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Research Note

Impact–generated activity period of the asteroid 7968 Elst–Pizarro in 1996: Identification of the asteroid 427 Galene as the most probable parent body of the impactors

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Abstract. One of the most interesting objects among the small bodies in the Solar System is the intermediate object 7968 Elst–Pizarro classified as an asteroid–comet orbiting in the Themis region of the main belt, which showed a temporary dust tail activity in 1996. The impact-induced processes generated by multiple collisions with a debris cloud associated with another asteroid, are the preferred explanations for this activity. A computer search has shown that the most probable candidate for the parent body of the impactors to generate this temporary outburst activity, is the field asteroid 427 Galene.

Key words: comets: individual: 133P/Elst–Pizarro (P/1996 N2) – minor planets, asteroids – Solar system: general

1. Introduction

Any small body in the Solar System that is found to display diffuse developing coma and that contains a monolithic nucleus consisting of ice and dust grains is a comet, and any that does not, is an asteroid of solid rock. Gas or dust tail developments are supplementary characteristics of the comets, and sometimes only the coma appears. The definition of comets was discussed by Jewitt (1992, 1994) and it is rather complex, involving the issue of the interrelation between the comets and some asteroid types being an inactive, dormant phase of the comets. Moreover, most comets move in rather elongated orbits, while most asteroids follow near–circular orbits close to the main plane of the Solar System. However, some intermediate objects have recently been discovered which seem to possess properties that are typical of both categories (asteroid-comet). On August 7, 1996 Eric W. Elst discovered an interesting intermediate object on exposures from July 14, 1996 taken by Guido Pizarro with the 1.0-m Schmidt telescope at the ESO, La Silla (Elst & Pizarro 1996). This object surprisingly showed a cometary tail and was designated as P/1996 N2 (Elst-Pizarro) (133P/Elst–Pizarro or 7968 Elst–Pizarro), while moving in a typical asteroidal orbit in the main belt of the minor planets. The presence of a thin tail is manifestly a cometary characteristic, but from the orbit–point of view, the object belongs to the outer asteroid belt and is a member of the Themis family (Boehnhardt 1997a). This object was revealed on prediscovery images: this is identical to the asteroidal object 1979 OW7, observed at Siding Spring and Palomar on July 24 and 25, 1979 (Marsden 1996; McNaught 1996a). McNaught (1996b) has communicated the asteroidal appearence of this object observed with the U.K. Schmidt on September 15, 1985. The discovery of this intermediate object generated a challenge to solve its puzzling physical characteristics in relation to its orbit class. Cometary outbursts are the most enigmatic phenomena in the physics of comets and this has been reviewed including the discussion of the impact–induced activity (Hughes 1991). Works by Jewitt (1992), Meech (1993, 1996), Gronkowski & Smela (1998) have demonstrated that many comets exhibit comae at large heliocentric distances – even greater than 10 AU from the Sun – owing to sublimation from highly volatile ices like CO, and CO_2. In principle, at the heliocentric distance r≈2.6 AU, where the activity of 133P/Elst–Pizarro was observed, the presumably most common water ice could have sublimated, since this process occurs within the limit distance (2.8 AU) coupling with the usual dust driving mechanisms.

However, observational evidence (cf. Appendix) suggests that the cause of the tail development at the 133P/Elst–Pizarro is the consequence of collision or (i) multiple collisions with a debris swarm of fragments broken off and separated from another asteroid or (ii) due to multiple collisions with an unseen satellite orbiting close to the Elst–Pizarro and the satellite reached the final stage of its orbital lifetime, e.g. due to the collisional strikes by other debris bodies. Large, catastrophic disruptive collision events have recently been rare in the asteroid belt, however, smaller, non-disruptive collisions are far more frequent, as evidenced by the heavily cratered surfaces of 951 Gaspra and 243 Ida (Chapman et al. 1996; Belton et al. 1996). The numerical models (Lien 1998) of the dust tails created by impact events on the asteroidal surfaces show that the dust is ejected at much lower velocities than those found for typical

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comets (1–50 m s^{-1}) and that the radiation pressure parameter, β is consistent with particles much larger in size than is typically found in the tails of active comets. Lien (1998) concluded that the most likely interpretation of these results and the observations of 7968 Elst–Pizarro is that (i) the observed dust is a result of a cratering event on the body surface; (ii) the low velocities of the ejected tail material are consistent with numerical cratering models; and (iii) the lack of a gas coma or higher β particles precludes normal comet dust emission models. Evolution of the orbit of 7968 Elst-Pizarro was calculated by Ipatov & Hahn (1997). They showed that Elst–Pizarro has the smallest inclination among the actual asteroids with close values of orbital semi-major axis, and so it has the largest probability of a collision with other asteroids.

