Newly Disrupted Main Belt Asteroid P/2010 A2

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Most main-belt asteroids are primitive rock and metal bodies in orbit about the Sun between Mars and Jupiter. Disruption, through high velocity collisions or rotational spin-up, is believed to be the primary mechanism for the production and destruction of small asteroids[1,2] and a contributor to dust in the Sun's Zodiacal cloud,[3] while analogous collisions around other stars feed dust to their debris disks[4]. Unfortunately, direct evidence about the mechanism or rate of disruption is lacking, owing to the rarity of events. Here we present observations of P/2010 A2, a previously unknown inner-belt asteroid with a peculiar, comet-like morphology that is most likely the evolving remnant of a recent asteroidal disruption. High resolution Hubble Space Telescope observations reveal an approximately 120 meter diameter nucleus with an associated tail of millimeter-

sized dust particles formed in February/March 2009, all evolving slowly under the action of solar radiation pressure.

P/2010 A2 was first detected on 2010 January 6 in data from the US Airforce LINEAR survey telescope[5] and was immediately classified as a short-period comet, based on the orbit and a diffuse appearance presumably caused by ejected dust. The orbital elements, however, are those of a main-belt asteroid (semimajor axis a = 2.290 AU, eccentricity e = 0.1244, inclination i = 5.25°), placing P/2010 A2 in the newly recognized class of objects known as main-belt comets[6].

Ground-based observations of P/2010 A2 taken in early January[7,8] revealed a peculiar morphology that was unlike any previously observed comet, suggesting an origin other than by the normal cometary process of water ice sublimation. The dust appeared in a thin, parallel-sided tail (sometimes called a "trail") detached from the nucleus, whereas typical cometary tails have their origin in a dust coma surrounding the nucleus and are fan-shaped. Hubble Space Telescope (HST) images taken at higher angular resolution (Supplement Table 1, Figure 1) confirm a point-like nucleus (N) at the leading edge of a thin, diffuse tail in which are embedded crossed filamentary structures (AA and BB). The filaments are the source of particles for the tail, including several dust streaks barely resolved even at HST resolution (F). Several persistent but faint and diffuse sub-nuclei (C) appear along the filaments. The filament morphology did not change as the Earth crossed the orbital plane of P/2010 A2 on 2010 February 9 (e.g. compare images from Jan 29 and Feb 22 in Figure 2, at plane angles

-0.9 and +0.9 , respectively), showing that the filaments and sub-nuclei are not confined to the plane.

Unlike other main-belt comets[6], P/2010 A2 orbits in the inner regions of the belt where S-type asteroids are most abundant[9]. The S-types are refractory rocks, dominated by materials formed at high temperatures, not by ice. Indeed, ice is thermodynamically unstable at the 184 K temperature expected of an isothermal blackbody at 2.29 AU. Primary nucleus, N, is unresolved and fades in accordance with the inverse square law (See Supplementary information). These properties together show that the nucleus is inert, with an estimated radius of $\sim$60 meters (Supplementary information).

P/2010 A2 shows modest morphological evolution on timescales of months (Figure 2), owing to changes in the distance (and resolution), the observing perspective and intrinsic changes in the object. Notable are a steady change in the position angle and a narrowing of the tail (Table 3). From a model of dust motions including solar gravity and radiation pressure[10], we calculate the expected tail position angle as a function of the date of emission of the dust particles from the nucleus. Particles emitted at a given time with negligible relative speed lie on straight lines emerging from the nucleus ("synchrones"), with larger particles being closer to the nucleus. The position angles of these synchrones are plotted in Figure 3, from which we infer dates of ejection in 2009 February/March, in agreement with another determination[11]. The dust dynamical model is a function of β, the ratio of the radiation pressure force on a particle to the solar gravitational attraction. We find that particles in the field of view of the HST observations have $\beta < 2\times 10^{-4}$, corresponding to particle sizes larger than 1 mm rising to $\sim$1 cm near the crossed filaments. The narrowing of the tail (Figure 2) occurs because particles launched perpendicular to the orbit reach maximum height above the orbit plane one quarter orbit (10 months) after ejection. The width of the dust tail implies out-of-plane dust velocities $\delta v \sim 0.2$ m s^{-1}. Relative velocities measured between the nucleus N and sub-nuclei in the filaments (e.g. between N and C in Figure 1) are $\delta v < 0.2$ m s^{-1}.

