THE NUCLEUS: PANEL DISCUSSION

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Almost all information about the physics of the nucleus is based on deductions from observations of the coma and tails. It is well to keep in mind the hierarchy of events on which these deductions are based:

1. The material properties of the constituents of the nucleus and the detailed physical and chemical structure of the nucleus form the basis for the behavior of coma and tails.

2. Interaction of solar radiation with the surface of the nucleus determines the overall temporal development of the coma.

3. The subsequent interaction of solar radiation and solar wind with the coma determine the gross features of the tails.

4. Short term fluctuations primarily in the solar wind (and associated magnetic field) cause disturbances of comparable duration observable mostly in the tail but also in the coma.

In a large number of cases (particularly if the coma is involved) it is difficult to isolate the cause of the disturbances, i.e., whether the observed effect is due to a fluctuation in the solar wind or due to an inhomogenity in the structure of the nucleus. The further removed an observed effect is in the hierarchy of events, the more difficult it is to relate it to the nucleus. Our concepts about the nucleus should therefore be based primarily on those observations which can be linked to the nucleus in the most direct manner.

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With this in mind let us follow an "average, new" comet on its way around the sun and note how the observed phenomena reflect on the properties of the nucleus. At a heliocentric distance comparable to the orbit of Jupiter the comet is a diffuse object. The diffuseness can be explained by the evaporation of highly volatile material, for example a frosty deposit accumulated during the long time that the comet spent in Oort's cloud. Embedded in this material may be grains of dust or water ice. The thickness of the shell must be small compared to the size of the nucleus but thick enough to drag dust or icy grains into the coma. In most cases there is no observable ion tail or spectrum; this indicates that the volatile material most likely is not composed primarily of CO. Spin of the nucleus reduces gravitational attraction and therefore aids in the development of a diffuse coma.

As the comet approaches the orbit of Mars the coma develops more fully, dust and particularly ice-covered grains are dragged into the coma and the spectroscopic radicals become observable. The surface of the nucleus begins to warm up and the more volatile components mixed with the less volatile frozen gases (e.g., H_2O) must be preferentially vaporized. Between Mars and Earth solar wind and solar radiation ionize part of the molecular coma. Through interaction with the solar wind the ions are transported to form an ion tail. The solar radiation also interacts with the grains in the coma and by the process of radiation pressure they form a dust tail. Dissociation of molecules and radicals in the coma gives rise to the observable ultraviolet coma which consists primarily of hydrogen and hydroxyl radicals. The thin layer of depleted volatiles on the surface of the nucleus schematically indicated in Fig. 1-A by cross hatching will now begin to vaporize more actively. As the heat slowly penetrates into the nucleus additional volatile material dispersed in the less volatile frozen gases will be brought to the surface and vaporize. Any pockets of volatiles which were on the surface have of course been depleted (Fig. 1-B). As the comet moves to still smaller heliocentric distances, say to about one half astronomical unit, the frozen gases (primarily water ice and some·mixed-in more volatile compounds) continue to be vaporized from the surface of the nucleus. This vaporization occurs rather uniformly. The data collected by Ulich and Conklin (1974) on methylcyanide shows no significant Doppler shifts. Methylcyanide is a relatively volatile compound with a latent heat of vaporization of $L \approx 8$ kcal/mol (in relation to water with $L \approx 13$ kcal/mol). Heat is transported relatively slowly for some small distance into the nucleus. As the comet moves further on its orbit around the sun this heat vaporizes pockets of more volatile gases trapped under the surface. These pockets of volatiles are now engulfed in a bath of somewhat warmer (say, ~150°K) less volatile components of the frozen nucleus. At this temperature the volatiles can build up a pressure which is several orders of magnitude higher than the vapor pressure of the surrounding, less volatile frozen gases. If these pockets are not too deep under the surface (~1 m) then the gases will be released rather explosively from the fluffy structure of the nucleus. For an adiabatic explosion the front of the escape velocity wave (Lelevier, 1965) is

