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Comet P/Gehrels 3: spectroscopic observations and nucleus models

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Abstract. In the framework of an observational campaign for increasing the knowledge on the relationship between cometary nuclei and asteroids, we performed spectroscopic observations of P/Gehrels 3. The Jupiter family comet P/Gehrels 3 moves on a particular orbit, with a very high Tisserand invariant with respect to Jupiter, that makes the encounters with the planet very effective. This implies that the comet spends part of its life as a temporary satellite of Jupiter, on an orbit that shows similarity with those of Trojans. This comet has been observed when it was far from the Sun, with the aim to acquire data on the nucleus status. In order to study from a theoretical point of view the possible status and evolution of a body on this orbit we have developed different nucleus models using a numerical code for the thermal evolution of the nucleus.

Key words: comets: general – comets: individual: P/Gehrels 3

1. Introduction

Observational discoveries and theoretical developments in the last few years have suggested that there may be an evolutionary link between comets and asteroids. These populations can be considered as a continuous suite of small objects with chemical, dynamical and physical interrelations.

Asteroids and comets have a close relationship with the planetesimals which formed in the solar nebula before 4.5 Gyrs ago. These objects are considered the remnants of the primordial processes which characterized the evolution of the Solar System. Small bodies should have preserved materials which witnessed the condensation and the early phases of the formation of the Solar System.

In the last years we have started the study of the interrelations between comets and asteroids because it can give new insights into the primordial evolution of the planetary bodies. Thermal evolution models of transition elements between comets and asteroids have been developed to see under which conditions a comet nucleus can become dormant or extinct, assuming an asteroidal appearance (Coradini et al. 1997a,b). The similarity between the spectra of comet nuclei and dark asteroids has been recognized on the basis of observational results. In particular the Trojans, while classified as asteroids on the basis of their lack of a detectable coma, seem to have physical properties close to those of the cometary nuclei. Jones et al. (1990) suggest that water ice can be incorporated in the surface of the supposed volatile-rich Trojan asteroids. Broadband visible photometry (Hartmann et al. 1987; Luu & Jewitt 1996) and spectroscopy (Jewitt & Luu 1990) showed that the distributions of the optical spectra of Trojans and cometary nuclei are similar.

A spectroscopic survey in the visible and near infrared of dark primitive asteroids belonging to the classes C, P and D has been performed (Barucci et al. 1994; Lazzarin et al. 1995). The spectra obtained have been used to better understand the relation between asteroids and comets, comparing these data to the available data on cometary nuclei founding no evidence of any distinction between the two populations, even if the data on comet nuclei are poor both in number and in quality (Luu 1993).

To improve the knowledge of cometary nuclei, we started to observe comets at high heliocentric distance where the coma might be still not present. Our observational campaign on cometary nuclei, performed at ESO and CFHT (Canadian-French-Hawaiian Telescope), started with the comet P/Gehrels 3.

The comet P/Gehrels 3 has a particular orbit with very low inclination, moderate eccentricity (Table 1) and a very high Tisserand invariant with respect to Jupiter all the time. For this reason the encounters with Jupiter are very important and the comet spends part of its life as a temporary satellite of Jupiter (Carusi et al. 1996). To better understand the evolution and the status of P/Gehrels 3, we have theoretically investigated the

Table 1. Dynamical parameters

Orbit	*a* (AU)	*e*	*Q* (AU)	*q* (AU)
multi-stage I	50	0.5	75	25
multi-stage II	25	0.4	35	15
multi-stage III	8	0.5	12	4
P/Gehrels 3	4.04	0. 15	4.64	3.43

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comet status during the observations, using a thermal evolution and chemical differentiation model of cometary nuclei (Coradini et al. 1997a,b; Capria et al. 1996; De Sanctis et al. 1999). The model was applied to a cometary nucleus with the estimated physical and dynamical characteristics of P/Gehrels 3, with various sets of initial physical conditions in order to infer the status and activity level of a body on such an orbit at the observation epoch.

