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A collision in 2009 as the origin of the debris trail of asteroid P/2010 A2

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The peculiar object P/2010 A2 was discovered[1] in January 2010 and given a cometary designation because of the presence of a trail of material, although there was no central condensation or coma. The appearance of this object, in an asteroidal orbit (small eccentricity and inclination) in the inner main asteroid belt attracted attention as a potential new member of the recently recognized[2] class of main-belt comets. If confirmed, this new object would expand the range in heliocentric distance over which main-belt comets are found. Here we report observations of P/2010 A2 by the Rosetta spacecraft. We conclude that the trail arose from a single event, rather than a period of cometary activity, in agreement with independent results[3]. The trail is made up of relatively large particles of millimetre to centimetre size that remain close to the parent asteroid. The shape of the trail can be explained by an initial impact ejecting large clumps of debris that disintegrated and dispersed almost immediately. We determine that this was an asteroid collision that occurred around 10 February 2009.

P/2010 A2 orbits much closer to the Sun (its semi-major axis is 2.29 astronomical units, AU) than the previously discovered main-belt comets, the activity of which seems to be driven by episodic ice sublimation[2]. The discovery of a parent body a few arcseconds (~1,500 km) away from the trail[4,5] implied that it was debris from a recent collision rather than the tail of a comet, although Earth-based observations alone are consistent with a comet model[6]. It was suggested that the trail formed between January and August 2009, and was comprised of relatively large (diameter >1 mm) grains[7]. Here we use the term 'trail' to describe a tail made up of large particles, rather than dust from a currently active comet. Hubble Space Telescope observations refine the diameter of the parent body to 120 m and the date to February/March 2009 (ref. 3).

We obtained an improved three-dimensional description of the trail geometry by observing it with the OSIRIS Narrow Angle Camera[8] on board the European Space Agency's Rosetta spacecraft on 16 March 2010. Rosetta was approaching the asteroid belt for its July 2010 fly-by of asteroid 21 Lutetia, and at the time of observation was 1.8 AU from the Sun and 10° out of P/2010 A2's orbital plane. From this vantage point the separation between the anti-velocity (orbit) angle and the anti-Sun (comet tail) direction was much larger than was possible to observe from Earth. We also obtained reference images of P/2010 A2 from Earth using the 3.6 m New Technology Telescope (NTT) at the European Southern Observatory's La Silla observatory and the 200″ Hale telescope at Palomar Mountain. Figure 1 displays images of P/2010 A2 at four epochs, from the Earth and from Rosetta. We measured the position angle of the trail and extracted the flux profile along the trail axis at each epoch (Fig. 2).

We simulate the shape of the observed trail at each epoch by modelling the trajectories of dust grains, as is commonly done for comet tails[9,10]. The motion depends on the grains' initial velocity and the ratio β between solar radiation pressure and solar gravity, which is related to the size of the grains[11]. Owing to the small phase angle as viewed from Earth it is not possible to find a unique solution for the dust ejection epochs from the ground-based observations alone: the best estimate indicates that particles must have been emitted before August 2009, and should be of at least millimetre size to account for the low dispersion and their apparent position close to the projected anti-velocity vector. The higher phase angle of the OSIRIS observations allows a more precise simulation of the trail, and consequently we obtained a very narrow time frame for the emission of the dust. The grains must have been released around 10 February 2009, plus or minus 5 days, with the uncertainty being due to the measurement of the position angle of the faint trail in the OSIRIS images. To account for the position angle and the length of the trail, we must consider grains ranging from millimetre to centimetre size and larger. The particle sizes from this model, together with the brightness profile shown in Fig. 2, allow us to measure the size distribution of grains, and from this derive a total mass of the ejecta of 3.7×10^8 kg, or approximately 16% of a parent body of diameter 120 m, assuming a density of 2,500 kg m^{-3} and an albedo of 15% for both the asteroid and the grains.

