COMET THERMAL MODELING

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The past year has been one of tremendous activity because of the appearance of Halley's Comet. Observations of the comet have been collected from a number of sources and compared with the detailed predictions of the comet thermal modeling program. Spacecraft observations of key physical parameters for the cometary nucleus (size, albedo, dust-to-gas ratio, etc.) have been incorporated into the thermal model and new cases run. These results have led to a much better understanding of physical processes on the nucleus and have pointed the way for further improvements to the modeling program.

A new model for the large-scale structure of cometary nuclei was proposed in which comets were envisioned as loosely bound agglomerations of smaller icy planetesimals, essentially a rubble pile of primordial dirty snowballs. In addition, a study of the physical history of comets was begun, concentrating on processes during formation and in the Oort cloud which would alter the volatile and non-volatile materials in cometary nuclei from their pristine state before formation. Dr. Gary Herman of Tel Aviv University spent one year at JPL as a NRC post-doc working on two interesting research tasks: internal temperatures in icy nuclei, and radiative transfer in dusty cometary comae.

The thermal modeling of Halley's Comet has shown that the asymmetric behavior of Halley's light curve pre- and post-perihelion cannot be explained by heat flow into sub-surface layers on the inbound leg of the orbit, providing an additional energy source as the comet moves away from perihelion. Within 2 AU of the sun, high values of surface thermal conductivity can yield post-perihelion brightenings of only about 10 or 20%, as compared to the 100 to 200% brightenings that are actually observed. Previous models which suggested this behavior did not allow for radiative cooling of the cometary nucleus at night.

The correct explanation for post-perihelion brightening appears to be seasonal changes on the inclined, rotating nucleus. As a result of the comet's highly eccentric orbit, as it rounds perihelion there is a very abrupt change in the declination of the sub-solar point from the southern to northern hemispheres of the nucleus. On the way towards perihelion the northern hemisphere receives only modest heating, in fact, none around the circumpolar region. The sudden change post-perihelion, at a time when the comet is very close to the sun, causes rapid temperature increases and resulting thermal stresses. The compressional hoop stresses on the non-volatile cometary crust material causes cracking and strike-slip fractures. Plates of crustal material are broken loose from the nucleus and substantial new areas of fresh ice are exposed beneath the crust. The activity continues to build as the sun moves northward in declination following perihelion. Eventually, the decreasing solar insolation as the comet moves away from the sun causes the activity to subside.

Activity is less on the inbound leg because of two factors. First of all, the heating is more gradual and the thermal stresses can be accomodated more readily without catastrophic failure of the non-volatile crustal material. Second, the gradual heating likely depletes near surface layers of volatiles while building a thicker non-volatile crust layer over the ice.

Detailed solutions for the seasonal behavior of the Halley nucleus are sensitive to rotation pole orientation. However, all the suggested pole orientations for Halley are within about 40 degrees of each other, with suggested obliquities of 20 to 30 degrees. Other factors such as the nucleus rotation period, a still poorly determined parameter, and the triaxial spheroid shape of the nucleus also will affect the detailed gas production rates that are derived from the comet model as a function of orbital position.

Comparison of the comet thermal model results with the observed behavior of the Halley nucleus versus heliocentric distance showed that the fraction of active sublimating area on the nucleus surface was not constant throughout the orbit but changed in unpredictable ways (though consistent with the seasonal dependence explanation above). This is further proof of the heterogeneous nature of the nucleus and of cometary phenomena in general.

The surface heat flow becomes important with regard to the behavior of the nucleus at large heliocentric distances where the energy going into heat flow is comparable to that going into sublimation. For high heat flows the comet does not "turn on" until relatively close to the sun, while for low heat flow the coma can become visible at over 6 AU from the sun. Given the observed turn on of the Halley coma at 5.8 AU inbound in early 1985, one can set an approximate value for the thermal conductivity of about one-tenth that of solid crystalline water ice. This is a relatively low conductivity, though not as low as observed for some dusty satellite regoliths in the solar system.