$$v = \frac{2c}{\gamma-1} \quad , \tag{1}$$

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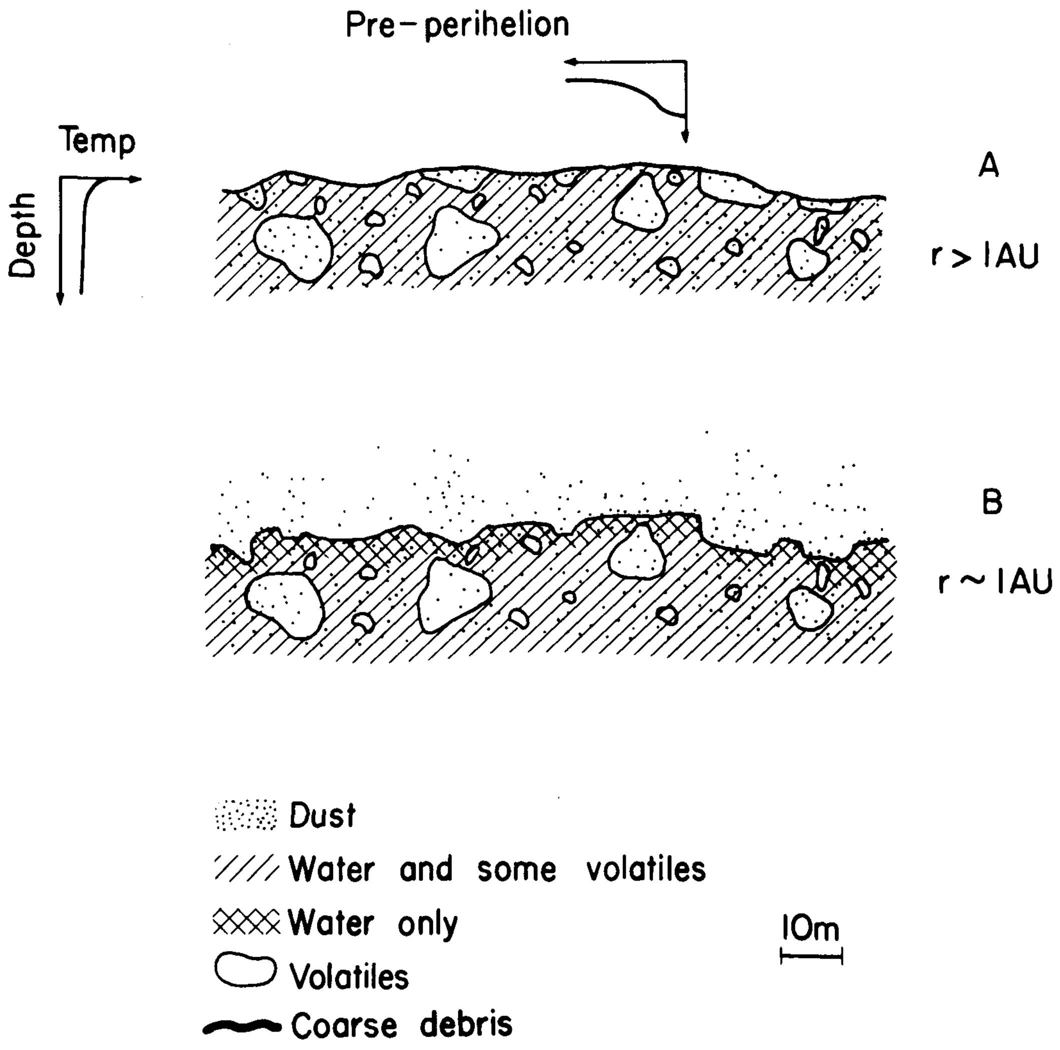

Fig. 1-A. A portion of a cross section near the surface of the heterogeneous model of a comet nucleus. At some heliocentric distance r > 1 A.U. the outgassing of the volatile components begins. The temperature profile on the left indicates a rise of the equilibrium temperature at the nuclear surface.

