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Dust loss from activated asteroid P/2015 X6

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ABSTRACT

We present observations and dust tail models of activated asteroid P/2015 X6 from deep imaging data acquired at the 10.4m Gran Telescopio Canarias (GTC) from mid-December 2015 to late January 2016. The results of the modeling indicate that the asteroid has undergone a sustained dust loss over a two-month or longer period. The dust parameters, derived from multidimensional fits of the available images, are compatible with either ice sublimation or rotational

instability processes. An impulsive event, as it could be associated to an impact with another body, is less likely. A power-law distribution of particles, with minimum and maximum radius of 1 μm and 1 cm, and power index of -3.3 is found to be consistent with the observations. Depending on the ejection velocity model adopted, the particle velocities are found in the 0.3 to 10 m s^{-1} range. The activation time was between 18-26 days before discovery. The total ejected mass from that time to the most recent observation is in the range $5\text{-}9 \times 10^6$ kg. No dust features giving indication of past activity earlier than the activation time have been observed.

Subject headings: Minor planets, asteroids: individual (P/2015 X6) — Methods: numerical

1. Introduction

The activated asteroid P/2015 X6 was discovered by Lilly & Weryk (2015) from Pan-STARRS 1 images on December 7.27, 2015. Follow-up images were obtained from several observatories until December 15, 2015, by Tubbiolo et al. (2015) from LPL/Spacewatch II. The object was described as having a non-stellar coma with a narrow tail of 6 " size towards PA=75 deg. The available astrometry indicates that the object is asteroidal from the dynamical point of view, as its Tisserand invariant respect to Jupiter (Kresak 1982) is $T_J=3.32$, derived from its orbital elements $a=2.756$ AU, $e=0.170$, and $i=4.56^\circ$. To date, more than fifteen objects of this kind have been discovered. Their activity might have been triggered by a variety of processes, like rotational instability (e.g. P/2012 F5 or P/2013 R3, Drahus et al. 2015; Jewitt et al. 2014), an impact with another object (e.g. (596) Scheila, Moreno et al. 2011a), or ice sublimation (e.g. 133P or 324P, Hsieh et al. 2010; Moreno et al. 2011b; Hsieh & Sheppard 2015), although in these latter cases no gas emission lines have been detected so far. For an in-depth review of the activation mechanisms involved and a detailed description of the individual objects, we refer to Jewitt et al. (2015). From the dynamical point of view, most of those activated asteroids are stable in time scales of 100 Myr or longer (Hsieh et al. 2012, 2013), so they are native members of the main belt, although there are two objects (238P and 259P) which are unstable on scales of only 10-20 Myr (Haghighipour 2009; Jewitt et al. 2015).

In this paper we report observations acquired with the 10.4m GTC, and models of the dust tail brightness of P/2015 X6, in order to characterize its dust emission pattern, the activation time and the duration of the activity, and the total dust mass loss, and attempt to identify which mechanism(s) could be playing a role in its activation.

2. Observations and data reduction

Images of P/2015 X6 were acquired under photometric conditions on the nights of 17 and 30 December 2015, and 7 and 25 January 2016. The images were obtained using a Sloan r' filter in the Optical System for Image and Low Resolution Integrated Spectroscopy (OSIRIS) camera-spectrograph (Cepa et al. 2000; Cepa 2010) at the GTC. OSIRIS is equipped with two Marconi CCD detectors, each with 2048×4096 pixels, providing a field of view of $7.8' \times 7.8'$. In order to improve the signal-to-noise ratio we used 2×2 binning, so that the plate scale was $0.254''/\text{px}$. The seeing (FWHM) in the images ranged from $0.9''$ to $1.2''$. After bias subtraction and flat-field correction a median stack of the available frames was computed. The resulting images were calibrated using standard stars, and then converted to solar disk intensity units, which are the output of the dust tail code. The journal of the observations is given in Table 1, where we indicate the date of the observations (in UT and days to the asteroid perihelion), the heliocentric (R) and geocentric (Δ) distances, the phase angle (α), the position angle of the Sun to comet radius vector (PsAng), and the angle between the Earth and the asteroid orbital plane (PIAng). The reduced images are shown in Figure 1, in which the directions to the Sun and the asteroid orbital motion are indicated. The Earth crossed the orbital plane of the comet during the observational period, being just $+0.01^\circ$ above this plane on the observation of January 7, 2015. No dust features that could be associated to early activity such as neck-line or trail are seen. The Sloan r' magnitudes shown in Table 1 are computed on circular apertures of radius $2''$. To set an upper limit to the asteroid size, we converted the r' magnitudes to absolute magnitudes H_v by the relation:

