Icarus 203 (2009) 560–570

Contents lists available at ScienceDirect

Icarus

journal homepage: www.elsevier.com/locate/icarus

2006 Fragmentation of Comet 73P/Schwassmann-Wachmann 3B observed with Subaru/Suprime-Cam

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ARTICLE INFO

Article history:
Received 18 February 2008
Revised 30 March 2009
Accepted 15 April 2009
Available online 23 May 2009

Keywords:
Comets, Dynamics
Comets, Nucleus
Near-Earth objects
Interplanetary medium

ABSTRACT

The fragmentation of the split Comet 73P/Schwassmann-Wachmann 3 B was observed with the prime-focus camera Suprime-Cam attached to the Subaru 8.2-m telescope. The fragmentation revealed dozens of miniature comets [Fuse, T., Yamamoto, N., Kinoshita, D., Furusawa, H., Watanabe, J., 2007. Publ. Astron. Soc. Jpn. 59 (2), 381–386]. We analyzed the Subaru/Suprime-Cam images, detecting no fewer than 154 mini-comets, mostly extending to the southwest. Three were close to the projected orbit of fragment B. We applied synchrone–syndyne analysis, modified for rocket effect analysis, to the mini-fragment spatial distribution. We found that most of these mini-comets were ejected from fragment B by an outburst occurring around 1 April 2006, and three fragments on the leading side of nucleus B could have been released sunward on the previous return. Several fragments might have been released by successive outbursts around 24 April and 2 May 2006. The ratio of the rocket force to solar gravity was 7–23 times larger than that exerted on fragment B. No significant color variation was found. The mean color index, $V-R = 0.50 \pm 0.07$, was slightly redder than that of the Sun and similar to that of the largest fragment, C, which suggests that these mini-fragments were detected mainly through sunlight reflected by dust particles and materials on the nuclei. We examined the surface brightness profiles of all detected fragments and estimated the sizes of 154 fragments. We found that the radius of these mini-fragments was in the 5- to 108-m range (equivalent size of Tunguska impactor). The power-law index of the differential size distribution was $q = -3.34 \pm 0.05$. Based on this size distribution, we found that about 1–10% of the mass of fragment B was lost in the April 2006 outbursts. Modeling the cometary fragment dynamics [Desvoivres, E., Klinger, J., Levasseur-Regourd, A.C., Lecacheux, J., Jorda, L., Enzian, A., Colas, F., Frappa, E., Laques, P., 1999. Mon. Not. Roy. Astron. Soc. 303 (4), 826–834; Desvoivres, E., Klinger, J., Levasseur-Regourd, A.C., Jones, G.H., 2000. Icarus 144, 172–181] revealed that it is likely that mini-fragments smaller than $\sim$10–20 m could be depleted in water ice and become inactive, implying that decameter-sized comet fragments could survive against melting and remain as near-Earth objects. We attempted to detect the dust trail, which was clearly found in infrared wavelengths by Spitzer. No brightness enhancement brighter than 30.0 mag arcsec^{-2} (3σ) was detected in the orbit of fragment B.

1. Introduction

73P/Schwassmann-Wachmann 3 (hereafter 73P/S-W3) is a member of the Jupiter-family comets (JFCs), orbiting the Sun with a 5.4-year period. During the apparition of 1995, 73P/S-W3 showed a huge outburst in activity. Afterward, four separate nuclei were confirmed and labeled A, B, C, and D. Of the four, fragment C was the largest and the presumed principal remnant of the original nucleus. The size of the nucleus was studied based on the standard assumption for a geometric albedo of 0.04 and a linear phase coefficient of 0.04 mag deg^{-1}; the upper limit of the pre-breakup radius was 1.1 km (Boehnhardt et al., 1999), and the radius of fragment C was 0.68 ± 0.04 km. Although the radius of fragment B was estimated to be 0.68 km from Hubble Space Telescope (HST) observations (Toth et al., 2003), Boehnhardt et al. (2002) established an upper limit of 0.2–0.3 km. Due to poor observing conditions, fragments A and D were not found in the 2001 apparition.

We had a good opportunity to observe these broken comet fragments during its 2006 return. From near-infrared spectroscopy, no remarkable differences between fragment B and fragment C were found (Kobayashi et al., 2007; Villanueva et al., 2006). HST photographed two fragments, B and G, on 18–20 April 2006. These images revealed several dozen mini-fragments. The Spitzer Space

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0019-1035/$ - see front matter © 2009 Elsevier Inc. All rights reserved.
doi:10.1016/j.icarus.2009.04.030

Telescope showed not only many fragments distributed nearly on orbit but also the debris trail between them. The debris trail (dust trail) is composed of large dust particles ejected before the last perihelion passage (Vaubaillon and Reach, 2006; Reach et al., 2007). Fuse et al. (2007) made optical observations of fragment B on 3 May 2006 using the wide-field optical camera attached to the Subaru 8.2-m telescope. R-band images confirmed 58 mini-comets in the vicinity of fragment B. No fragments were found along the orbit of fragment B in their Subaru images (Fuse et al., 2007).