2. Spectroscopic observations

P/Gehrels 3 has been observed at Mauna Kea Observatory, Hawaii, on June 20th, 1996 using the 3.6 m Canadian-French-Hawaiian telescope equipped with the MOS (MultiObject Spectrograph) and the CCD STIS2 (2048x2048 pixels). The grism used is the V150 with a dispersion of 433 Å/mm. The spectral range covered is about 400 nm $< \lambda <$ 980 nm with a spectral dispersion of 7 Å/pixel. A spectral resolution of about 30 Å has been obtained with a slit aperture of 1.7 arcsec. In this wavelength range both emission and absorption features can be seen. This range includes some of the most diagnostic features needed for the spectral classification: the 0.9 μm absorption feature, which is critical for the interpretation of the surface reflectance spectra and the C_2 emission bands.

The observations of comet nuclei are very difficult: when the comet is active, the nucleus is obscured by the coma and dust emissions. Contamination can be removed only with careful modelling and the spectrum of the bare nucleus can be obtained. Luu (1993), using this technique, observed 5 comets at large distance, finding that the optical spectra are very different from each other, ranging from blue, as for Chiron, to red, as for Tempel 2. This variety of slopes was also found in the Trojan population (Jewitt & Luu 1990).

The observations have been performed when the comet had passed the perihelion, at 4.5 AU from the Sun and 3.5 AU from the Earth; the visual magnitude was of 21.8 and the airmass was 1.5. Several solar analog spectra have been secured during the night and the reflectivity of the comet, shown in Fig. 1, results from the division by the spectrum of 16 Cygnus B. The spectrum is normalized at 5500 Å. No sign of activity has been detected in the comet spectrum. The spike near 0.76 micron is due to a not perfect removal of the atmospheric telluric absorption.

The optical spectrum shows a featureless, red continuum with a reflectivity gradient S' equal to 13.3±0.1%/10^3 Å in the wavelength range 550 and 800 nm. This value is statistically consistent with the mean slope of the optical spectra of comet nuclei, S' = 14±5%/10^3 Å (Jewitt & Luu 1990; Fitzsimmons et al. 1994), with that of Trojans, S' = 10±4%/10^3 Å (Jewitt & Luu 1990), D-type asteroids, S' = 13.5±1.0%/10^3 Å (Lazzarin et al. 1995), and some Centaurs (Barucci et al. 1999). The value of the reflectivity gradient S' suggests a similarity of the P/Gehrels 3 surface composition with that of Trojans and dark asteroids. The similar red colors and low albedos may be evidence for common organic compounds (possibly mixed with a limited amount of ice) on the surface of the two populations (dark asteroids and comets), but we must remember the strong

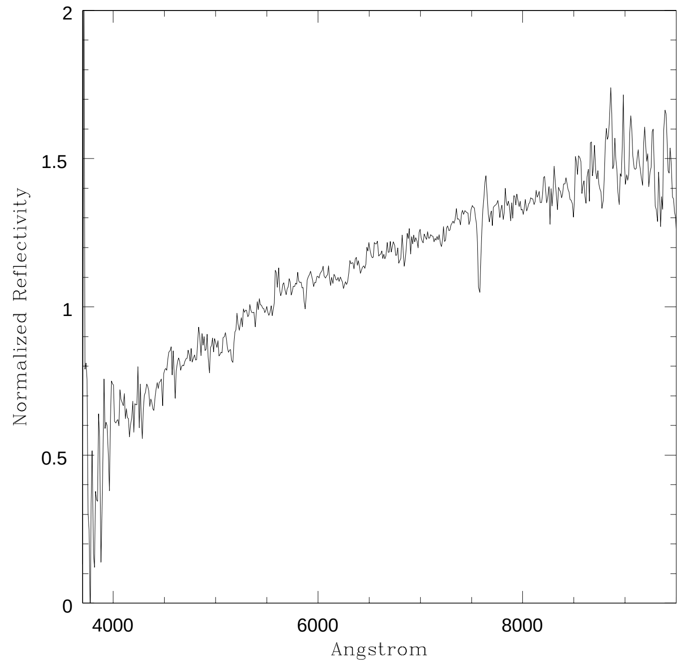


Fig. 1. Spectrum of P/Gehrels 3 observed at Mauna Kea Observatory, Hawaii, on June 20th, 1996. The spectrum is normalized at 5500 Å.