Fig. 1-B. At r ~ 1 A.U. volatiles have been depleted from the surface, heat begins to penetrate.

where c is the speed of sound which is approximately the thermal velocity of the gas. If the gas causing the outburst consists of polyatomic molecules then its polytropic index is $\gamma = 1.1$ to 1.3. For an average value of $\gamma = 1.2$ the front of the escape velocity is therefore approximately ten times the speed of sound or approximately ten times the thermal velocity of the gas. This is in agreement with the observed Doppler shifts of HCN and CH_3CN as observed by Buhl, et al. (1974). If the surface is uneven then the outbursts can occur in almost any direction from the sunward hemisphere of the nucleus (Fig. 1-C). After the pressure in a pocket has been relieved the vent may close again until the pressure has built up to its critical value and another puff of volatile gas is issued, similar to the action of a water droplet emersed in nearly boiling oil in a frying pan. Under these conditions the surface of the nucleus may approach Shul'man's spotty model of the nucleus. The rather limited observations available at this time indicate that for larger pockets the escape of gas occurs for a few hours but less than 24 hours. From the column density of radio observations and the measured Doppler shifts one obtains for the size of the larger pockets a diameter of the order of a few times 10 m.

The peak of the temperature distribution continues to travel into the nucleus even after perihelion. Therefore outbursts can still be detected even after the comet is receding from the sun (Fig. 1-D). Interpretation of the radio observations (particularly of HCN) indicate that the structure of the nucleus is inhomogeneous on a scale of about 10 m. As the comet recedes further from the sun the temperature distribution in the nucleus flattens out and outbursts become more rare

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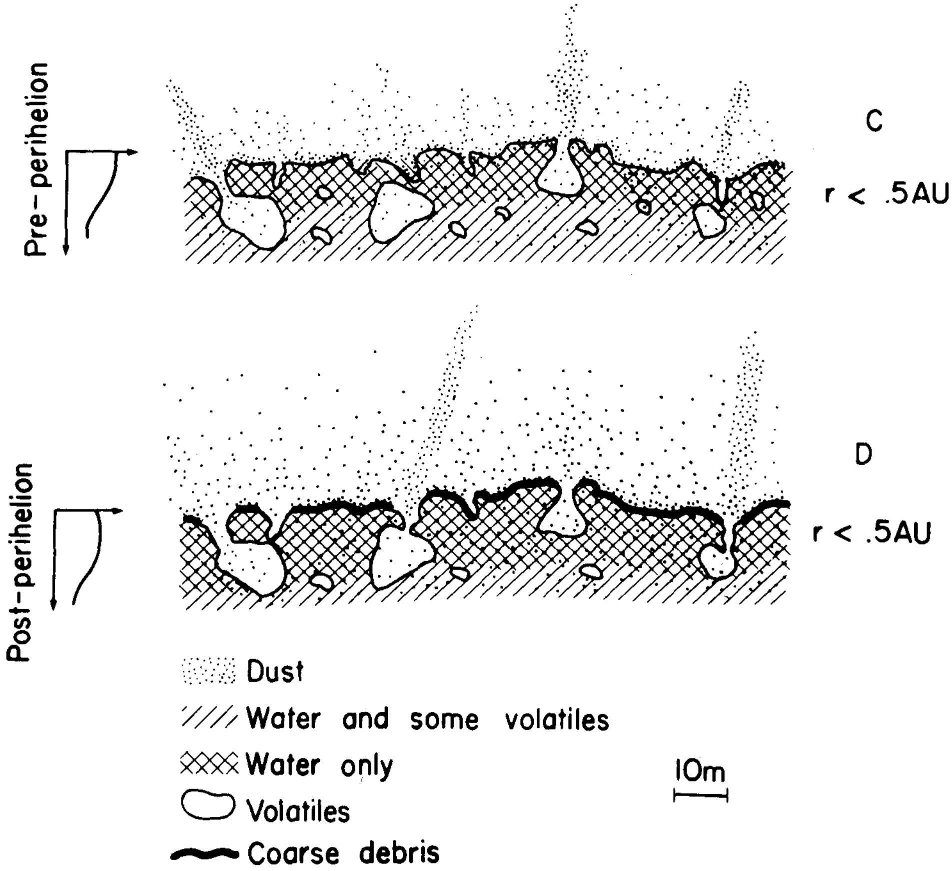

Fig. 1-C. At r < 0.5 A.U. heat has penetrated to pockets of volatiles and causes them to erupt in jets.