The question arises in connection with the hitherto unknown source of parent body of the colliding projectiles. This paper reveals the existence of a closest known asteroidal orbit on which the asteroidal debris projectiles can collide with the asteroid 7968 Elst–Pizarro. Results of different observations are briefly summarized in the Appendix to recall the enigmatic properties of this object.

2. Impact–induced activity

The observations (Boehnhardt et al. 1996; Boehnhardt 1997a,b) and models (Sekanina 1996a,b; Lien 1998), recalled in the Appendix, as well as investigating the orbital evolution (Ipatov & Hahn 1997) suggest various scenarios of the impact induced activity. The relatively long-duration dust emission activity at low ejection velocities at 7968 Elst–Pizarro can be explained either (i) by soft multiple collisions with its unseen satellite companion or a debris cloud orbiting around the primary body, or (ii) by collisions of a debris cloud associated with another asteroid orbiting in a close orbit to 7968 Elst–Pizarro. A qualitative scenario will be described here about these processes.

2.1. Collisions with the satellite or its debris cloud

Duplicity among the asteroids could be common (Chapman et al. 1995). What is the orbital stability domain for a satellite companion to the 7968 Elst–Pizarro and how large are the orbital velocities in this region ? A quantitative measure of stability region based on Hill's definition is given for direct and retrograde satellite orbits. Recently, detailed studies were performed on the stability and dynamical evolution of the binary asteroid systems (e.g. Hamilton & Burns 1991; Hamilton & Krivov 1997, and numerous other references therein). However, to guess the extension of the stability domain, the simplest and most conservative estimation is applied. The size of the solar–tidal stability region around a primary can be evaluated by the Szebehely's (1978) stability criterion, which gives the lowest and therefore the most conservative estimate of the stability radius R_s in a given binary system. The R_s is not the radius of the primary body zero velocity Hill oval R_H, but rather $R_s = 1/3\ R_H$. For objects orbiting between R_s and R_H, instability is possible. Evaluating the radius R_s of the stability domain for 7968 Elst–Pizarro, assuming a spherical shaped body 10 km in diameter and with bulk density between 2.0 to 4.0 g cm^{-3}, the secondary to primary mass ratio ranges from 0.001 to 0.5. The resulted R_s are ranging from 75 to 105 km, i.e. the Hill's radius from 235 to 315 km. The typical orbital velocities of a satellite falls in the range of 0.03 to 0.2 m s^{-1}, with orbital period of about 4 to 80 days, respectively, so the collision could be a very soft and slow process. Ejecta from the asteroid itself would mostly re-impact after a fraction of an orbit and would be short-lived anyway, apart from special cases (Giblin et al. 1998). The predicted effects due to the collisons strongly depend on the impact angle: (i) in cases of a grazing the impact stirs up the surface of the target body, breaking up the surface soil material (rocks, regolith and dust) removing the surface material along the path of the impactors ploughing up grooves, while the projectile rolling, tumbling and hopping-bumping at the relief of target body surface or (ii) excavating small, flat craters or depressions in the surface if the collisions are not oblique impact events. Consequences of the soft collisions are the compacting of the surface material around the craters and impact depressions. The resulting ejection velocity can exceed the surface escape velocity of the target body and dust tail formation is initiated. The seismic shakings can be generated during the collisions and the effect of these depends on the impact energy and the elastic properties of the material of the target body. No significant surface heating effects are expected during these soft collisions therefore the impact melting or developing of impact vapor clouds cannot occur. Moreover, jetting and primary impact spherule forming processes cannot occur during these soft collisional encounters between the primary and its satellite debris. Furthermore, these could not be catastrophic breakup processes for neither the target nor impactor satellie debris bodies, so the repeating, recurrent excavation of the surface material could proceed (e.g. in the special cases discussed by Giblin et al. 1998).