influence of the grains size on the spectra and also on the influence of dark material on the spectral reflectance. Considerable reduction of reflectivity of pure ice is achieved even with very small amounts of inclusions: the pure snow reflectivity which, in the visible, is approximately 0.9, can be reduced to less than 0.3 with a dust to ice mass ratio of only 10^{-3} (Warren & Wiscombe 1980). Very small amount of grains can reduce the reflectance spectra on an ice surface (Clark 1982). The presence of carbonaceous material mixed with water ice, even in low percentages ($<$ 20 percent), will mask the ice spectral features and reduce considerably its albedo (Clark & Lucey 1984). The presence of organic material on the surface of comet nucleus can mask the absorption features of silicates in the visible and in the near IR.

3. Theoretical nucleus model

The nucleus models presented in this paper have been computed with a numerical code, solving the unidimensional heat conduction and gas diffusion equations through an idealized spherical comet nucleus. This model was applied many times and is accurately described in various papers (Capria et al. 1996; Coradini et al. 1997a,b; De Sanctis et al. 1999), to whom the reader should refer to have more details: here only the main characteristics will be briefly described.

The comet nucleus is assumed to be initially homogeneous and uniformly porous, composed by different ices (H_2O, CO_2 and CO) and dust particles embedded in the ice matrix. The initial dust grain size distribution is given. In our simulations the dynamical history is taken into account: the evolution starts when the cometary nucleus is in the Kuiper belt, far from the Sun. We then compute a number of revolutions large enough to reach a quasi stationary state. The resulting nucleus conditions are then used as initial parameters for the next stage, with the aim to simulate the so-called multi-stage capture process (Fernandez 1985) from the Kuiper belt to the final Jupiter family orbit of P/Gehrels 3 (Table 1). When the nucleus reaches the present orbit of P/Gehrels 3, the internal structure is affected by the previous thermal history and the upper layers are already differentiated.

The thermal evolution of the nucleus leads to its differentiation due to sublimation-recondensation processes taking place in its interior. The dust grains are released by the sublimation of the ices and undergo the drag exerted by the escaping gas, so that they can be blown off by the flux and be lost in space, or they can accumulate on the nucleus surface to form a dust mantle.

Thermal evolution and chemical differentiation models of P/Gehrels 3 have been computed in order to study the characteristics of this body during the epoch of the observation. Some of the initial parameters assumed in the models are derived by the observations, while some others are commonly accepted in cometary nuclei modelling.

The estimated nucleus radius is about 3 km, obtained from the comet absolute magnitude assuming an albedo of 0.04. At the beginning of the evolution, in the Kuiper belt, an initial temperature of 30 K is assumed. The initial mean pore radius has been fixed to $10^{-5}\ m$. Due to the lack of information on the rotation period, we assumed a period of 10 hours, a value typical for the rotation periods of minor bodies. The models assume a dust density value of 1000 kg/m^3, according to the fact that grains are considered the result of an accumulation process and are therefore highly porous, like Brownlee particles. The initial bulk porosity is 0.8. The models are computed in the fast rotator approximation.

In model A we have assumed a set of parameters considered “standard” for a comet nucleus (Rickman & Hübner 1990; Hübner et al. 1999), while in model B we have tried to use the characteristics that can favor the activity.

In all the models dust on ice mass ratio was assumed to be 1, but the dust distributions are different. The models are developed with two different initial dust distributions, the “primordial” (a) (Coradini et al. 1977) and the “small grains” (b), to see the effects of a large amount of very small dust particles on the comet evolution. In Fig. 2 are shown the two dust distributions.

The accumulation of dust on the nucleus surface depends on the forces exerted on the single particles: as long as they are embedded in the icy matrix they are considered trapped and cannot be dragged away from the nucleus. When the ices (water, CO, CO_2) begin to sublimate the dust particles that are embedded in them, are considered free and not interacting among themselves.