The shape of the trail cannot be reproduced with a traditional comet-tail model, even when considering a longer timescale for the event. Cometary models all produce tail geometries in the OSIRIS image with a fan that reaches a point at the nucleus and becomes wider farther from it (see Supplementary Information for examples). All images of P/2010 A2 show a distinctive broad edge at the 'nucleus' end and then a trail with parallel edges. From the Rosetta observing geometry this edge is even broader than it is from Earth. This shape can be reproduced by a number of parallel synchrones: contours in the model that show the location of dust produced at the same time. In this model, an initial dust cloud is formed (presumably by a collision) in February 2009, which initially does not spread much (less than 1,000 km) but over a year solar gravity and radiation pressure expand this small trail to its observed width and length, respectively. Higher-resolution images from the Hubble Space Telescope[3] show the presence of parallel striae in the trail, very well aligned with the synchrone representing the original event as estimated from our simulations. These striae indicate that some areas of higher densities existed in the original cloud: larger clumps of material that fragmented and dispersed as they were ejected. The width of the broad front end of the trail from these different geometries can be used to constrain the speed of particles in the original ejecta cloud to less than 1 m s^{-1}. Impact

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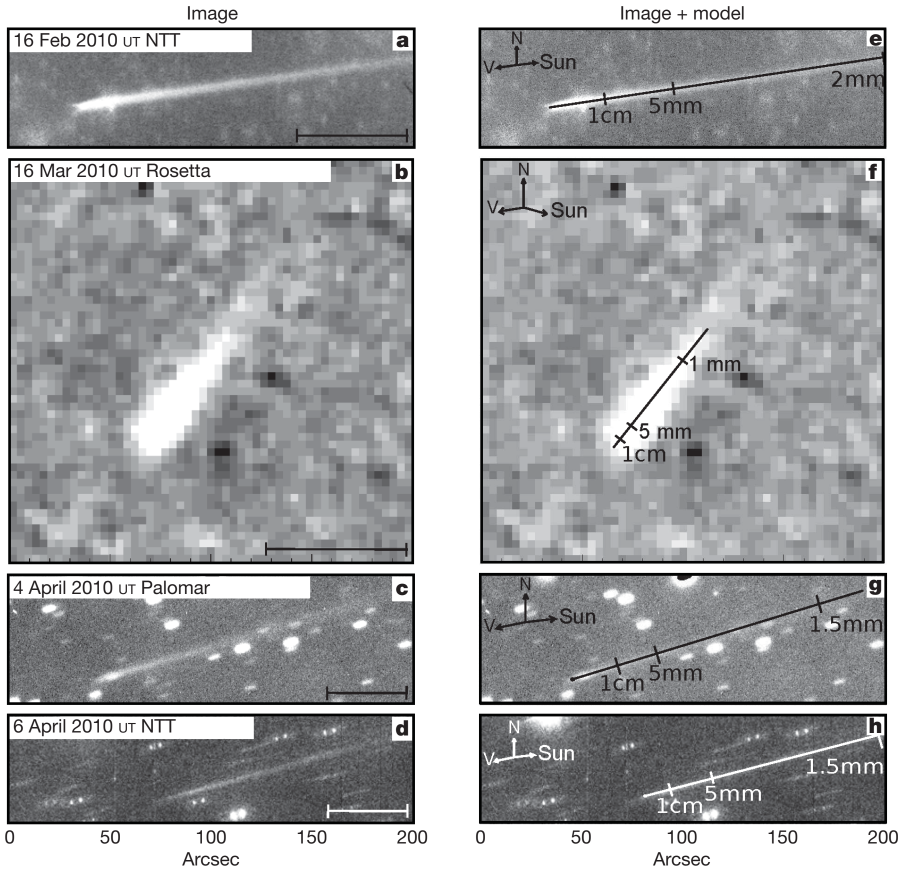

Figure 1 | Images of P/2010 A2 at four epochs. These are, from top to bottom, from the NTT (February), Rosetta (March), Palomar (April) and the NTT (April), respectively. The scale bars in the lower right of **a**–**d** show a projected distance of 5×10^4 km. When possible, we median-combined images centred on the object to increase the signal-to-noise ratio (relative to a single exposure) of the trail and remove background stars. To isolate the faint dust trail in the OSIRIS data we first subtracted an image of the background star field from each frame before shifting the frame on the basis of the motion of the object and then median-combining. On the right we show the same images overlaid with synchrones generated from the Finson–Probstein model. Numbers indicate estimates of the particle size distribution along the synchrones, derived from the model. The orientation of the images is North up, East left. The compass in the top left of panels **e** to **h** shows the direction of the heliocentric velocity vector (orbit) V and the direction to the Sun. The advantage of the Rosetta observing geometry is clear, with the broad head of the trail and obvious difference between the observed position angle and the anti-velocity vector apparent in the OSIRIS image. Models based on a period of cometary activity (rather than a single event) or smaller particle sizes produce a significantly different pattern of synchrones in **f** (see Supplementary Figs 2–4) that does not fit the observations. The same models all produce similar synchrones to those in the impact model for **e**, **g** and **h**, and therefore cannot be ruled out on the basis of Earth-based data alone.