2.2. Collisions with a debris cloud of another asteroid

The formation and origin of the IRAS dust bands are considered to have arisen from collisional activity in the main asteroid belt. The evolution of the size distribution of fragment debris and their orbits as well as the formation of the dust band torus were analyzed in former studies (Sykes & Greenberg 1986; Sykes et al. 1989). The material is distributed along the orbit and fills a widened region in the space where the material spread due to various perturbing effects, thus the recent encounters with the larger bodies in the dust belt are far more frequent if a target body approaches that zone. The case of Elst–Pizarro could be an example confirming this recent collisional activity. The most probable relative orbital velocities in the main asteroid belt are 2–4 km s^{-1} which belong to the high velocity collision range (Vedder 1998). It is obvious from the observations that 7968 Elst–Pizarro as a target did not disintegrate therefore the collision or multiple collisions were not total catastrophic events for this target body. The impacts could excavate one or more craters and grooves, and could generate impact ejecta and surface jetting, heating, melting processes as well as forming primary im-

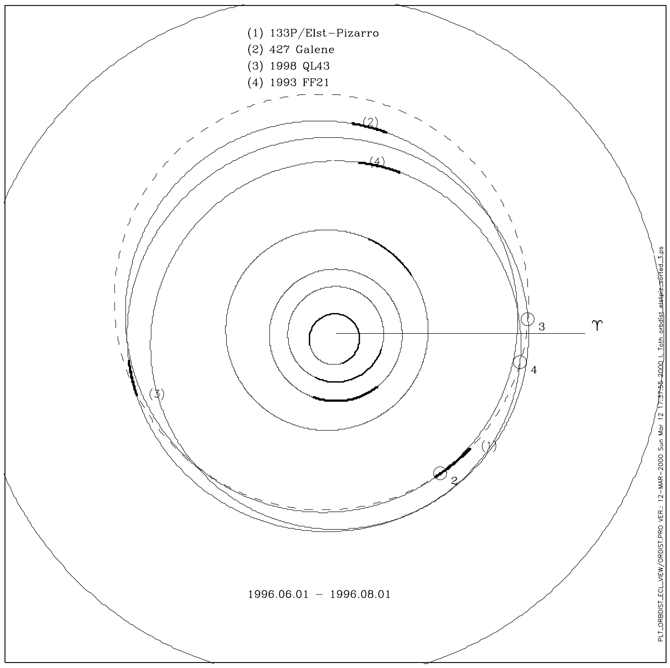

Fig. 1. The orbits of the asteroids projected onto the plane of ecliptic. The numbers in brackets are the actual positions of the objects in the time interval (June 1 – August 1, 1996). The numbers without brackets are the locations of the closest points (open circles) between the trajectories of the Elst–Pizarro (dashed line) and other objects. Vernal Equinox direction and the orbits of the inner planets and of Jupiter are also drawn.

pact spherules. The nature and effects of impact cratering and related processes on small bodies are described by e.g. Cintala et al. (1979), Nolan et al. (1996). The results of cratering events strongly depend on the impact angle (Gault 1974; Melosh 1980; Holsapple 1993). The ballistic ejecta and some amount of the ejected material can orbit in the complicated gravitational potential field of a presumably irregularly shaped target asteroid. The small grains in the orbiting ejecta material can be the source of the dust tail forming due to solar radiation pressure. Strong seismic shaking can stress the surface of a small asteroid body even at the antipodal side with respect to the location of the impact. The consequence of these events could be the stirring up and displacement of the surface regolith and dust and finally the grains are removed from the surface if their velocity is greater than the escape velocity. Other consequences could be the changing of the rotational state and parameters of a small body: both spinning down and up and/or exciting the tumbling motion, generating a complex rotational state. Moreover, the large impacts can create surface crack-type grooves (Kawakami et al. 1991), as well as spallation of fragments separating from the target body. This depends on the impactor energy and the material strength of the target (Thomas & Veverka 1979; Nolan et al. 1996). We note an opposite consequence of the cratering process: the compaction of the surrounding near-surface material resisting the excavations or crater creations during future impacts (Cintala 1979).