To determine quantitatively how many particles can be blown off by the gas flow, and how many can be accumulated on the nucleus surface, we compare the different forces that act on the single dust grains. The balance between the drag of the outflowing gas plus the centrifugal force and the gravitational attraction force exerted by the nucleus has to be determined.

For each model, for each time step, we compute the amount of free dust particles and how this amount is redistributed between the grains that are ejected from the surface, forming the dust flux, and those that are deposited on the nucleus surface. The dust crust is formed by particles of different sizes when the surface layer is completely depleted of ice. This layer of crust is very porous and the gas can flow through the dust crust. In these models we consider two different surface regimes: the *free sublimation* regime and the *gas diffusion* regime. In the free sublimation regime, the grains can reside on the nucleus but these are considered isolated from each other and do not interact with the escaping gas. In the second case, a coherent dust layer obstructs the free passage of gas molecules: the gas can diffuse through the dust layers with different regimes (viscous, Knudsen and an average between the two). This scheme is applied to models A and B while for the model C we have introduced a “trapping” mechanism favoring crust formation (De Sanctis at al. 1999).

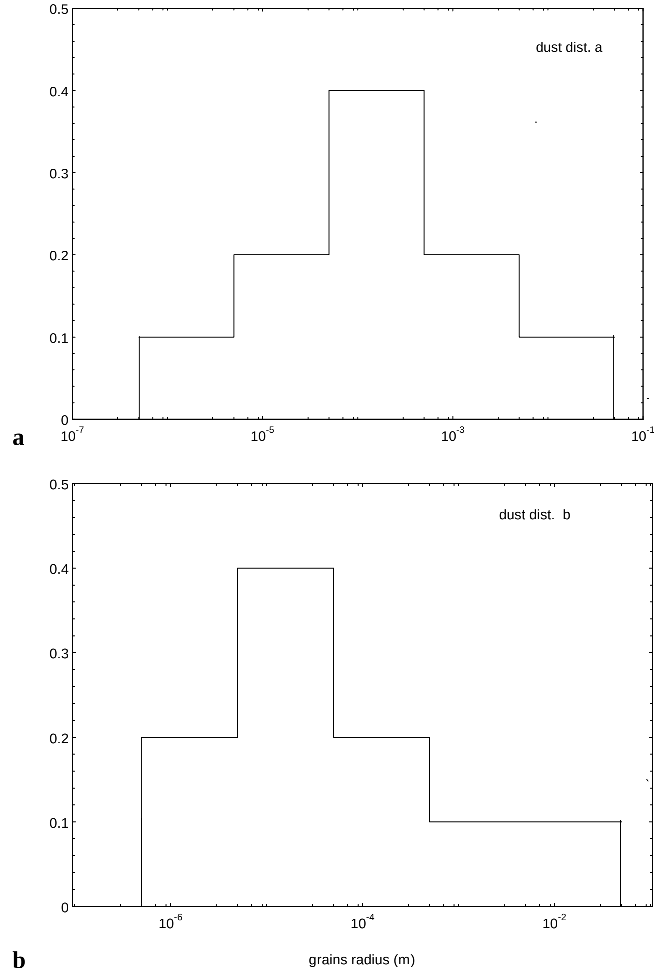


Fig. 2a and b. Initial dust distributions embedded in comet matrix: **a** Primordial, **b** Small grains.

Model A. The dust distribution assumed in model A, *a*, is derived from studies of grains accretion in the primordial Solar System (Coradini et al. 1977) and has been largely used and discussed in previous papers (Coradini et al. 1997a,b; Capria et al. 1996). The initial value of CO/H_2O and CO_2/H_2O was 0.01. The orbit of P/Gehrels 3 has a very low eccentricity and a

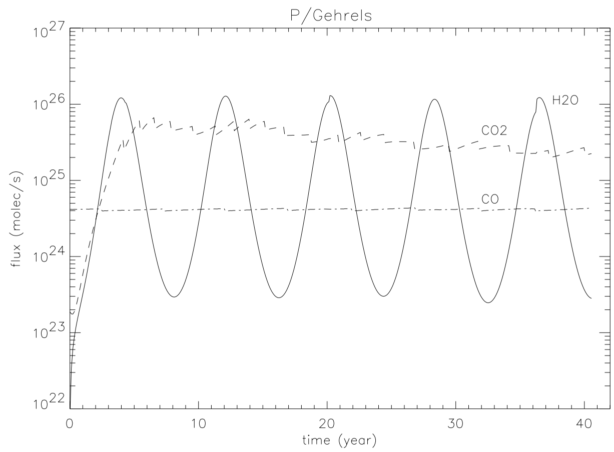


Fig. 3. Model A. Gas flux versus time on the current orbit of P/Gehrels 3.

