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THE COMETS OF THE CENTURY – NUCLEI OF P/SHOEMAKER-LEVY 9 AND HALE-BOPP

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RESUMEN

La pregunta actual más central acerca de los cometas es si éstos preservan el material primordial de la nube presolar en su forma original, o si este material fue sujeto a sublimación y recondensación en las regiones exteriores de la nebulosa solar. Estrechamente asociado a lo anterior es el problema de las propiedades estructurales y la construcción química de los núcleos cometarios. Esta contribución ha sido motivada por la aparición, en un período de apenas un par de años, de dos cometas famosos, cada uno de los cuales brindará importante información vinculada a estos temas. Presentaré aquí un resumen de los indicios preliminares obtenidos hasta comienzos de 1996.

ABSTRACT

The currently most central question about comets is if they preserve the material of the presolar cloud in original shape or if this material was subject to sublimation and recondensation in the outer parts of the solar nebula. Closely associated to this is the question of the structural properties and chemical build-up of cometary nuclei. The present contribution is prompted by the occurrence, within a period of just a couple of years, of two famous comets, each of which will bring important information bearing on these issues. Here I summarize the preliminary indications as of early 1996.

Key words: **COMETS**

1. STRUCTURAL PROPERTIES OF P/SHOEMAKER-LEVY 9

This comet approached Jupiter in July 1992 along a temporary satellite orbit and reached deep inside the Roche zone. At its discovery in March 1993 the tidally split comet presented an unusual appearance like a string of pearls with the fragments, each having a coma and tail of solid grains, aligned in a direction nearly perpendicular to the orbital motion. More than 20 such condensations were observed, but models of the dynamical evolution (Sekanina 1995) indicate that the initial splitting involved about half as many major pieces, having occurred near perijove at a planetocentric distance of about 1.35 R_J, R_J being Jupiter's radius.

Dobrovolskis (1990) investigated the conditions for tidal splitting of non-rotating bodies and found that the central shear dominates over the greatest tension at all planetocentric distances, so a ductile body for which the tensile, compressional and shear strengths are equal will first yield by shear flow at the center. For a cometary nucleus, imagined as a porous aggregate of tiny grains, the assumption of ductile material seems nearly inescapable. Thus one may use the formula given by Dobrovolskis:

$$S' \simeq 2.55 P_0 (R/d)^3 \qquad (1),$$

for the central shear S' in terms of the central gravitational pressure P_0, the "equivalent planetary radius" $R = R_J \cdot (\rho_J/\rho)^{1/3}$, where ρ_J and ρ are the planetary and cometary mean densities, respectively, and d is the planetocentric distance.

Applying Eq. (1) with $d = 1.35 R_J$, then values of $0.3 - 0.9$ g/cm^3 for the cometary density yield values of $4.6 - 1.6$ for S^*/P_0, where S^* is the material strength inferred. The remaining problem is to estimate P_0, for which we assume the parent nucleus to be a homogeneous sphere, yielding: $P_0 = 2/3 \cdot \pi G \rho^2 r^2$, calling G the gravitational constant and r the nuclear radius. The decreasing trend of S^*/P_0 with increasing ρ is more than

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compensated by the ρ^2 dependence of P_0, and for a radius of 1 km, we get S^* ranging from 60 to 180 Pa for densities of $0.3 - 0.9$ g/cm^3.

The diverse indirect pieces of evidence for the size of the parent nucleus at the final stage of splitting (the process may have been hierarchical, as suggested by Dobrovolskis 1990 and Asphaug & Benz 1994) may be interpreted as indicating $r \simeq 1 - 2$ km. This would be consistent with *HST* imaging before impacts (Weaver et al. 1995), ejecta blanket opacities (West et al. 1995), impact plume modelling for the major events as well as some models for the tidal breakup scenario. It seems in particular quite difficult to imagine a size much larger than the above-mentioned range, and hence our estimate of S^* remains of the order of several hundred Pa at most.

This is a very low value by most standards, and it may be interpreted to indicate a very fluffy structure for the cometary nucleus (cf. Greenberg 1986). Indeed, Greenberg et al. (1995) have estimated the van der Waals bonding strength of a porous aggregate of icy grains and they found values of $\sim 10^2 - 10^3$ Pa for an assumed density of ~ 0.3 g/cm^3. This may be seen as a check on the model of cometary material, and the agreement with the estimated range of strength for P/Shoemaker-Levy 9 yields support for the model in question and for a low density.

2. OUTGASSING MECHANISM OF COMET HALE-BOPP

Comet C/1995 O1 Hale-Bopp was discovered by amateurs in July 1995 at a heliocentric distance exceeding 7 AU and yet with a magnitude as bright as 10–11 and in a state of major activity. It is easy to realize that this activity cannot have been driven by H_2O sublimation. The outgassing flux at the distance in question would be so low that a nucleus of enormous dimensions would be required, large enough to likely inhibit the formation of an unbound coma by its gravity. In addition, Hale-Bopp was not detected on plates taken four years before the discovery (McNaught 1995).