Other, internal structure-dependent activities could also be initiated, e.g. the crater and groove penetration could induce possible outgasing or dusty-gas activity on asteroids revealing a comet-like behaviour. But in the case of 7968 Elst–Pizarro there was not a direct indication for the outgasing activity. The impact flashes and impact vapor clouds were not observed directly because the discovery was after these events. However, the development of a normal dust tail between September and November 1996 (Boehnhardt 1997a) could be indirect evidence for some comet-like gas activity driven dust motion. However, initial trigger collision seems to be feasible.

Other consequences of the crater creation are that the crater shape and compaction of the surrounding surface material could change the heat conduction and radiation reflection parameters of the surface. Finally hot spots can be observed. The collisions with sporadic asteroidal or cometary impactors, which otherwise do not belong to the main belt, are also possible. Therefore all types of small bodies with known orbits should be considered in the search for the possible impactor parent body.

3. Parent body of the impactors

The clue to solve the enigma of the outburst activity seems to be the impact–induced activity of 7968 Elst–Pizarro, finding the parent body of the projectile or projectiles being responsible for generating the temporary activity colliding with the target body as supported by Boehnhardt (1997a) and Lien (1998).

3.1. Computer search

The known asteroidal, cometary and meteor shower orbits were considered as far as is possible in a computer search for the probable parent body of the impactors. The minimum distances between the orbits of 7968 Elst–Pizarro and all other objects were calculated. The objects were sorted according to the values of the determined minimum distances and in the first round, ten objects with the smallest values in the minimum distance were selected. It was found that among the ten selected objects the largest minimum distance was around 10^{-4} AU, while the first five have about 10^{-5} AU. The time interval from June 1 to August 1, 1996 was chosen to calculate the heliocentric ecliptic coordinates of the selected objects because this interval was the critical for the events generating the activity of Elst–Pizarro. The first five objects found with orbits close to 7968 Elst–Pizarro are listed in Table 1 and their locations are displayed in the time interval (Fig. 1). The heliocentric ecliptic coordinates, minimum distances from the orbit of Elst–Pizarro and the relative orbital velocities are also given in Table 1. The objects Nos. 3–6 as well as the loci of the minimum distance points in their orbits were far from the position of 7968 Elst–Pizarro in the given interval except in the case of the minimum distance point of asteroid 427 Galene. This minimum distance point was approached by the Elst–Pizarro on June 9.249 UT, 1996 at about 6170 km distance. The 427 Galene itself was both far from Elst–Pizarro and the minimum distance point of its orbit in that time interval (Fig. 2). The other object candidates are also asteroids but their minimum

Table 1. Orbits having the closest known approach distance to the orbit of 7968 Elst-Pizarro

No.	Object	d_{min}	r (AU)	L^o	B^o	v_{rel}
2	427 Galene	6170	2.63726	306°.51	0°.76	2.27
3	1998 QL43	10530	2.90737	4.36	-0.56	4.18
4	1993 FF21	11502	2.81298	350.85	-0.25	3.83
5	1990 QH3	12210	3.45370	161.72	0.03	5.17
6	1995 WJ1	12646	3.06187	204.23	0.96	2.61

d_{min} is the minimum distance between the target and other orbits (km).
r, L, B are the heliocentric distance, ecliptic longitude and latitude (J2000) of the closest points in the orbits, respectively.
v_{rel} is the relative velocity (km s^{-1}) at the encounter.

distances are far from the critical position of Elst–Pizarro. Thus, in spite of the close proximity of their orbits they were omitted from further discussion. Consequently, the main belt asteroid 427 Galene is the most probable candidate for the suspectable responsible parent body of debris to cause impact-induced activity on Elst–Pizarro. The perihelion passage of Elst–Pizarro was on April 18.479 UT, 1996, so this object was around the largest orbital velocity regime (its velocity in the perihelion is 19.85 $km\,s^{-1}$ and in aphelion it is 14.15 $km\,s^{-1}$). The relative velocity in the orbit of Elst–Pizarro to the orbit of 427 Galene computing at their minimum distance points amounts to 2.27 $km\,s^{-1}$ which is close to the lower limit (about 2 $km\,s^{-1}$) of the high velocity collision events as was shown by Vedder (1998).