$$H_v = m_v - 5 \log(R\Delta) + 2.5 \log[\phi(\alpha)] \quad (1)$$

where m_v is the apparent visual magnitude, and $\phi(\alpha)$ is the ratio of the scattered flux at phase angle α to that at $\alpha=0^\circ$. To obtain m_v from r' magnitudes we used the Fukugita et al. (1996) relationship:

$$m_v = r' - 0.49(B - V) + 0.11 \quad (2)$$

where we assumed the solar $B - V = +0.65$ (Cox 2000). Then, we obtained a maximum $H_v = +18.16$. We adopt the HG formulation (Bowell et al. 1989) with parameter $g=0.15$ (appropriate for a C-type asteroid). From the $a-i$ and $a-e$ albedo maps of Masiero et al. (2011), a geometric albedo of $p_v \sim 0.1$ is obtained. However, all the objects found having a sustained activity are from type C-complex (Licandro et al. 2011, 2013) which have darker albedoes ($p_v \sim 0.05$). Then, adopting the Harris & Lagerros (2002) formula relating geometric albedo to asteroid diameter D (in km):

$$D = \frac{1329}{\sqrt{p_v}} 10^{-0.2H_v}, \quad (3)$$

we obtain, for p_v between 0.05 and 0.1, a diameter D in the range 980 to 1390 m. This provides a very stringent upper limit for the asteroid size, as the dust coma is likely dominating the observed brightness in the 2'' aperture, but would be an useful ingredient for the discussion of the dust models as described in Section 4.

3. The Model

In order to perform a theoretical interpretation of the obtained images, and to retrieve the dust parameters, we used our Monte Carlo dust tail code, which has been used previously on several works on activated asteroids and comets, including comet 67P/Churyumov-Gerasimenko, the Rosetta target (e.g., Moreno et al. 2016). The model computes the position on the sky plane, and their contributions to the tail brightness, of a large amount of particles ejected from the nucleus since a given epoch, under certain hypotheses about the particle physical properties and size distribution, and the dust mass loss rate. It is assumed that the particles, after leaving the object's surface, are subjected to the solar radiation pressure and gravity forces. We neglect the object's gravity, an assumption valid for small-sized objects. Under those conditions, the trajectory of the particles becomes Keplerian, being defined by their orbital elements, which are functions of their sizes and ejection velocities (e.g. Fulle 1989).

The ratio of radiation pressure to the gravity forces exerted on each particle is given by the β parameter, expressed as $\beta = C_{pr}Q_{pr}/(2\rho r)$, where $C_{pr}=1.19 \times 10^{-3} \text{ kg m}^{-2}$, Q_{pr} is the radiation pressure coefficient, and ρ is the particle density. Q_{pr} is taken as 1, as it converges to that value for absorbing particles of radius $r \gtrsim 1 \text{ }\mu\text{m}$ (see e.g. Moreno et al. 2012a, their Figure 5).

A number of simplifying assumptions on the dust physical parameters must be made in order to make the problem tractable. Thus, the particle density is taken as 1000 kg m^{-3} , and the geometric albedo is set to $p_v=0.04$, indicative of dark material of carbonaceous composition (see e.g. Moreno et al. 2012a). In addition, a linear phase coefficient of $0.03 \text{ mag deg}^{-1}$ was used to correct for the phase function of the dust particles, a typical value found for comet dust in the $1^\circ \leq \alpha \leq 30^\circ$ range (Meech & Jewitt 1987). The particles are assumed to be broadly distributed in size, with minimum and maximum particle radii set initially to $1 \text{ }\mu\text{m}$ and 1 cm , and following a power-law function of index κ . In order to keep the fitting parameters to a minimum, we set this value to $\kappa=-3.3$, which is within the range

of previous estimates of the size distribution of particles ejected from activated asteroids and comets. Isotropic ejection of the particles is assumed.