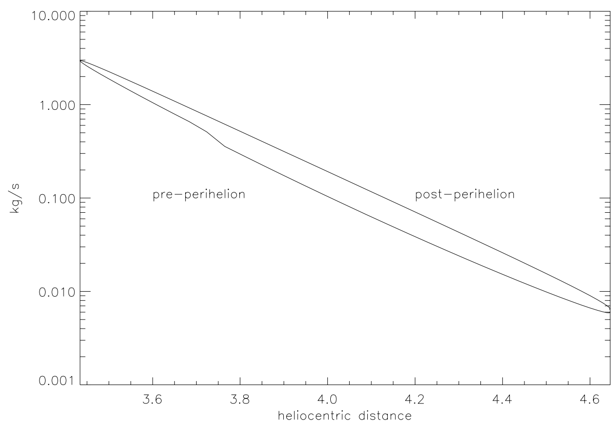
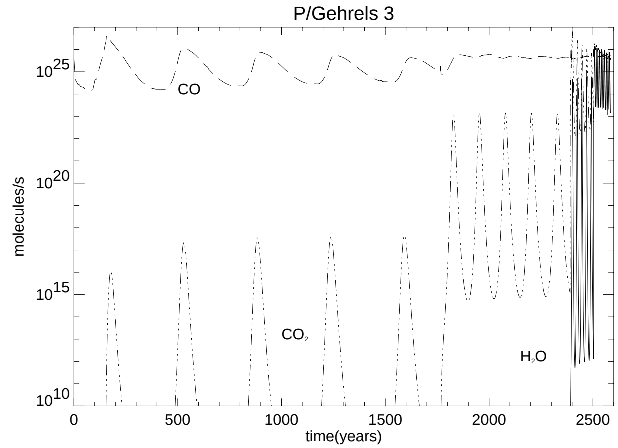
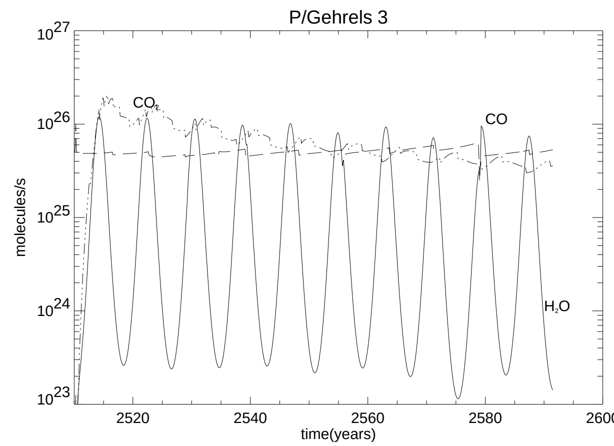


Fig. 4. Model B. Dust flux versus heliocentric distance along one orbit.



a



b

Fig. 5a and b. Model B. **a** Water, CO and CO_2 flux evolution from the Kuiper belt to the current orbit of P/Gehrels 3. **b** Enlarged view of the final part of Fig. 5a: gas flux versus time on the current orbit of P/Gehrels 3

semiaxis of 4.04 AU: the comet never arrives close to the Sun and the maximum surface temperature, reached at perihielion, is quite low ($\sim$ 157 K) and not very different from that at aphelion ($\sim$ 136 K). Accordingly, the activity level is low: the peak of water flux is $\sim 10^{26}$ molec s^{-1} (Fig. 3), while those of CO and CO_2 are respectively $\sim 3 \cdot 10^{24}$ molec s^{-1} and $\sim 10^{25}$ molec s^{-1}. At the perihelion the gas flux is dominated by the water, while the CO flux is constant along the orbit because it is coming from deep layers at a quasi-constant temperature. The CO_2 emission tends to diminish due to the sink of the CO_2 sublimation front. The low gas flux is coupled with low dust flux: only the smaller particles can be ejected from the nucleus, the larger ones tend to accumulate slowly on the comet surface. Revolution after revolution a thin, porous layer of dust tends to cover the comet surface.