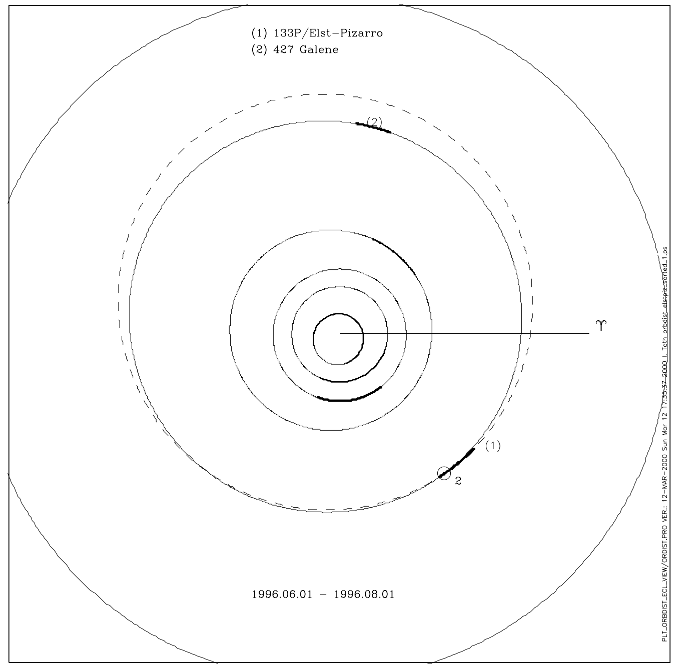

Fig. 2. The orbit of asteroid 427 Galene and the orbit of 7968 Elst–Pizarro (dashed line) are displayed only. (See also Fig. 1).

3.2. Parent body of the impactors and the largest possible impactor body

The minor planet 427 Galene (1897 DJ) was discovered by A. Charlois in Nice on August 27, 1897 (Pilcher 1979). This is a field asteroid in the outer main belt and there is no taxonomic class established (Tholen 1989). There is no lightcurve and consequently rotational period and pole orientation reported for this minor planet (Lagerkvist et al. 1989). The magnitude parameters H=9.41 and G=0.15 are given in the two-parameter magnitude system, the visual geometric albedo is 0.26±0.03 (1σ), the diameter is 33.8±2 km (1σ) derived from the IRAS observations (Tedesco 1989).

Is it possible that 7968 Elst–Pizarro will collide with a hypothetic satellite of the asteroid 427 Galene or with a debris cloud orbiting on a stable orbit around the primary in the future ? Computing the stability radii taking the parameters of 427 Galene, it was found that 7968 Elst–Pizarro could not have collided directly with a hypothetic satellite or debris cloud orbiting around 427 Galene because the values of R_s are too small (250–360 km) comparing with the minimum distance between the orbits of the asteroids, unless these objects have escaped from the primary, if e.g. they had moved between the distances R_s and R_H in the instability domain before escaping.

Although, repeated multiple collision events should have taken place but it would be interesting to estimate the largest possible mass of the individual impactors. Knowing the high relative velocity of the possible impactors on 7968 Elst–Pizarro, the upper limit of the largest impactor mass can be evaluated. A number of investigators have estimated the energy densities needed to demolish asteroids of various assumed compositions. The impact events including scaling laws are recently described by Holsapple (1993), Nolan et al. (1996), for instance. However, in this simple evaluation here, former simple assumptions are applied to illustrate the process, since the usage of the more complicated models is out of the scope of this note but later it will be necessary to elaborate more sophisticated models for Elst-Pizarro. Following the calculations described by Housen et al. (1979), and Thomas & Veverka (1979), it is instructive to estimate the size of the largest possible crater on a spherical object as well as to compute the possible maximum mass of the impactor at the critical limit when the target body is not disintegrated but the impact energy leads to spallation but not to total destruction. Basic assumptions and calculations given by Thomas & Veverka (1979) are closely followed. The target object strengths and scaling parameters were taken from Thomas & Veverka (1979) for the asteroids or small planetary satellites as for Phobos and Deimos, for example. The impact energy limits and the largest possible crater diameters are given both for strong and weak targets in Table 2. The impact energy limits for the strong and weak targets in equivalent units are roughly 373 Mt TNT and 0.1 Mt TNT, respectively. The largest possible spherical impactor body (bulk denstity 2 $g\,cm^{-3}$ is assumed) diameters are about 800 m for the strong and 50 m for the weak target models.