The ejection velocity of the particles will depend on the activation mechanism involved, which is unknown. In previous works of activated asteroids, we assumed ejection velocities depending on the particle size following a function of the kind $v \propto \beta^\gamma$. Values of γ of order 0.5, derived from simplified hydrodynamic considerations has been used by many authors (including ourselves) for activity driven by ice sublimation. A weak correlation between velocity and mass (or size) have been obtained for fragments ejected in collision experiments (e.g., Giblin 1998), in the range 0-0.5, with mean value of 0.23. We have obtained, in fact, values of γ as low as ~ 0.05 in the analysis of the tails of activated asteroid (596) Scheila, that was likely the result of an impact (Moreno et al. 2011a) .

On the other hand, recent work on comet 67P, the target of Rosetta, has shown that the velocity of the particles, measured in-situ from OSIRIS and GIADA instruments, do not show any evident trend regarding size when the comet was far from perihelion (3.6–3.4 AU) (Rotundi et al. 2015). Closer to the Sun (3.36-2.29 AU), the size dependence, estimated with the same instrumentation, became more apparent, being characterized by a steep power-law function, although with a considerable dispersion around the most probable value ($\gamma=0.96\pm 0.54$, Della Corte et al. 2015). Taking into account these results and the uncertainty in the particle ejection mechanism, we consider two different models by adopting two kind of ejection velocity functions: a customary power-law given by $v = v_0\beta^\gamma$, which will be called Model 1, and a random function of the form $v = v_1 + \zeta v_2$, where ζ is a random number in the $[0, 1]$ interval, and v_1 and v_2 are the fitting parameters. This model will be referred as to Model 2.

For the dust loss rate, we have adopted a half-Gaussian function whose maximum denotes the peak dust-loss rate (\dot{M}_0), located at the start of the particle emission event (t_0). The half-width at half-maximum of the Gaussian (HWHM) is a measure of the effective time span of the event.

For Model 1, we have a set of five fitting parameters in total, \dot{M}_0 , t_0 , HWHM, v_0 , and γ , and for Model 2, we have also five fitting parameters, namely \dot{M}_0 , t_0 , HWHM, v_1 , and v_2 . To fit the observed dust tails brightnesses, we searched for a minimum of the function $\chi = \sum \sigma_i$, where the summation is extended to the four images under consideration, and $\sigma_i = \sqrt{(\sum [\log(I_{obs}(i)) - \log(I_{fit}(i))]^2 / N(i))}$, where $I_{obs}(i)$ and $I_{fit}(i)$ are the observed and modeled tail brightness, and $N(i)$ is the number of pixels of image i . In order to avoid regions of the images contaminated by field stars, the summation was restricted to pixels outside those regions. The minimization procedure was performed by the multidimensional downhill simplex algorithm (Nelder & Mead 1965), as described in Press et al. (1992). Since the

algorithm always searches for a local minimum in the five-dimensional space of parameters, we used different starting simplex in order to increase the probability that the minimum of the different minima found was the deepest one.

