VOLATILE LOSS FROM ACCRETING ICY PROTOPLANETS;

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A large self-gravitating body does not easily lose significant mass because the escape velocity is much larger than the sound speed of atmosphere-forming species under ambient thermal conditions. The most significant exceptions to this are giant impacts or impact jetting by fast-moving projectiles[McKinnon, *Geophys. Res. Lett.* **16**, 1237(1989)]. A very small object (e.g. a comet) also does not easily lose significant volatile mass upon formation because the energy release associated with its accretion is so small. (It can however lose a great deal of mass if it is subsequently moved closer to the Sun.) I argue that there is an *intermediate mass range* (corresponding to bodies with radii of ≈300-800 km) for which the ambient steady-state mass loss is a maximum. By ambient, I mean those conditions pertaining to the formation region of the body. By steady state, I mean to exclude infrequent traumas (giant impacts). The existence of a preferred intermediate mass arises through the competition of growing gravitational containment and growing energy release by accretion; it corresponds typically to $GM/(Rc_S^2) \approx 2$ to 4, where M is the protoplanet mass of radius R, and c_S is the sound speed. Several factors determine the amount of volatile loss in this vulnerable zone during accretion but in general the loss is a substantial fraction of the volatiles, sometimes approaching 100%. *The principal implication is that bodies larger than a few hundred kilometers in radius will not have a "primitive" (i.e. cometary) composition.* This is relevant for understanding Triton, Pluto, Charon and perhaps Chiron.

Accretional Heating and Volatile Loss. When a protoplanet accretes material, most of the infalling material hits the surface at velocities only slightly in excess of escape velocity. The resulting temperature rise in the subsurface of the body is

$$\Delta T \approx 5\varepsilon\,(R_2)^2 \quad \mathrm{K}$$

where ε is an efficiency factor (plausibly 0.2-0.3 at low temperatures) and R_2 is the radius of the body in units of 100km. This would seem like a very small temperature rise but even a few degrees can be important in the outermost solar system where highly volatile constituents such as CO, N_2 and CH_4 are of considerable interest.(This is principally what I mean by volatiles in this paper.) The *surface* temperature of the protoplanet is much less affected if it is determined by radiative equilibrium, including insolation and the much smaller gravitational energy input (even if the latter is supplied on a timescale of a million years or less). Indirectly, the surface is affected because volatiles released by accretional heating in the subsurface can migrate up to the surface, forming a reservoir for atmosphere formation. This surface layer may actually be *less* stable than the material from which it was derived (clathrate, amorphous water ice or adsorbed on fine-grained water ice surfaces) since it has accumulated as a bulk surface deposit that is much more than a monolayer in thickness (i.e. it would have similarity to the *present* surface of Triton.) It is perhaps more relevant to ask how much volatile icy material can be mobilized by the subsurface heating: this is determined by a latent heat (of sublimation or clathrate breakdown or whatever) which is probably very low to judge by the activity of fresh comets at very large heliocentric distances. The fraction f of mobilized material per gram of accreted material is given by

$$f \approx 0.02\varepsilon(R_2)^2/L_2$$

where L_2 is the latent heat in units of 100cal/g (a nominal value that is somewhat less than for H_2O sublimation yet more than for sublimation of the ices in question).

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Solar insolation can then ensure the final escape provided the gravitational containment is not too great. The ability to escape is characterized by the parameter

$$\lambda \equiv GM/Rc_S^2 \approx 0.11(\mu/28)(R_2)^2/T_2$$

where μ is the molecular weight of the species in question and T_2 is the temperature in units of 100 K. Roughly speaking, the escape of volatiles is then given by

$$dM_{vol}/dt \approx \mathrm{Min}[\ fdM/dt, 4\pi R^2 P_{vap} e^{-\lambda}/3c_S, \pi R^2 \delta S/(GM/R)]$$

where Min[....] means the smallest of the expressions contained within, M_{vol} is the volatile mass that leaves , dM/dt is the accretion rate , P_{vap} is the vapor pressure of the species in question, S is the solar constant and δ is the fraction of the insolation available for driving escape. The last term inside Min[...] is relevant since there is an energy limit to the amount of material that can escape the body. The expression for evaporation flux assumes an isothermal atmosphere but allows for an escape that proceeds from an exobase that is not necessarily coincident with the physical surface. In practice there is a mixture of volatile species and some interesting fractionation effects can arise. Clearly there are many parameters in play here but it is obvious that the smallest (i.e relevant) of the expressions in the square brackets is necessarily the first at low mass (since it tends to scale as R^4 while the second scales as R^2 and R^0 respectively) and necessarily the second or third at high mass (because they are bounded above by something independent of R, unlike the first.) The radius where loss is greatest is dependent on many variables but it is typically in the range 300-800km. For those cases where a substantial fraction of insolation is used to promote escape (a fairly readily achievable circumstance) most of the volatiles mobilized (the parameter f above) do in fact escape until λ becomes substantially larger than unity.

Other Considerations. I have also considered the role of the nebula streaming by a growing protoplanet. Despite the fact that the wind is greater than the sound speed of relevant volatiles or the escape velocity (for most of the mass range of greatest interest), the very low density of the nebula at Uranus orbit or beyond greatly limits the ability of the nebula to promote the escape of volatiles. "Giant" impacts (any impact with a body of order 0.1 the mass of the protoplanet or more) can obviously be important for both differentiation (preferential loss of the most volatile material) and bulk loss (changing the ratio of total ice to total rock?)

Conclusions. (1) It is not correct to think that bodies in excess of a few hundred kilometers in radius will have the mean composition of the smaller bodies from which they accumulated. There will be preferential loss of the most volatile constituents as a continual wind during accretion (and perhaps beyond, depending on the final mass). (2) The fraction of the total volatile loss (here meaning CH_4 and anything more volatile) is dependent on many variables, some of which are poorly known and others of which will have varied from object to object. But this fraction is usually in the range of a few percent to over 90%. (3) It follows that it is not correct to use cometary or primitive solar nebular condensate compositions as the starting point for structural and evolutionary models of Triton, Pluto, Charon....even aside from traumas that these bodies may have experienced.