Fig. 1-D. After perihelion, but still at small heliocentric distances (r < 0.5 A.U.) the temperature profile broadens and heat still penetrates somewhat deeper, but the temperature begins to decrease at the surface. A few more pockets of volatiles explode. Coarse-grained dust (indicated by a black surface contour) accumulates. At still later times only the frozen gases remaining on the surface receive sufficient heat from incident radiation to vaporize. This causes the observed dimming of the comet when its brightness is compared to that at the same heliocentric distance before perihelion.

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and finally cease. Vaporization then occurs entirely from the surface which has been virtually depleted of volatile gases. This explains the general dimming of the comet after perihelion when its brightness is compared to that before perihelion at the same heliocentric distance.

I have given a possible interpretation of recently acquired data as it reflects upon the structure of the nucleus. Let us briefly look at the chemical abundances. With the exception of water for which there now exists considerable indirect as well as some direct evidence (Jackson, et al., 1974) all of the identified mother molecules have very strong molecular transitions in the radio range. Of the five molecules most likely to be found in a comet because of their strong transition probabilities HCN, CH_3CN, CH_3NC, H_2CO, and HNCO (see Huebner, 1971) the first two have been detected. HCN appears to be abundant to a few percent in comet Kohoutek. The abundance of methylcyanide cannot be ascertained because it appears not to be in equilibrium. The point to keep in mind is that there may be other molecules, perhaps even more abundant than HCN, but it is more difficult to detect them because of their weak line transitions. A few unidentified lines in the radio range have been reported, but these lines seem to correspond to a different class of transitions. Typically, a mother molecule exhibits a line width of 100 to a few 100 kHz. The unidentified lines are however much broader: of the order of 1 MHz. A possible explanation is that these transitions correspond to molecules or radicals which have undergone an exothermic reaction or an exothermic dissociation. It is also very likely that they are light molecules.

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As indicated above much new data is becoming available: New molecules give information about the chemistry of the nucleus, Doppler shifts give us information about the structure of the nucleus, infrared observations tell us about the composition of the grains, observations of light reflected in the coma and the antitail give us information about the dynamics of grains close to the nuclear surface, and about the latent heats of the propelling gases. Spectroscopy has of course for many years given some indication about the general constituents to be expected in the frozen nucleus. The question now really is: do we interpret the data correctly? Do we have enough physical and chemical information to interpret the data? I believe that the basic data needed in comet physics is not always of the common variety. I therefore propose that serious thought be given to the establishment of a laboratory for comet physics and that an effort be made to organize the data which already is available. Of particular need, I believe, are data on physical chemistry. For example, data on vaporization; data on mixtures; data on chemical reaction rates; and data on grain scattering, to mention a few specific areas. Much work is already being done, for example, at Leningrad Kaimakov and Sharkov work on physical chemistry. Here at NASA Donn and Stief work on photochemistry. In Canada Prof. Herzberg does outstanding work on laboratory spectroscopy. At Toledo Delsemme works on clathrates. At NBS Lovas and Johnson work on radio line transitions. In Munich Michel has carried out some basic work on grains and infrared spectroscopy. And in Italy Cosmovichi works with molecular beams. Undoubtedly, there are many other laboratories at work on physics and chemistry relevant

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to comet problems (which usually are also of interest to interstellar problems). But it will be necessary to stimulate some work currently in progress to make it relevant to the physics and chemistry of comets; and in other cases it will be necessary to analyze the results for their relevance to comet research.

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References

Buhl, D., W. F. Huebner, and L. E. Snyder, 1974, "Detection of Molecular Microwave Transitions in the 3 mm Wavelength Range in Comet Kohoutek (1973f)." Proceedings of this conference.

Huebner, W. F., 1971, Bull. Am. Astron. Soc. 3, 500.

