GEOPHYSICAL IMPLICATIONS OF FAST KBO ACCRETION.

C. J. Bierson[1], F. Nimmo[1], C. Goldblatt[2], S. Jacobson[3,4], [1]University of California Santa Cruz, Santa Cruz, CA, USA (CThomas1@ucsc.edu), [2]University of Victoria, Victoria, BC, Canada, [3]Bayerisches Geoinstitut, Bayreuth, Germany, [4]Observatoire de la Cote d'Azur, Nice, France.

Introduction: Studies on the formation of widely separated binary Kuiper belt objects (KBOs) have proposed they may have accreted simultaneously and very quickly via gravitational collapse [1]. Simulation results suggest that most of the growth happens on timescales of less 10^2 years. This is significantly faster than previous coagulation models which suggested a much longer timescale of ~10^6 yr [2]. Internal models of KBOs have assumed they formed on timescales longer than 10^6 yr [3,4]. In this work we look at how fast timescales of accretion would affect the bulk structure of KBOs.

Power Budget: We can make a first estimate of the power budget of a growing KBO by considering the incoming gravitational potential energy,

$$\dot{U}_{grav} \approx \frac{GM}{R}\dot{M} \approx \frac{3}{5}\frac{GM}{R}\frac{M}{\tau} \qquad (1)$$

Here G is the gravitational constant, M is the body mass, R is the body radius, and τ is the characteristic timescale of formation. The total energy from accretion for KBOs is likely less than the energy released by radiogenic decay [5]. During formation however, the gravitational power exceeds the radiogenic decay by several orders of magnitude. We can estimate this energy flux as

$$F_{grav} \approx 100\, W/m^2 \ldots$$

$$\left(\frac{0.1\,Myr}{\tau}\right)\left(\frac{R}{1000\,km}\right)^3\left(\frac{\rho}{1800\,kg/m^3}\right)^2 \qquad (2)$$

where ρ is the bulk density of the body. It is important to note that while this equation gives an estimate of the mean energy flux, most of the energy will be deposited in the final stages of accretion. Assuming that all the energy is deposited in a shallow near-surface region [6] and is neither deeply buried nor dissipated in the gas disk we can estimate the surface temperature of the growing KBO by balancing this with the outgoing blackbody flux,

$$F_{Therm} = \sigma T^4 \qquad (3)$$

This simple calculation neglects many possible effects, but is nonetheless instructive. Because the incoming energy flux will increase as the body grows, this will result in an inverted temperature structure with the warmest temperatures in the near surface [6]. In this work we present some of the effects pebble accretion may have on KBOs. For all the figures in this work we assume that $\dot{M}$ is a constant.

Internal Structure: A warm start for KBOs will have little effect on the long-term thermal evolution [5] because the radiogenic energy budget exceeds the gravitational one. But the high temperatures could have a significant effect on the interior state. Desch et al. (2015) [3] suggests that for a Charon-sized object with ammonia in the ice shell local differentiation may begin at temperatures as low as ~150 K. If the outer layers of a forming KBO differentiated the resulting Rayleigh-Taylor instability and concentrated radiogenic heat in the denser silicates may drive further differentiation as the body evolves. Unfortunately without knowing the moment of inertia this prediction is difficult to confirm.

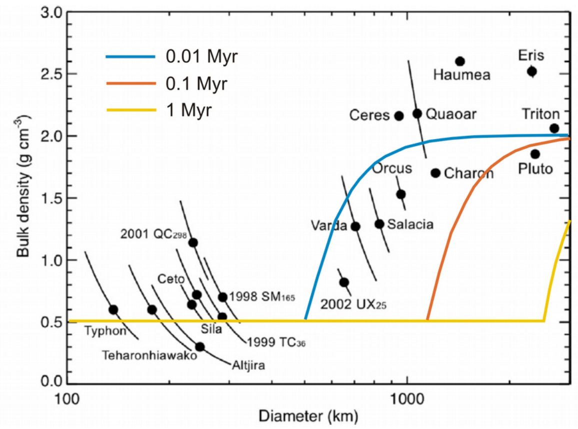

Figure 1: Density of KBOs compiled by [7,8,9]. The overlying curves show the expected density assuming a non-porous density of 2000 kg/m^3 and 75% porosity (comparable to comets). Each color corresponds to a different assumed formation timescale. The curves are based on the volume fraction of the body that exceeds 170 K ignoring all subsequent thermal evolution.