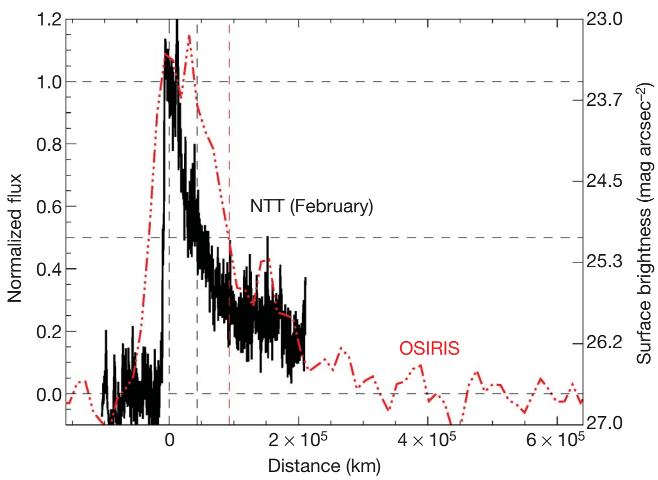

Figure 2 | Flux profiles along the trail. The normalized profiles for the February NTT (solid black line) and the OSIRIS data sets (dot-dashed red line) are shown. The *x* axis is in kilometres along the trail, with the conversion from the projected scale in arcseconds on sky based on the geometry derived from our model. The vertical dashed lines indicate the half-maximum of the profiles, used to measure the scale length of the trails in these images with different sensitivities. The two profiles have scale lengths of 4.3×10^4 and 9.3×10^4 km along the trail. The right *y* axis shows the calibrated surface brightness of the NTT profile in R-band magnitudes per square arcsecond. The flux profiles from the other Earth-based observations match the NTT one, but are omitted for clarity because they have higher noise owing to the shorter integration times. We derive a size distribution using the NTT flux profile and the size of particles as a function of distance along the trail from the Finson–Probstein model. This is done by converting the total flux across the trail at each distance to a reflecting area (assuming an albedo of 15%), and finding the corresponding number of particles of the appropriate size. The resulting cumulative size distribution is shown in Supplementary Fig. 6, and has a slope that matches the prediction for a population of collisional remnants[24].

experiments[12] find that such a low velocity implies a parent body of low strength and high porosity, although recent computer simulations suggest that impacts on such a small asteroid will lead to low-velocity ejecta independently of porosity[13].

Previously, asteroid collision models have been used to explain the dust trails associated with main-belt comets[14], but the longer-lasting dust production and repeated activity of comet Elst–Pizarro at each perihelion[15,16] rule out recent (within the past few years) collisions. Collisions inferred from asteroid families[17] or large-scale denser regions in the zodiacal dust cloud[18] have ages of 10^4 to 10^9 years. Our observations show direct evidence for a collision that is recent in observational terms, with a debris trail that is still evolving. From estimates of the population of the main asteroid belt[19,20] and an estimated impactor diameter of 6–9 m (ref. 21), we expect roughly one impact of this size every 1.1 billion years for a parent body of diameter 120 m, or approximately one every 12 years somewhere in the asteroid belt. This is in agreement with a single detection by the LINEAR survey; we expect that more small collisions will be detected by next-generation surveys. Collisions of this size therefore contribute around 3×10^7 kg yr^{-1} of dust to the zodiacal cloud, which is negligible compared with comets and the total required to maintain a steady state[22], in agreement with recent models[23].

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Supplementary Information is linked to the online version of the paper at www.nature.com/nature.

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