In fact, we now know that comets often present remote activity (Meech 1993), far enough to rule out H_2O sublimation, and that this activity shows a great deal of outburst-like behaviour. From this point of view, comet Hale-Bopp is by no means exceptional though still remarkable by its brightness. Based on measured molecular abundances in comets (Crovisier 1994), suspicion early fell on CO as the activity driver. This gas was first detected in Hale-Bopp in September 1995 (Matthews et al. 1995; Rauer et al. 1995), and its production rate was found appropriate to explain the visible grain coma. However, the quest for the outgassing mechanism has to be further pursued, because the CO molecules may originate from several, quite different processes.

The mechanism that first comes to mind and has been very often considered in the literature is sublimation of CO ice from the nuclear surface. Now, if there is a surface reservoir of CO ice on a cometary nucleus at a heliocentric distance $r_H \simeq 6 - 7$ AU, its very high vapour pressure will necessarily lead to a sublimation flux large enough to consume essentially all the insolation received. The same holds true even at distances $\sim 15 - 20$ AU. We thus face a situation analogous to that of a usual, water-dominated comet at $r_H \sim 1$ AU. From the experience of the brightness behaviour of such comets, the probability distribution of the photometric index spans a wide range, but under usual circumstances (for an index of $\sim 4 - 6$) the extrapolated magnitude for $r_H \simeq 14$ AU at the time of the negative observation (McNaught 1995) appears too bright.

One would thus have to assume somewhat unusual circumstances leading to very rapid brightening along the pre-perihelion branch, like e.g., a seasonal effect such that a surface patch of CO ice receives insolation only starting from a point between $r_H = 14$ and 7 AU inbound. For a comet with a perihelion distance near 1 AU this is even less likely than it might appear due to the small range of true anomaly involved. But in fact, whatever is the physical reason of the rapid brightening, its a priori likelihood remains small. Moreover, the same argument applies also to another outgassing mechanism, i.e., subsurface sublimation of CO ice. In this case the latent heat of sublimation is supplied by conduction from the surface, so the flux for a CO layer at a given depth is proportional to the thermal gradient, or roughly to the surface temperature which in turn varies approximately as $r_H^{-1/2}$ in the absence of seasonal effects. It is therefore evident that a special mechanism is required to explain the rapid brightening, and at the current state of knowledge the idea appears somewhat far-fetched.

There exists another mechanism that may offer a real explanation in the sense of a physical process that acts to increase the rate of CO production just in the range of $r_H \sim 10$ AU inbound. This is the near-surface crystallization of amorphous H_2O with the release of trapped CO (Prialnik & Bar-Nun 1990). The rate of this phase transition increases exponentially with temperature (Schmitt et al. 1989) and reaches substantial values in a range close to 120 K. To reach this threshold at $r_H > 7$ AU inbound in a subsurface amorphous layer, the overlying crystalline crust has to be thin. On the other hand, if the amount of trapped CO is as large as ~5–10%, then previous models (e.g., Tancredi et al. 1994) clearly indicate the possibility of a large outgassing rate.

A further consequence of this picture is that the crystallization and ensuing outgassing should be burst-like in character, and such behaviour appears to have been clearly borne out by the observations of the visible grain coma during August-September 1995 (e.g., Kidger et al. 1996). This leads finally to the question: what is the distinctive property of comet Hale-Bopp that makes it so bright? The possibility of a very high outgassing flux for near-surface crystallization relaxes the requirement of an exceptionally large nucleus but shifts the question into: why is crystallization occurring so near the surface in this very comet? The question is in particular prompted by the fact that Hale-Bopp is a dynamically old long-period comet that should have had the time to crystallize to a large depth on previous occasions. In fact, one can only speculate that the Hale-Bopp nucleus arose from splitting of a precursor at the previous apparition. We are again facing a suggestion of a peculiar event, but statistics show that the splitting of a long-period comet is not a very remote possibility.

Regarding the size of the nucleus, the measured CO outgassing rate of $\sim$ 1000 kg/s (Biver et al. 1996) is about half that of P/Schwassmann-Wachmann 1 (SW1) at a similar distance (Senay & Jewitt 1994). For the latter comet, H_2O crystallization appears to possibly yield an adequate explanation of the outgassing rate (Tancredi, Rickman, & Greenberg, as yet unpublished), but it is certainly occurring at large depth and thus the flux should be much smaller than in Hale-Bopp. On the other hand, the jet-like dust production of the latter comet indicates that the source is active over a smaller fraction of the surface. It is impossible at present to make detailed inferences about the mean radius of the Hale-Bopp nucleus, but the above would seem to suggest a size comparable to that of SW1. If so, the comet will be very bright, though not exceedingly bright, as it reaches perihelion in 1997.

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