Table 2. Characteristics of major cratering events on 7968 Elst–Pizarro

Target object strength	E_2 (erg cm^{-3})	Largest possible crater diam. (km)	Maximum impactor mass (kg)	Impact energy (Joule)
Strong	3.0×10^{7}	6.2	6.1×10^{18}	1.5×10^{18}
Weak	1.0×10^{4}	0.4	2.0×10^{11}	5.2×10^{14}

E_2 is the volume enegy density (strength) of the target against total disruption (Thomas & Veverka 1979).
Target body diameter 10 km and
relative velocity 2.27 km s^{-1} are used.

4. Conclusions

The majority of the observational evidence showed that 7968 Elst–Pizarro is a Themis asteroid in the main belt. Moreover, this object revealed comet-like activity only partially, developing dust tail and anti-tail, i.e. it did not have clear and unambiguos cometary activity because there were no coma and spectral features of the gas components reported during the whole activity period and after a few months the object returned quiescent phase. The velocities of the injected material from the surface to form the dust tail are much lower than those found for typical comets. The activity phase was temporary only, has never been observed before and has never returned later. In summary the conclusions are as follows:

1. A computer search showed that the most probable candidate for the parent body of the impactors to cause the temporary outburst activity of 7968 Elst–Pizarro in 1996 is the field asteroid 427 Galene.
2. The prolonged tail developing activity of 7968 Elst–Pizarro can be explained either (i) by subsequent collisions with the debris cloud distributed along the orbit of the parent asteroid during the close proximity to the orbit of the target body 7968 Elst–Pizarro; or (ii) by a relatively major single impact generating crater or huge grooves and exciting seismic waves shaking and elevating the surface material. The remained impact ejecta material close to the surface was the source of the grains to supply the dust tail and after the dust trail is presumably distributed along the orbit.
3. The impact energy limit of the largest impact event was estimated and in the case of the multiple impactors for the largest impact events did not disrupt the target object.
4. The impact events can generate outburst activity for asteroids excavating the regolith or deeper layers. Moreover, activity of a dusty-ice cometary nucleus obviously can easily be triggered by impactors. However, the possible causes of the observed temporary outburst activity of this object cannot exclude some comet-like behaviour (some volatile contents), but the majority of the observational evidence supports that 7968 Elst–Pizarro is an asteroid in the outer region of the main belt. The asteroid designation 7968 Elst–Pizarro or 1979 OW7 is suggested to be used in the future instead of the comet designations as 133P/Elst–Pizarro or P/1996 N2 (Elst–Pizarro).

427 Galene is one of the less observed main belt asteroids with unknown rotational and other parameters. To observe both 427 Galene and 7968 Elst–Pizarro could be beneficial to collect data to derive the important physical characteristics of these objects e.g. rotational status of Elst-Pizarro after the probable impact events.

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Appendix: observational evidence and models

Characteristics of the object pointed out by previous observations and studies can be summarized as follows. The continued presence of a tail in 1996 seemingly confirmed the object as a comet, even though the orbit is completely that of a main belt minor planet with the implied long-term stability. The comet's narrow, straight, structureless tail is likely to be a signature of a past dust–emission episode. The observations show narrow dust tail and anti-tail from the discovery to mid-November, 1996 (Elst & Pizarro 1996; Pravec 1996; Offutt 1996; Boehnhardt 1996, 1997a; Boehnhardt et al. 1996). Sekanina (1996a) concluded that the presumed outburst probably occured between late May and early July 1996, or some 40 to 80 days after perihelion, in which case the maximum effect of solar radiation pressure on dust in the tail was between $\beta = 0.05$ and about 0.4, where β is the ratio of solar radiation pressure acceleration to the solar gravitational attraction, implying the presence of micron- or submicron-sized grains. Sekanina (1996a) also noticed the difficulties of the timing and position determination of the tail due to the special aspect geometry. The Finson–Probstein calculations on the dust tail of this object indicated that, until late 1996, dust emitted before T+40 to 60 days will be located on the sunward side of the nucleus (Boehnhardt 1996).

