})	Peak Flux (km^{-2} hr^{-1})	Note
2036 Nov 30, 23:50 UT	8 hr	$\alpha_g = 3°$, $\delta_g = -26°$	9.5	6×10^{-3}	Faint meteors; ZHR ≈ 20
2041 Dec 1, 3:08 UT	1 hr	$\alpha_g = 4°$, $\delta_g = -25°$	9.6	2×10^{-3}	Faint meteors; ZHR ≈ 10

Note. ZHR is the equivalent Zenith Hourly Rate calculated from the peak flux assuming a power-law distribution with a size index of -2.8 (Koschack & Rendtel 1990).

diffusivity, and $P = 5$ yr is the orbital period of the comet). If P/Blanpain only reached its current orbit very recently, amorphous ice located $\gg 4$ m below the surface would have been largely unperturbed by the thermal shocks, and could be the source of the 2013 outburst if located at a suitable depth. Preliminary dynamical simulation shows that P/Blanpain had a higher perihelion ($q \gtrsim 2$ au) a few 10^3 yr ago, which is consistent with the abovementioned assumption. Given that the characteristic timescale of thermal excitation is $\propto r_N^2/\kappa$, smaller nuclei should be more prone to rotational disruption (whose timescale $\propto r_N^4$).

7. Conclusion

A 9-magnitude outburst of the small, 0.3 km diameter comet P/Blanpain at an appreciable heliocentric distance (3.9 au) is one of the largest cometary outbursts ever observed. Despite the magnitude of the outburst, our analysis showed the ejected material only accounts for $\sim 1\%$ of the total mass of the nucleus, therefore the nucleus likely has survived the outburst. This echoes a few previous examples of multi-magnitude outbursts exhibited by sub-kilometer-sized comets, of which the comets have seemingly survived (Ye 2017).

The observed coma morphology and light curve matches an impulsive ejection of dust likely driven by the crystallization of amorphous water ice. Such a process can be triggered by rotational breakup of the nucleus. Smaller fragments generated from the disruption, if any, could have a rotational excitation timescale of $\ll 100$ yr, and may exceed their own critical rotation periods within our lifetime.

We found that the bulk of the material released in the 2013 event will not reach the Earth in the next ~ 300 yr. A small fraction of the material, dominated by 10 μm-sized dust, will encounter the Earth on 2036 December 1 and 2041 December 1, and could produce minor enhancements of the Phoenicid meteor shower. The small sizes of the dust particles, coupled with the low encounter speed, means that the activities will be dominated by very faint meteors best observed by certain radio techniques.

P/Blanpain will have a close encounter with the Earth in 2020 January at a distance of 0.09 au. Preliminary dynamical simulation shows that this is one of P/Blanpain's closest encounters to the Earth, before a close encounter with Jupiter in the year of 2292 that will move the comet to the outer solar system (Q.-Z. Ye et al. 2019, in preparation). Observations during this close approach will likely reveal the current state of P/Blanpain and provide information about cometary breakups.

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