The effective scattering cross-section of the dust tail is comparable to the area of a circle of radius $r_e = 2100$ m. If contributed by particles in the mm to cm size range, this cross-section corresponds to a dust mass $M =$ (6 to 60) $\times 10^7$ kg, equivalent to a sphere of the same density and having a radius $r_p =$ 17 to 36 m (See supplementary information).

One possibility is that P/2010 A2 was disrupted by rotational bursting, perhaps caused by spin-up under the action of radiation torques (the timescale for spin-up is very uncertain but it can be $<10^5$ yr for a sub-kilometer body[12,13]). If the dust following P/2010 A2 was produced by an impact, r_p gives an upper limit to the radius of the projectile since, in a hypervelocity impact, orders-of-magnitude more mass is ejected from the target than is delivered by the projectile. We infer that the projectile was of the order of a few meters in radius, tiny compared to the primary nucleus. The velocity dispersion among asteroids in the main belt is $\Delta V \sim 5$ km s^{-1} ([1]). From these parameters we infer that the energy per unit target mass in the responsible impact was $E/M = 1/2\ [r_p/r_n]^3 \Delta V^2 < 10^5$ to 10^6 J kg^{-1}, which encompasses the E/M needed for catastrophic fragmentation in a direct impact[14]. Experiments[15] and calculations[16] show that most mass in hypervelocity impacts is displaced at low velocity, consistent with the speeds measured.

The expected interval between collisional disruptions of 0.1 km diameter asteroids in the main-belt is ∼1 yr [17], while damaging but non-disruptive impacts should be more frequent. The >1 yr duration of visibility of the P/2010 A2 debris cloud suggests that we should expect to find one or more similar objects at any time, in any all-sky survey with sensitivity equal to that of LINEAR or greater. Comparable disruption events occurring annually will release into the Zodiacal cloud about 2 to 20 kg s^{-1} of dust, on average. This is only 0.1 to 1% of the 600-1000 kg s^{-1} mass injection rate needed to keep the Zodiacal cloud in steady state[18], suggesting that most of the mass comes from comets[19] or another source.

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Supplementary Information is linked to the online version of the paper at

www.nature.com/nature.

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Author Contributions D. J. identified P/2010 A2 as an object of special interest, secured HST observing time and lead the effort behind the paper. H. W. was responsible for the execution of the observations and assisted with data reduction. Max Mutchler processed the raw images and was responsible for the removal of cosmic rays and other artifacts. J. A. computed the dynamical models. M. Drahus checked the work and critiqued the proposals and paper.

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Figure Legends

Figure 1

Key to the major features in P/2010 A2 on UT 2010 Jan 25. The principal nucleus, N, leads an arcuate dust feature, AA. A second arcuate feature, BB, crosses AA at a large angle. Objects at C are distinct but diffuse features detected at more than one epoch. Particles emitted along AA and BB define the width of the main dust tail. A separate and very diffuse dust structure, E, extends beyond the boundaries of the tail. Linear dust streaks (striae) are visible embedded within the tail at F. Their narrowness shows that they emanate from discrete sources within the AA, BB arcs with negligible initial velocity. Interfering field stars are marked S, while SL is a band of internally scattered instrumental light which could not be removed by image processing.