Jackson, W. M., T. Clark, and B. Donn, 1974, "Radio Observations of H_2O in Comet Bradfield," Proceedings of this conference.

Lelevier, R., 1965, "Lecture Notes on Hydrodynamics and Shockwaves," Lawrence Radiation Laboratory report UCRL-4333 Rev. 1.

Ulich, B. L., and E. K. Conklin, 1974, Nature 248, 121.

DISCUSSION

Z. Sekanina: There is one thing I'd like to ask both Dr. Huebner and Dr. Delsemme with respect to the expression for the escape velocity.

I understood from the papers of Dr. Delsemme that the escape velocity is basically only that of the thermal velocity, whereas you suggested you get essentially one order of magnitude larger velocity than is the thermal velocity.

W. F. Huebner: I don't think that's any conflict. When you get evaporation from the surface, you indeed get evaporation from thermal velocity. What is happening here is an explosion of the pockets of high pressure of volatile material which has a vapor pressure of the order of 100 to 1,000 times higher than that of the surrounding water.

B. Donn: I have one question about the amount of material. What the pocket implies is only a small amount of material goes out in the jet. But if we look at your slides, these displaced components of HCN seem to me to have comparable intensity as the perhaps normal one, which suggested that a lot of material is going out in these jets and therefore a lot of material is going out with high velocity. Can you put this into a consistent picture?

W. F. Huebner: I didn't show the spectrum for the CH_3CN, but in CH_3CN you do not see a quiescent state. I therefore interpret the spectrum to mean that the zero Doppler shifts are also outbursts, but in a direction perpendicular to the line of sight. And they all are about the same order of magnitude, and therefore they all correspond to exploding pockets.

B. Donn: But in that case, what's bothering Sekanina is that you have a high velocity of ejection of the material, not the nearly thermal one that we use. And this, it seems to me, presents lots of problems with all these models of the coma, if the gas is coming off with these high velocities.

W. F. Huebner: I think the fluctuations that we see are the high velocity components, and those explode in pockets. The material which was lying on the surface has already disappeared by this time. We are observing at heliocentric distances which are smaller than 0.5 AU, something like 0.3 to 0.4.

H. Keller: I think in this connection in the first 1000 to 10,000 km we should have a lot of collisions of the exploding gas. I wonder whether you can keep up this beam direction or would this effect make things more isotropic so that you wouldn't see such high velocity components, at least not this high velocity coming out of the pockets, because the density is pretty high in the vicinity of these explosions.

W. F. Huebner: The spectra is already a few hundred kilohertz wide, and theoretically it's best to assume that by broadening it would only be about 90 kilohertz wide. I think we see some broadening effects on that.

M. Dubin: I would like to be on record as I think the water molecule is a parent molecule.

(Podashnick & Scheuerman) published in Nature recently, an interesting aspect of the phase of water, amorphous water at 140 K changes phase.

The change in phase is such as to be endothermic and to be expansive the density changes. The effect, then, is to transfer the phase change to some depth and to spall the ice.

Now, I think this has a clear connection with the Podashnick-Scheuerman type of description you've given.

W. F. Huebner: If you take the paper of Delsemme, I think the one difficulty in the paper is that it assumes the density for the amorphous water as a density of 2.3 grams/cm^3, which is rather high, and with the difficulty of understanding how it's got to be that high.

A. H. Delsemme: I just want to comment about this high density of amorphous ice. We had found high density. It has never been confirmed. I believe this high density was spurious. I still am unable to explain why we have found it, although we have observed amorphous water, of course.

So let's put it this way. I believe that the density of amorphous water is rather high, but certainly not as high as we have found. It looks to me, when I haven't looked at my results for a few weeks it looks impossible. When I go back to the dates, of course, I'm again convinced by myself, but that's another story.

Voice: Then you should tell the key point, I think.

A. H. Delsemme: No, I think—what I would like to discuss now is the chemical nature of the nucleus.

Of course, this implies the discussion of the interface of the nucleus with the coma because that's our only source of information about the nucleus. That's the vaporization that is happening at the coma level.