According to the ground-based observations made with large ESO telescopes in accordance with Sekanina (1996a,b) Boehnhardt et al. (1996) concluded that the preliminary analyses show that the dust was being released from the object over a period of many weeks or months until approximately mid-July 1996, when the comet was discovered by Elst & Pizarro (1996). Boehnhardt et al. (1996) stated that this evidence eliminated the possibility that the features are products of an instant event (e.g. a collision) in other words by a single impact. Finally, this conclusion on the long-duration sequence implicitly suggests activity triggering impact events and does not exclude the possibility of multiple impact events. Dust particles with values of $\beta = 0.05$ are clearly apparent in the anti-solar tail (Boehnhardt et al. 1996).

The images and spectra of 7968 Elst–Pizarro were obtained by Hammergreen (1996) with the Apache Point Observatory 3.5-m telescope on September 18, 1996 detecting the main sunward tail noted previously and a faint anti-sunward tail which was independently discovered by Boehnhardt et al. (1996). Preliminary Finson–Probstein models by Hammergreen (1996) indicated that the dust emission could not have been confined to a single, short outburst but rather must have occured over an extended period of at least several weeks. Hammergreen (1996) concluded that this excludes a collisional origin for the dust emission, and provided circumstantial evidence for the existence of sublimating volatiles on the object. However, the 0.38–1.0 microns reflectance spectra taken by Hammergreen (1996) reveal a neutral continuum absent of emission or strong absorption features, similar to the known cometary nuclei but also similar to a subset of the low-albedo asteroids, notably incuding the Themis family asteroids. The scenarios and immediate questions given by Hammergreen (1996) favour the comet-like behaviour to explain the observed activity period of this object: either (i) this is a true comet with a presumed origin in the outer Solar System, or (ii) this object is simply a volatile-rich asteroid which has had a pocket of ices recently exposed.

The follow-up observations made by Boehnhardt (1997b) with the 2.2-m reflector at the ESO, La Silla on October 1, 1997 confirmed that the 7968 Elst–Pizarro exhibited a completely stellar-like appearance with R magnitude of 20.9 without any tail or diffusity. Boehnhadt (1997) summarized the pros and cons for impact-induced activity and confirmed the idea that an initial collision still seems to be feasible to explain the activity period. The observations of the asteroid 1979 OW7 made in 1979 and 1985 did not exhibit cometary behaviour. Accordingly, it was only a temporarily long-term (few months) activity of this object in 1996.

In addition, the approximate size of 7968 Elst–Pizarro is estimated now using the value of visual absolute magnitude H=14.0 (E.L.G. Bowell's data) in the IAU two-magnitude system for atmosphereless bodies (Eq. (A6) of Bowell et al. 1989). The low values of visual geometric albedo adopted for Themis-family members range from 0.04 to 0.20 (Tedesco et al. 1989), thus the corresponding diameters derived from the photometry are about 10.7 and 4.8 km, respectively.

References

Belton M.J.S., Chapman C.R., Klaasen K.P., et al., 1996, Icarus 120, 1

Boehnhardt H., 1996, IAU Circ. 6473

Boehnhardt H., 1997a, Interactions between planets and small bodies. 23rd meeting of the IAU, Joint Discussion 6, 22-23 August 1997, Kyoto, Japan

Boehnhardt H., 1997b, MPEC 1997–T03

Boehnhardt H., Schulz R., Tozzi G.P., Rauer H., 1996, IAU Circ. 6495

Bowell E.L.G., Hapke B., Domingue D., et al., 1989, In: Binzel R.P., Gehrels T., Matthews M.S. (eds.) Asteroids I, Univ. of Arizona Press, Tucson, p. 524

Chapman C.R., Veverka J., Thomas P.C., et al., 1995, Nat 374, 783

Chapman C.R., Veverka J., Belton M.J.S., et al., 1996, Icarus 120, 231

Cintala M.J., Head J.W., Wilson L., 1979, In: Binzel R.P., Gehrels T., Matthews M.S. (eds.) Asteroids I, Univ. of Arizona Press, Tucson, p. 579