We performed a preliminary, zero-th order analysis, of the images by constructing a syndyne-synchrone map for each observing date. From those maps, we inferred that the activation time of the asteroid should be close in time to the discovery date, owing to the absence of dust features that could have shown-up at the corresponding locations of synchrones approximately two months before discovery date or older. In particular, no neck-line or trail features appear in the January 7th 2016 image ($PIAng \sim 0^\circ$), that could have indicated past activity. In addition, no dust condensations along the direction of isolated synchrones, that could have indicated short bursts of activity (e.g., the case of P/2012 F5 (Gibbs), Moreno et al. 2012b), or several separated short bursts, as in the case of P/2013 P5 (Jewitt et al. 2013; Moreno et al. 2014) are shown. According to this, it is reasonable to start the search for a minimum in the function χ defined above placing the activation time (t_0) between a few days before the discovery date (102.5 days before perihelion) and about 60 days before. Regarding the duration of the activity, the smooth variation in absolute magnitudes (from $H_v=17.88$ to $H_v=18.16$, see equation [1]) over the ~ 40 days period of observation and the aforementioned lack of single-synchrone dust features would suggest a long-lasting process and not an impulsive one, short-duration event, like a collision with another body. In any case, we considered both long- and short-duration events by varying HWHM in a wide range between a few days and several months in the starting simplex of the five-dimensional parameter space search. For the peak dust mass loss, we imposed a wide range between a minimum of 0.1 kg s^{-1} and 100 kg s^{-1} , while for the velocities set broad limits for the parameters v_0 , v_1 , and v_2 , so that the velocities ranged from 0 to $5 \times 10^3 \text{ m s}^{-1}$ (the mean velocity in the asteroid belt), and the parameter γ from 0.5 to 0, i.e., from typical gas drag to nearly flat distribution of velocities.

4. Results and Discussion

The resulting best-fit parameters for Models 1 and 2 are given in Table 2. We consider a limiting value of $\chi \leq 0.15$ to consider a fit as acceptable. The uncertainties provided correspond to the range of variation of the best-fit parameter for which $\chi \leq 0.15$. Models 1 and 2 shows very similar χ values and very similar isophote fields, so that we only provide the results of Model 1 in terms of those isophote fields (Figure 2, panels a1 to d1). The peak dust loss rate varies between 1 kg s^{-1} and 1.6 kg s^{-1} , while similar activation times are found for both models: 120 and 128 days before perihelion for Model 1, and 2, respectively. The

HWMH are also close between the two models: 75 days for Model 1, and 84 days for Model 2. The greatest difference between the models is found in the range of ejection velocities. For Model 1, the minimum velocity, corresponding to the largest sized particles ejected ($r=1$ cm), is 1 m s^{-1} , and the maximum (for $1 \mu\text{m}$ radius particles) is only a factor of 3 larger, because of the low value of $\gamma=0.12$. However, for Model 2, we found a broader range between 0.29 and 9.8 m s^{-1} , giving a median value of $\sim 5 \text{ m s}^{-1}$. If the minimum velocities found would correspond to escape velocities, then, for Model 1, we would obtain asteroid diameters between 1544 and 1890 m (for bulk densities of 3000 and 2000 kg m^{-3} , respectively), while for Model 2, the diameters would range from 450 to 550 m , for the same densities. According to the upper asteroid size limit imposed by the absolute magnitude determination (D in the range 980 to 1390 m , see above), Model 1 would not meet this constraint, and, consequently, should be rejected. However, there is not a priori a specific physical reason to think that the slowest particles should be ejected at velocities near the escape velocity, because this would depend on the ejection mechanism involved, which is not known.

Let us assume first a rotational instability as the cause of the event. A short-duration event was needed to explain the activity in P/2012 F5 (Gibbs), (e.g., Stevenson et al. 2012; Moreno et al. 2012b) and, although an impact with another object was invoked as the cause, the discovery of several trailing fragments in follow-up images by Drahus et al. (2015) led them to infer a rotational instability as the most likely mechanism. For P/2012 F5, we inferred quite low dust ejection velocities, of the order of $8\text{-}10 \text{ cm s}^{-1}$ (Moreno et al. 2012b). This would be in fact compatible with rotational instability causing particles to be ejected at velocities near the escape velocity of the parent body. In the case of asteroid P/2013 R3, that was observed to broke apart in several fragments, a rotationally induced mechanism was also invoked, and the inferred dust speed was also low, of the order of 1 m s^{-1} (Jewitt et al. 2014). In contrast to P/2012 F5, however, the activity was sustained during 2-3 month period, the fragments becoming individual dust sources (Jewitt et al. 2014). In the case of P/2015 X6, we have also inferred a sustained activity, of the order of months, and low velocities ($2\text{-}5 \text{ m s}^{-1}$ in average, depending on the model), so that in principle its activation mechanism would be compatible with a rotational instability. It is important to note, however, that we have not seen any fragments, although this is hampered by the spatial resolution and the limiting magnitude reachable with the used instrumentation.