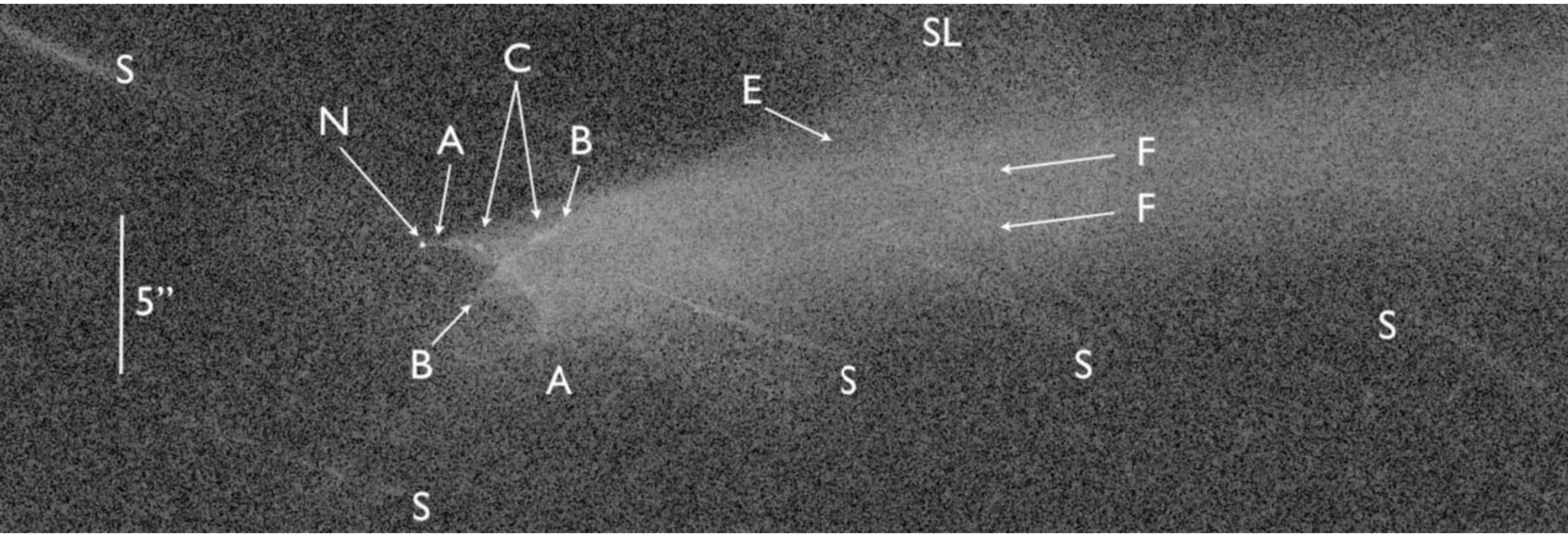
Figure 2

HST images of P/2010 A2 at the eight indicated epochs. Images in each panel have been rotated so that the tail lies approximately horizontally. The images, from Wide Field Camera 3, have 0.04 arcsecond pixels and are combinations of images with total integration times of about 2600 seconds through the F606W filter. Each panel subtends 10 arcseconds in height. Numerous cosmic rays and trailed background objects have been removed from the data. Residual streaks in some panels (e.g. diagonal streaks on Jan 25 and 29) are due to the incomplete removal of trailed background stars and galaxies.

Figure 3

Position angle of the tail as a function of time showing changes caused by the viewing geometry. Measured position angles of the tail (black symbols) are shown with error bars denoting 1 standard deviation. Calculated position angles of different synchrones (color-coded curves) as functions of the epoch of observation. The position angle of the projected orbit is shown in grey. To measure the difference between the position angles of the tail and of the projected orbit, we rotated the images such as to align the x-axis with the projected orbit. At constant intervals, we obtained profiles perpendicular to the orbit by averaging over 200 pixels parallel and 10 pixels perpendicular to the orbit. To each profile we fitted a Gaussian function. We then fitted a linear function to the peak of the Gaussian versus the distance from the nucleus. The slope and root-mean-square of the slope give us the position angle of the tail and the corresponding error bars. The coloured curves indicate the position angles of specific synchrones, i.e. dust emitted at a specific date (see label) with zero relative velocity. Simulations demonstrate that dust emitted at a given time with zero speed is seen in projection along a straight line starting from the nucleus and with the distance to the nucleus proportional to the radiation pressure coefficient, β, with larger particles (with smaller beta) closer to the nucleus for a given release time. For a given observation date, the position angle of the synchrones is a unique function of the time of emission. The coloured lines show the change of the synchrone position angles with time, primarily due to the changing viewing geometry. In particular, all synchrones were projected to the south of the orbit before the Earth crossed the orbital plane of the comet on 2010 February 9, and to the north afterwards. The measured position angles of the tail are best matched by the