This spectacular Subaru image presents several concerns. We noticed that most of these fragments were distributed between the anti-solar direction from fragment B and the negative orbit velocity vector. This positioning was quite interesting because these mini-comets behaved dynamically like dust particles pressed back by solar radiation pressure against the solar gravity. No obvious dust trail was found in the Subaru optical image, even though it was clear in the Spitzer infrared image. In this study, we re-analyzed the Subaru/Suprime-Cam images using the masking method developed for the detection of faint cometary dust clouds (Ishiguro et al., 2007; Sarugaku et al., 2007; Ishiguro, 2008) and constructed a comet image without contaminants (e.g., stars and galaxies). This technique enabled us to detect mini-comets brighter that 26.5 mag and diffuse light sources associated with the comet brighter than 30.0 mag arcsec^{-2}. Applying a unique method of examining fragment size and onset time (modified synchrones and syndynes), we examined the dynamical properties of the mini-fragments. We also studied the brightness profile of these mini-comets and deduced their sizes. Given the dynamical properties and sizes, we considered the activity of the mini-comets.

2. Data and observations

2.1. Data

We re-analyzed the Subaru data provided by the SMOKA data server, which is operated by the Astronomy Data Center, National Astronomical Observatory of Japan (Baba et al., 2002). Observations of 73P/S-W3 were carried out by Fuse et al. (2007) using the Subaru 8.2-m telescope on Mauna Kea, Hawaii, on a single day, 3 May 2006, when fragment B was at a heliocentric distance r_h = 1.070 AU, a geocentric distance Δ = 0.112 AU, and a solar phase angle α = 54°. Fuse et al. (2007) used an optical CCD camera, Suprime-Cam, attached to the prime focus of Subaru. This combination provided wide-field imaging capability, $34' \times 27'$, with a pixel resolution of 0.20″ pixel^{-1}. The seeing was about 0.7″ (FWHM), which projects to 57 km at the position of the comet. The exposure time and filters are summarized in Table 1. All comet images were taken in comet-tracking mode. Although Fuse et al. (2007) did not use the short exposure-time R-band images (10–30 s) and V-band images, we found that these were essential to (i) determining the brightness of mini-comets near fragment B, (ii) improving the signal-to-noise ratio, and (iii) identifying detected sources as having a cometary origin. Fragment B was so bright that a large area of sky near B was saturated in 120-s exposures. The signal-to-noise ratio was improved by combining all images. We used the V and R composite image to confirm the mini-fragments because the color index V–R avoids false detections (see Section 2.2). Further explanations of the Suprime-Cam and 73P/S-W3B observations appear in Miyazaki (2002) and Fuse et al. (2007), respectively.

Table 1
Subaru/Supreme-Cam data we used in this paper.

UT (2006 May 03)	Filter	Exposure time (s)	Number of exposure
14:13	R	30	1
14:17–14:28	R	120	4
14:32	R	10	1
14:41–14:53	V	120	4

2.2. Data reduction

As a first step, the obtained data were reduced in the standard way with bias and flat-field corrections. These ancillary data were also provided through the SMOKA system. Because useful bias data were not obtained during the night of 3 May, we used bias frames taken on 1 May. Flux calibration was done using Landolt standard stars in the SA113 region (Landolt, 1992).

The sky background was contaminated by elongated stars and galaxies because the observations were carried out in comet-tracking mode. We removed these stellar objects using the masking algorism developed for the data reduction of cometary dust trails (Sarugaku et al., 2007; Ishiguro et al., 2007; Ishiguro, 2008), outlined as follows. We first made images to align the stars, because this is an effective way of detecting faint stars and galaxies. Using these images, stars were automatically detected by a source extractor program, SExtractor (Bertin and Arnouts, 1996). We masked the identified objects using $18'' \times 6''$ rectangular masks. We also masked pixels identified as bad in the bias (hot pixels and lines) and flat-fielding images (pixels with sensitivity 10% higher or lower than the average). We combined the masked images with offsets to align the comet, excluding the masked pixels and shifting the background intensity to zero. Because the comet moved relative to the stars, it was possible to exclude nearly all masked pixels in the resultant composite image. Finally, we obtained V- and R-band composite images without stars. For the composite images, we used images with 120-s exposure times. Approximately 17% of the pixel values in the images were masked by this method. Therefore, the effective total exposure times were 400 s in each wavelength.

To extract the mini-comets in the composite images, we first flattened the sky background by subtracting the 23-pixel × 23-pixel ($4.6'' \times 4.6''$) running median images. This is a standard image-processing technique known as "unsharp masking." The large-scale components associated with the mini-comets could be subtracted out by this method. The R-band image is shown in Fig. 1. Because we detected no significant difference in appearance between the V- and R-band subtracted images, we combined these two into single image. This VR composite image was used for the detection of faint mini-comets. We used the SExtractor again to detect the mini-comets. We found 211 mini-comet candidates in this VR composite image. The positions and magnitudes of these mini-comets were examined using the "phot" command in the IRAF/APPHOT package. We set a fixed aperture size of 2.0″. This aperture gathered the light from nuclei and a portion of the light from the coma components. Assuming that fragment B was at the brightest point in the 10 s exposure image, we determined the relative positions of the mini-comets.

Of the 211 mini-comet candidates, we determined R-band magnitudes for 176 objects, V-band magnitudes for 161 objects, and both R- and V-band magnitudes for 154 objects. In Fig. 2, we compare the V- and R-band magnitudes of 154 comet candidates. A glance at Fig. 2 reveals that the V–R color indices of these 154 objects were slightly redder that of the Sun (V–R_{Sun} = 0.367; Rabinowitz, 1998). The mean color of the mini-comets, V–R = 0.50 ± 0.07, was similar to that of main nucleus C, V–R = 0.48 ± 0.17 (Boehnhardt et al., 1999; Lamy et al., 2004). Accordingly, we can state that at least 154 mini-comets were detected by our data analysis methods.