Another possibility is the occurrence of an impact that produced the excavation of surface layers of the asteroid, exposing ices that might exist in its interior to sunlight, or, alternatively, that on some surface regions of the asteroid the temperature becomes high enough when the asteroid approaches perihelion that surface ices can sublimate. In any of those cases, this would led to a sustained dust activity induced by the sublimation, as is very likely the case of activated asteroids 133P, 238P, 313P, and 324P (Hsieh et al. 2004, 2011;

Jewitt et al. 2015; Pozuelos et al. 2015; Hsieh & Sheppard 2015), although the strongest reason for this mechanism to occur is the fact that they show recurrent activity when near-perihelion. In consequence, ice sublimation would very well explain the sustained activity we have found for this object, but more observations during next perihelion passages would be needed to assess the likelihood of this mechanism.

We could not find a solution with a comparable fit quality as the best-fit Models 1 or 2 for an impulsive, short-duration event. Thus, limiting the HWHM to 2 days or less for the Model 1 parameters, the code converges to a solution with a very large $\chi=0.435$. Assuming the Model 2 parameters, the results improve significantly, but still $\chi=0.159$, far from the best χ values of Models 1 and 2. The isophote fields from this short-burst model (called Model 3) are shown in figure 2, together with the results of Model 1, and the best-fit parameters are shown in Table 2. Figure 3 display intensity scans along the tails of the best-fit Models 1 and 3, in which it can be seen the much better agreement of Model 1 with the data as compared to Model 3. In summary, a short-duration event seems unlikely.

5. Conclusions

From the GTC observations and the dust tail modeling of the activated asteroid P/2015 X6, the following conclusions can be drawn:

1) The analysis performed by a simultaneous multidimensional fit to the four available dust tail images implies most likely a sustained activity pattern spanning at least two months until the most recent observation, but probably much longer. The nature of the activation could not be determined, as both ice sublimation and rotational instability can be invoked as plausible mechanisms. Future near-perihelion observations would be needed to search for recurrent activity. The possibility of a short-duration burst of activity that could be caused by an impact and subsequent ejection of material is unlikely from the model fits.

2) Two ejection velocity models, one based on a customary $v \propto \beta^\gamma$ (Model 1) and another based on a random distribution of the kind $v = v_1 + \zeta v_2$ (where ζ is a random number in the (0, 1) interval) (Model 2), have been proposed. For Model 1, a nearly flat distribution of particle velocities are found, in the range 1-3 m s⁻¹. The best-fits for Model 2 imply a wider range of velocities in the 0.3 to 10 m s⁻¹ range. The quality of the fits obtained was very similar, so that none of those models can be favored over the other.

3) The derived dust mass loss rate is characterized by a peak value of 1 and 1.6 kg s⁻¹, with a time span of ~ 75 and ~ 100 days, for Models 1 and 2, respectively. The total ejected dust mass since activation date until the most recent observation reported was $5-9 \times 10^6$ kg.

4) The activation times found were of 18 and 26 days before the discovery date, for Models 1 and 2, respectively. No dust features that could be attributed to older activity were found.