Model B. In model B we have tried to assume values of parameters that can favor the comet activity, such as the amount of volatile ices (CO/H_2O=0.1 and CO_2/H_2O=0.05), stressing out the influence of the dust distribution, using very small dust particles (dust distribution *b*). In this case the smaller grains, with very low mass, are blown off from the nucleus contributing to the dust flux. The dust flux resulting is very low: only few kilograms for second (Fig. 4). The gas flux, from the beginning of the evolution (in the Kuiper Belt) to the current orbit is shown in Fig. 5a. The water flux (Fig. 5b) is still low but similar to that of the previous model, while the CO_2 and CO flux are much higher than in model A. After few revolution the water is the dominant species at the perihelion. Sublimation fronts and the crystallization front drop down slowly in the nucleus. It is possible to foresee a quite constant flux of volatiles along the whole orbit of P/Gehrles 3.

Model C. In the model C, that is the analogue of model A, we introduced a mechanism that favors the crust formation (De Sanctis et al. 1999). The idea of trapping was introduced by Shul'man (1972): as the large dust grains accumulate on the surface, the interstices between the particles become too small to allow the escaping of the smaller grains, even if these particles are smaller than the critical radius. Here we try to simulate the behaviour of cometary nuclei covered by a dust crust. This crust should be cohesive (Komle et al. 1996), but still porous and permitting the gas flux passage. The resulting thermal conductivity of the dust layers is higher than that of the ice/dust mixture. In this model the time needed for a stable crust formation is less than in the previous cases and the crust thickness is

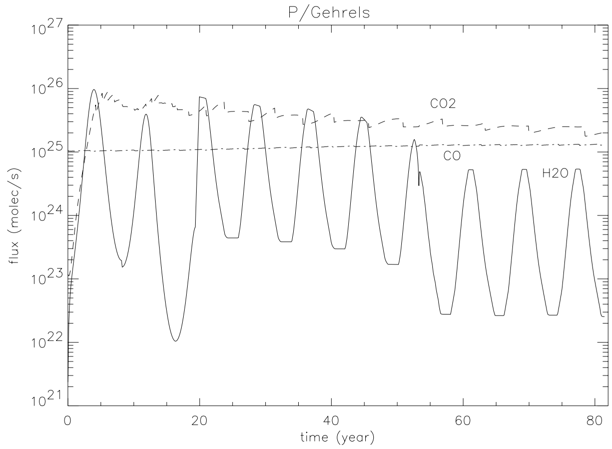


Fig. 6. Model C. Gas flux versus time on the current orbit of P/Gehrels 3.

higher. The presence of the crust strongly influences the dust and gas flux: the dust flux is quenched and the water activity is reduced (Fig. 6). The water flux is related to the crust thickness and decreases proportionally to the distance of the sublimation front from the surface. CO and CO_2 fluxes are not so strongly influenced by the presence of a stable crust: the depth of the sublimation fronts tends to increase with time and, consequently, CO_2 flux tends to decrease. The distance from the surface of the CO sublimation front remains quite stable, increasing very slowly: due to the near presence of crystallization front and to the high volatility, the CO emission tends to increase very slowly. It appears that model C reaches earlier a kind of "extinction", due to the presence of a stable and thick crust that strongly reduces the gas and dust emissions.

4. Conclusions

The spectrum of P/Gehrels 3 does not show any sign of activity but a featureless red continuum.