2009 March 2 synchrone and inconsistent with synchrones more than a few weeks before or after that date.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Jan 25
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Apr 02
Apr 19
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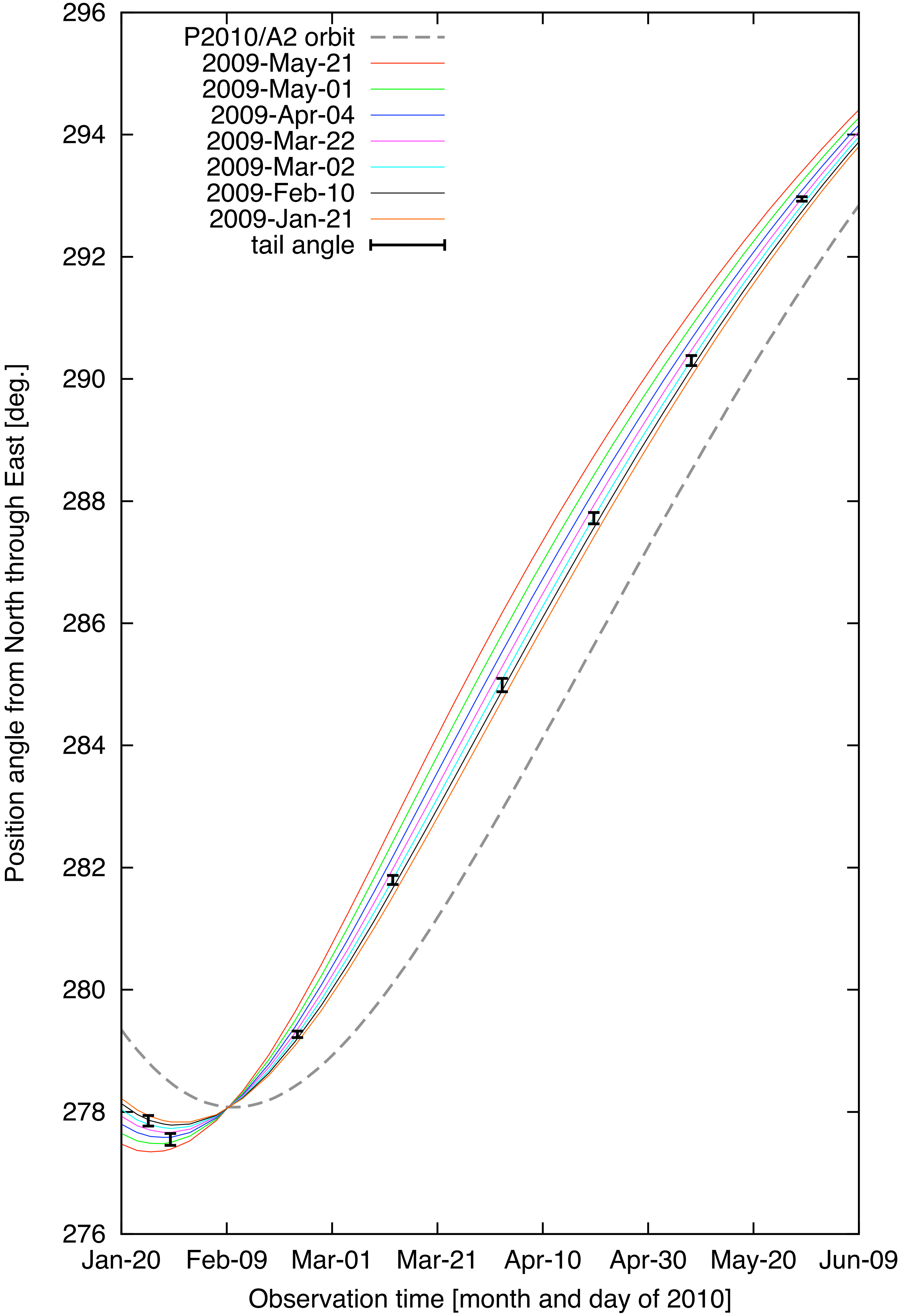
May 29


P2010/A2 orbit
2009-May-21
2009-May-01
2009-Apr-04
2009-Mar-22
2009-Mar-02
2009-Feb-10
2009-Jan-21
tail angle
Position angle from North through East [deg.]
296
294
292
290
288
286
284
282
280
278
276
Jan-20
Feb-09
Mar-01
Mar-21
Apr-10
Apr-30
May-20
Jun-09
Observation time [month and day of 2010]