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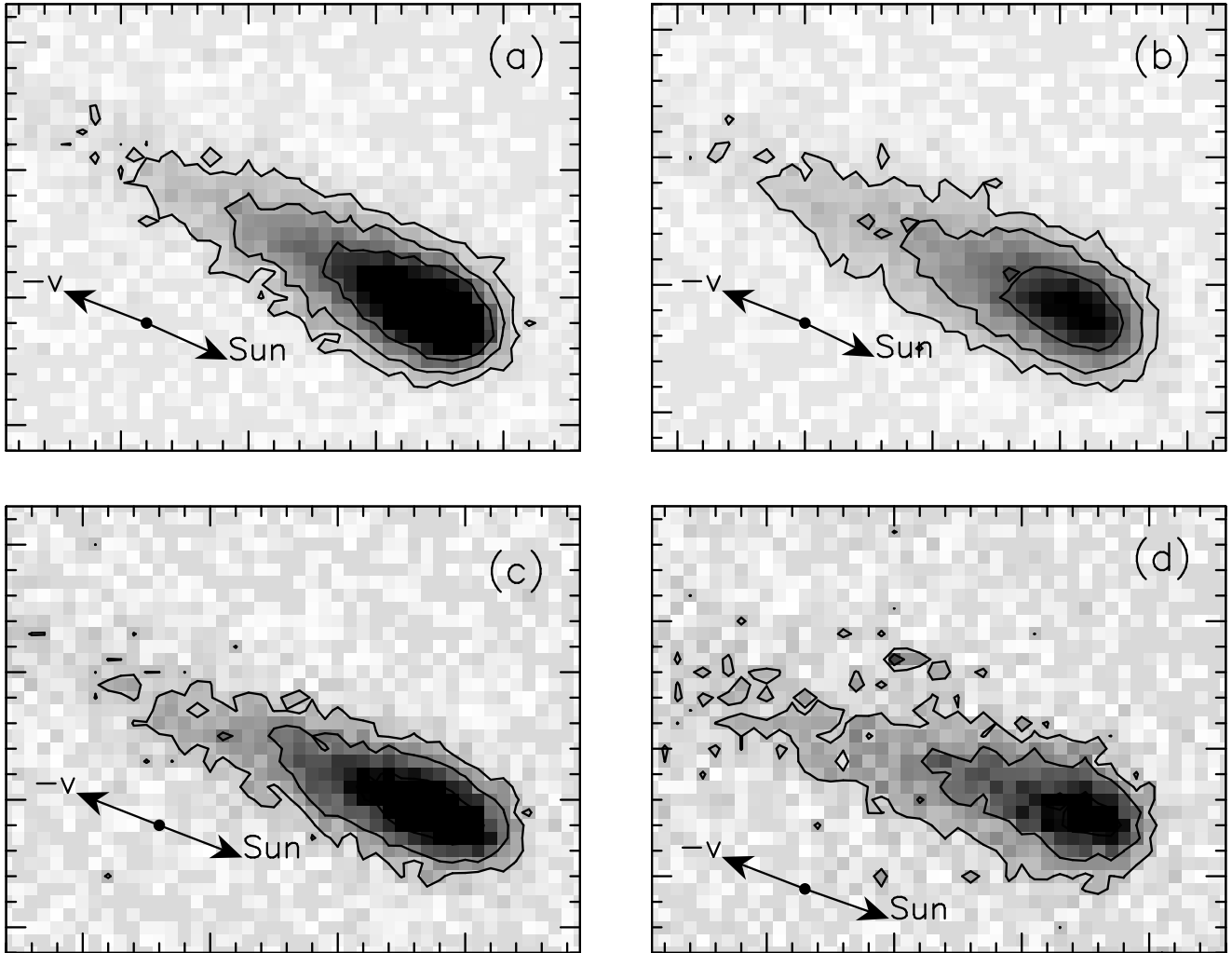


Fig. 1.— Median stack images of P/2015 X6 obtained with the OSIRIS instrument of the 10.4m GTC through a Sloan r' filter, on UT 2015 Dec 7 (a), 2015 Dec 30 (b), 2016 Jan 07 (d), and 2016 Jan 25. North is up, East to the left. The directions to the Sun and the negative of the orbital velocity motion are shown. The spatial dimensions of the images at the asteroid distance (in km), in each panel, are as follows: (a): 13728×10677 ; (b): 14839×11541 ; (c): 15577×12115 ; (d): 17301×13456 .