Elst W., Pizarro G., 1996, IAU Circ. 6456

Gronkowski P., Smela J., 1998, A&A 335, 761

Gault D.E., 1974, In: Greeley R., Schultz P. (eds.) A primer in lunar geology. NASA AMES, p. 574, 137

Giblin, I., Petit J., Farinella P., 1998, Icarus 132, 43

Hamilton D.P., Burns J.A., 1991, Icarus 92, 118

Hamilton D.P., Krivov A.V., 1997, Icarus 128, 241

Hammergreen H., 1996, AAS Meeting 189, No. 19.04

Holsapple K.A., 1993, Annu. Rev. Earth Pl. Sci. 21, 333

Housen K.R., Wilkening L.L., Chapman C.R., Greenberg R., 1979, Icarus 39, 317

Hughes D.W., 1991, In: Newburn R.L. Jr., Neugebauer M., Rahe J. (eds.) Comets in the post-Halley Era. Vol. 2, IAU Colloq. 121, Kluwer, Dordrecht/Boston/London, p. 825

Ipatov S.I., Hahn G.J., 1997, In: LPSC 28th LPI Houston, TX, p. 619

Jewitt D.C., 1992, In: Brahic A., Gerard J.-C.,, Surdej J.S. (eds.) Proc. 30th Liége Internat. Astrophys. Colloq., Inst. d'Astrophys., University Liége, Belgium, p. 85

Jewitt D.C., 1994, EMPl 72, 185

Kawakami S., Kanaori Y., Fujiwara A., et al., 1991, A&A 241, 233

Lagerkvist C.-I., Harris A.W., Zappala V., 1989, In: Binzel R.P., Gehrels T., Matthews M.S. (eds.) Asteroids II, Univ. of Arizona Press, Tucson, p. 1162

Lien D.J., 1998, In: DPS 30th. Abstract 12.07

Marsden B.G., 1996, IAU Circ. 6457

McNaught R.H., 1996a, MPEC 1996-R07

McNaught R.H., 1996b, IAUC Circ. 6473

Meech K., 1993, In: Huebner W.F., Keller H.U., Jewitt D., Klinger J., West R. (eds.) Workshop on the activity of distant comets. SWRI, San Antonio, TX, p. 12

Meech K., 1996, Physical properties of cometary nuclei. Invited paper, ACM VIth 1996 Paris-Versailles (in press)

Melosh H.J., 1980, Annu. Rev. Earth Planet. Sci. 8, 65

Nolan M.C., Asphaug E., Melosh H.J., et al., 1996, Icarus 124, 359

Offutt W., 1996, IAU Circ. 6456

Pilcher F., 1979, In: Binzel R.P., Gehrels T., Matthews M.S. (eds.) Asteroids I, Univ. of Arizona Press, Tucson, p. 1130

Pravec P., 1996, IAU Circ. 6459

Sekanina Z., 1996a, IAU Circ. 6459

Sekanina Z., 1996b, IAU Circ. 6473

Sykes M.V., Greenberg R., 1986, Icarus 65, 51

Sykes M.V., Greenberg R., et al., 1989, In: Binzel R.P., Gehrels T., Matthews M.S. (eds.) Asteroids II, Univ. of Arizona Press, Tucson, p. 336

Szebehely V., 1978, Cel. Mech. 18, 383

Tedesco E.F., 1989, In: Binzel R.P., Gehrels T., Matthews M.S. (eds.) Asteroids II, Univ. of Arizona Press, Tucson, p. 1090

Tedesco E.F., Matson D.L., Veeder G.J. 1989, In: Binzel R.P.,, Gehrels T., Matthews M.S. (eds.) Asteroids II, Univ. of Arizona Press, Tucson, p. 290

Tholen D.J., 1989, In: Binzel R.P.,, Gehrels T., Matthews M.S. (eds.) Asteroids II, Univ. of Arizona Press, Tucson, p. 1139

Thomas P., Veverka J., 1979, Icarus 40, 394

Vedder J.D., 1998, Icarus 131, 283