At temperatures of ~170 K the ice viscosity is low enough for porosity in the ice shell to close [10]. Using Equations 1 and 3 we can make a simple estimate of the volume fraction of the forming KBO that reaches temperatures >170 K. The results of this calculation are presented in Figure 1 with a porous density of 500 kg/m^3 and a non-porous density of 2000kg/m^3. Also shown are the density estimates compiled by [7,8,9]. As noted by Grundy et al. (2015) [8] the difference in density between small and large KBOs is far too large to explain by self-compression. Radiogenic heat flux is also insufficient to remove porosity in objects less than ~1000 km [11,12].

Early Volatile Loss: For very fast formation timescales the surface temperature can easily exceed the melting point of water (Figures 2). As the body warms sublimation, and then surface melting, will produce an atmosphere in vapor pressure equilibrium. Without more sophisticated modeling details of this atmospheric structure are hard to estimate. However, we can do some simple estimates of the volatile mass that may be lost during the lifetime of such an atmosphere.

How long an atmosphere of this type exists will be governed mainly by the incoming power. In a water vapor atmosphere, the outgoing energy flux is limited to ~280 W/m^2 [13]. For formation timescales of 0.1 Myr objects larger than 1000 km will have an incoming energy flux greater than this limit. For τ~0.01 Myr this happens for objects >450 km. This stored energy could extend the lifetime of the atmosphere for 10^4-10^5 years after accretion ceases.

Jean's Escape: Jean's escape is atmospheric escape that occurs when the thermal velocity is close to the escape velocity. For a Pluto sized object with a surface temperature of 250 K the ratio of these velocities is of order unity and thermal escape occurs. Given the short timescales over which these atmospheres may be maintained, however, the total mass loss is negligible (~10^{-4} of the total mass).

Hydrodynamic Escape: Hydrodynamic escape is atmospheric loss driven by a radial wind that at some altitude becomes supersonic. For large bodies (like the Earth) the surface gravity is so large that hydrodynamic escape cannot occur without unreasonably high temperatures or a large ultraviolet flux at the top of the atmosphere to give the particles the energy they need to escape. However, for a small warm body, hydrodynamic escape is extremely efficient [14]. At 250 K surface temperature and an adiabatic profile set to the equilibrium vapor pressure at the surface atmosphere, this process is so efficient that it may be able to remove mass as fast as it is accreted. For an adiabatic atmosphere the minimum surface temperature needed to achieve hydrodynamic escape in an adiabatic atmosphere can be estimated [14] (dashed line on Figure 2). We estimate that for bodies R<1000km and τ<0.1 Myr hydrodynamic escape could cause significant volatile loss, and thereby raise the bulk density. But for bodies which are too small, the surface temperatures never reach the point at which atmospheric escape becomes possible. There is thus a restricted size window (500-1500 km – encompassing both Pluto and Charon) in which accretion-driven volatile loss is likely to occur for τ~0.01 Myr.

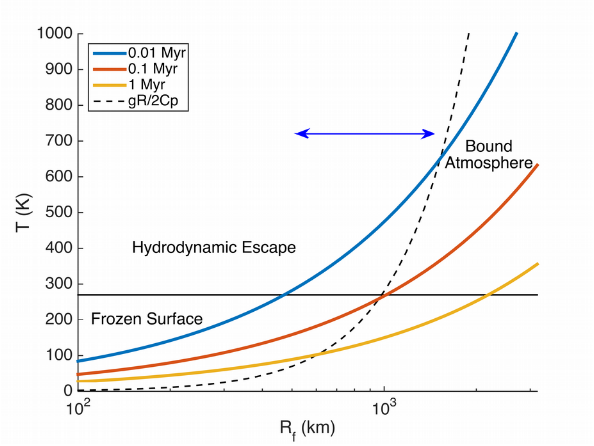

Figure 2: Maximum temperature achieved during formation as a function of radius calculated by combining Equations 1 and 3. The horizontal line is 270 K. The dashed black line shows the minimum temperature at which hydrodynamic escape in an adiabatic atmosphere may occur. The blue arrow indicates the radii range over which hydrodynamic escape will occur for τ=0.01 Myr.

Implications: The very short formation timescales for KBOs have implications for their initial state and evolution that are only crudely estimated here. But even these crude calculations suggest that for KBOs formed in less than 1 Myr, that formation process should have affected their bulk structure and density in ways observable today.

Future Work: Going forward we will perform more detailed modeling of the atmospheric evolution. We aim to set the boundary conditions for these models by different formation scenarios and see how the formation history of KBOs may be preserved in their structure today.

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