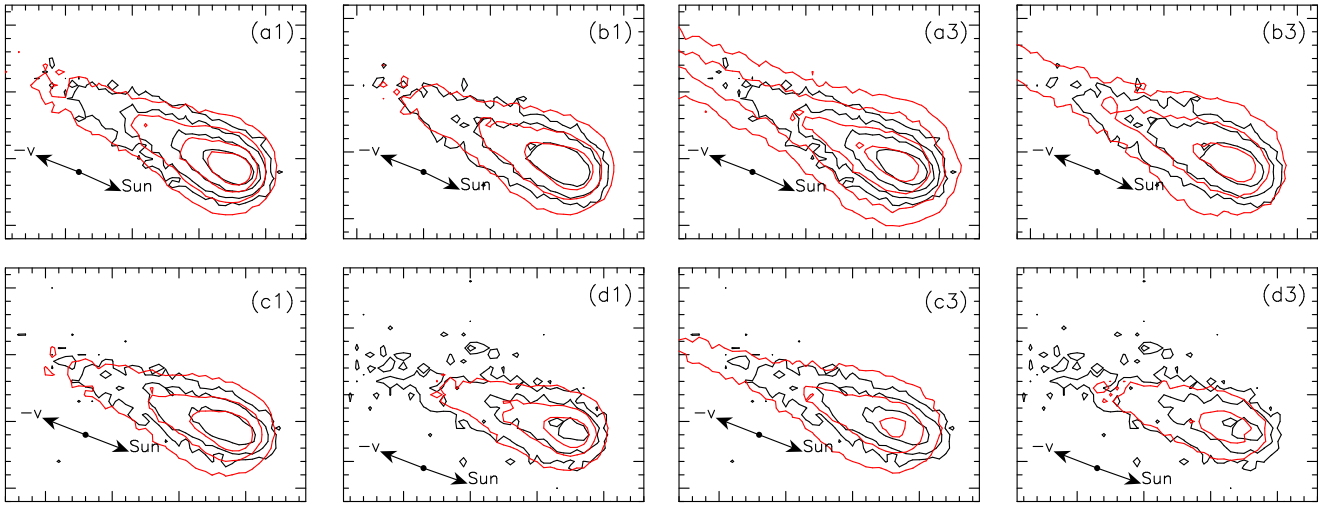


Fig. 2.— Measured (black) and modeled (red) isophotes for Model 1 (four leftmost panels a1 to d1) and Model 3 (four rightmost panels a3 to d3). The panels correspond to the same dates as in figure 1. Innermost isophote levels are 1.5×10^{-14} solar disk intensity units, and decrease in factors of two outwards.