The proposed new model for cometary nuclei, known as the "primordial rubble pile," considered what a cometary nucleus should look like based on present scenarios for planetesimal formation in the outer solar system, and attempted to explain a variety of observed cometary phenomena. The lack of major energy sources means that cometary material will likely not be brought together into a single, well consolidated body, but will retain the composite structure of an agglomeration of smaller dirty ice snowballs. Phenomena such as cometary outbursts and splitting might be explained by such a structure, as smaller pieces break off to become secondary nuclei, and freshly exposed faces result in sudden brightening and activity from the main nucleus. Evidence from radar studies of large debris clouds around nuclei tends to support this suggestion of a possible "rubble pile" structure, with small debris being briefly elevated off the nucleus surface and then falling back very slowly in the weak cometary gravity field.

Imaging of the Halley nucleus did not have sufficient resolution to determine if the primordial rubble pile model is correct. Giotto images did show a highly irregular nucleus with surface roughness on the order of 10% the mean radius, or more. But better images, presumably from the CRAF mission, will be needed to resolve this question. In addition, it is possible that after long years of physical evolution, the original rubble pile structure of the nucleus is hidden by external modification and mass movement.

Dr. Herman developed a detailed analytical solution to the nucleus heating problem and a one-dimensional numerical model of the means by which cold nuclei from the Oort cloud warm as both their perihelia and orbital semimajor axes decrease. He showed that previous models were inaccurate because they ignored surface heat flow. The internal temperature is a complex function of both the comet's semimajor axis and eccentricity, as well as the nature of the ice making up the nucleus, i.e., amorphous versus crystalline. The time required for the nucleus to reach equilibrium temperature is often quite long, exceeding the dynamic time scale for substantial changes in the comet's orbit due to close planetary encounters.

Another research effort was concerned with radiative transfer in dusty cometary atmospheres. It had been shown that a dusty coma can increase the total energy reaching the cometary nucleus as a result of multiple scattering and thermal emission by the dust. Dr. Herman showed that most past estimates of this phenomena tended to over-estimate the effect, and that it was difficult to get a large energy increase. However, the coma does serve to redistribute energy around the cometary nucleus, illuminating the night hemisphere while cutting down the total radiation reaching the dayside. This would lead to a more isothermal nucleus when the coma opacity was high. A Monte Carlo simulation of the radiative transfer by Dr. Herman and Dr. H. Salo showed that a modest, on the order of 10%, increase in total flux reaching the nucleus was possible, if one assumed forward scattering particles ($g = 0.7$), and an accelerating dust velocity due to entrainment in the evolving gas.

Finally, an analysis of possible mechanisms for modifying cometary nuclei during their formation stages, and/or during their long residence time in the Oort cloud was begun. Because of the small size of the nuclei and their formation in zones far from the sun where orbital velocities are small, their total gravitational potential energy and degree of compaction is probably quite small. The radii of the cometary nuclei are sufficiently small that they were likely not substantially heated by long-lived radio-isotopes. Short-lived isotopes like aluminum 26 may have melted the interiors of comets, but only if comets formed over a time span short as compared to the lifetime of that radionuclide. That appears to be unlikely. Sputtering of nucleus surfaces by galactic cosmic rays is an important process, removing much of the volatiles and polymerizing all the carbon compounds down to a depth of a meter or more. This leads to the interesting possibility that comets may have already developed non-volatile crustal layers before they entered the planetary system. Although comets might accrete a thin veneer of interstellar dust and gas while resident in the Oort cloud, it appears more likely that hypervelocity impacts by interstellar dust grains result in a net erosion of the cometary surfaces, though the effect here is only on the order of centimeters, as compared with modification to a depth of a meter or more by cosmic rays. Thus, comets may not be as entirely pristine as originally thought, and it will be important to consider these various modification processes in interpreting the results form the Halley's Comet missions, and from future missions such as CRAF and CNSR.