The spectrum presented in Fig. 1 has been obtained when the comet was at 4.5 AU from the Sun: at that distance the models without stable crust foresee an activity level of the order of $\sim 10^{24}$ mol s^{-1} for H_2O flux, while the model with a stable crust shows a water activity of $\sim 10^{23}$ mol s^{-1}. The volatiles flux remains quite constant along the whole orbit of P/Gehrels, depending on the original amount of volatiles defined in the models. The dust flux is, in any case, very low.

From the results described above it can be argued that a comet, without crust, on the present orbit of P/Gehrels 3 should have a level of water flux quite low, due to the large distance from the Sun (the minimum distance from the Sun is $\sim$ 3.5 AU) and the low surface temperatures reached by the body. Also the dust flux is very small, being of the order of few kilograms per second at the perihelion. At 4.5 AU from the Sun, the distance where the comet was at the epoch of this observation, the dust flux foreseen by our models is of the order of 0.01 Kg/s.

In the model in which a thick crust is present, the dust flux is negligible and the water flux is strongly reduced. The activity level depends on the crust thickness and porosity: in the hypothesis of a very "old" and devolatilized comet, with a large amount of material forming a cohesive crust, the comet could be quite completely inactive and could assume an asteroidal aspect.

At 4.5 AU from the Sun, all the models discussed foresee very low dust and gas fluxes, even if the most volatile species are emitted along the whole comet orbit. No sign of gas emission has been found in the P/Gehrels 3 spectrum. This observation should be consistent with the general results of the models. The obtained featureless spectrum can be considered as typical for comet nuclei and can be added to the few spectra of comet nuclei known to date. The spectrum of the comet P/Gehrels 3 is very similar to those of D-type, primitive asteroids. This implies that Trojan and dark asteroids need more investigation to better understand their composition, evolution and origin.

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References

Barucci M.A., Lazzarin M., Tozzi G., 1999, AJ 117, 1929
Barucci M.A., Lazzarin M., Owen. T., Barbieri C., Fulchignoni M., 1994, Icarus 110, 287
Clark R.N., 1982, Icarus 49, 244
Clark R.N., Lucey P.G., 1984, J. Geophys Res. 89, 6341
Capria M.T., Capaccioni F., Coradini A., et al., 1996, Plan. Space Sci. 44, 987
Carusi A., Kresak L., Valsecchi G., 1996, Electronic atlas of evolution of short-period comets. http://titan.ias.rm.cnr.it/ias-home/ias-home.html
Coradini A., Federico C., Magni G., 1977, Ap&SS 48, 79
Coradini A., Capaccioni F., Capria M.T., et al., 1997a, Icarus 129, 317
Coradini A., Capaccioni F., Capria M.T., et al., 1997b, Icarus 129, 337
De Sanctis M.C., Capaccioni F., Capria M.T., et al., 1999, Planet. Space Sci. 47, 855
Fernandez J.A., 1985, Icarus 64, 308
Fitzsimmons A., Dahlgren M., Lagerkivst C.-I., Magnusson P., Williams I.P., 1994, A&A 282, 634
Hartmann W.K., Tholen D.J., Cruikshank, 1987, Icarus 69, 33
Hübner W.F., Benkhoff J., Capria M.T., et al., 1999, ISSI Report
Jewitt D.C., Luu J.X., 1990, AJ 100, 933
Jones T.D., Lebofsky L.A., Lewis J.S., Marley M.S., 1990, Icarus 88, 172
Komle N.I., Kargl G., Thiel K., et al., 1996, Planet and Space Sci. 44, 675
Lazzarin M., Barbieri C., Barucci M.A., 1995, AJ 110, 3058
Luu J.X., 1993, Icarus 104, 138
Luu J.X., Jewitt D., 1996, AJ 112, 2310
Rickman H., Hübner W.F., 1990, In: Hübner W.F. (ed.) Physics and chemistry of comets. Springer Verlag, Berlin, p. 245
Shul'man L.M., 1972, In: Chebotarev G.A., Kazimirchak-Polonskaya E.I., Marsden B.G. (eds.) The motion, evolution of orbits and origin of comets. Reidel, Dordrecht, p. 271
Warren S.G., Wiscombe W.J., 1980, J. of Atmosph. Sci. 37, 2734