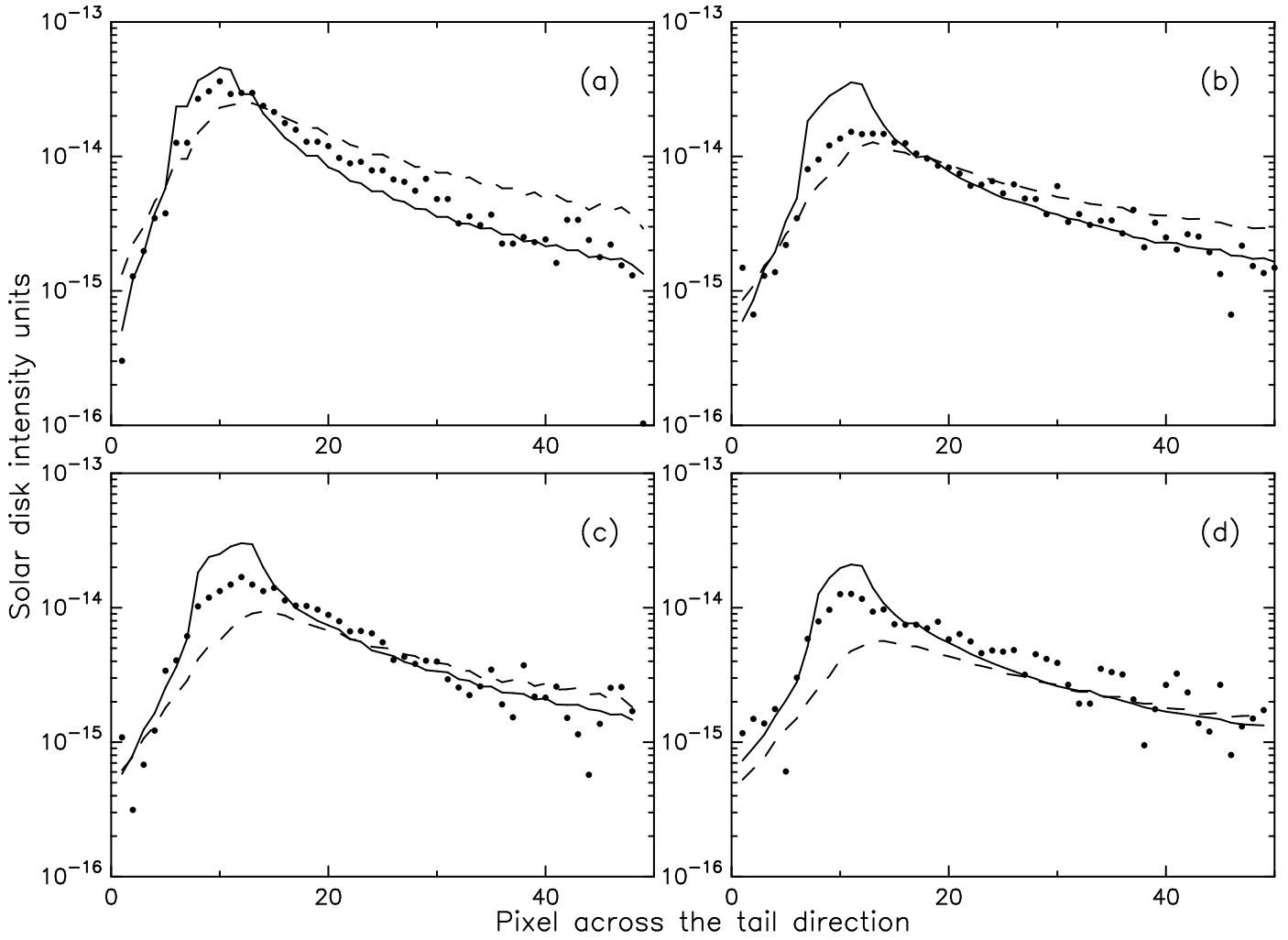


Fig. 3.— Scans along the direction of the tail for the observed images (solid circles), Model 1 images (solid lines), and Model 3 images (dashed lines). Labels (a) to (d) correspond to the different observing dates as shown in figure 1.

Table 1. Log of the observations

UT YYYY/MM/DD HH:MM	Days to perihelion	r' mag	R (AU)	Δ (AU)	α ($^{\circ}$)	PsAng ($^{\circ}$)	PIAng ($^{\circ}$)
2015/12/17 22:39	-91.8	21.64 \pm 0.01	2.327	1.656	21.13	65.79	+1.00
2015/12/30 21:53	-78.9	22.06 \pm 0.01	2.317	1.790	23.53	67.67	+0.37
2016/01/07 22:55	-70.8	22.28 \pm 0.01	2.311	1.879	24.47	68.65	+0.01
2016/01/25 20:17	-52.9	22.41 \pm 0.01	2.301	2.087	25.33	70.64	-0.66

Table 2. Best-fit parameters of the models

	\dot{M}_0 (kg/s)	t_0 (days)	HWHM (days)	v_0 (m s ⁻¹)	v_1 (m s ⁻¹)	v_2 (m s ⁻¹)	γ	Total mass (kg)	χ
Model 1	$1.0^{+0.3}_{-0.1}$	-120^{+10}_{-10}	$75^{+\infty}_{-25}$	$0.32^{+0.09}_{-0.08}$	–	–	$0.12^{+0.05}_{-0.07}$	4.6×10^6	0.122
Model 2	$1.6^{+0.5}_{-0.3}$	-128^{+30}_{-15}	$103^{+\infty}_{-20}$	–	$0.3^{+0.7}_{-0.3}$	$9.1^{+2.4}_{-4.0}$	–	8.8×10^6	0.120
Model 3	41.4	-131	2.0	–	0.08	1.0	–	6.0×10^6	0.159