FORMATION TIME OF THE GALILEAN SATELLITES FROM CALLISTO'S STATE OF PARTIAL DIFFERENTIATION. William B. McKinnon. Department of Earth and Planetary Sciences and McDonnell Center for the Space Sciences, Washington University, St. Louis, MO 63130; mckinnon@wustl.edu.

Introduction: Callisto's unique state of partial differentiation [1] can be used to constrain satellite accretion models. It is well appreciated that the satellite must have accreted slowly enough (over >10^6 yr) so as to not trigger an accretional melt-down [2,3]. It must also not have accreted so early as to be melted by short-lived radiogenic heating due to ^{26}Al and ^{60}Fe. Structural models for Callisto indicate a hydrated rock mass fraction very close to 0.5. With an initial (t = 0 at CAI condensation) ^{26}Al/^{27}Al = 5.25 x 10^{-5} [4] and a contribution from ^{60}Fe [5,6], a primordial, undifferentiated Callisto can warm from 100 to 251 K and melt ~all its ice at t = 2.5 Myr. This is a hard lower limit to the formation time of Callisto as it ignores accretional heating. It may also constrain the formation time of Jupiter. A softer lower limit is obtained by only requiring Callisto not reach the ice minimum melting temperature at depth, after which otherwise the gravitational energy released by unmixing would trigger runaway differentiation (as described by [7]), t = 3.5 Myr. The sizes of the satellitesimals that built Callisto must also not be so large that they bury their accretional heat deeply enough that it cannot reach the surface on the accretional time scale. Large, multi-100-km satellitesimals would be especially adept at triggering differentiation, as the dense rock or ice-rock slurry created at impact would sink rapidly to the satellite's center, even if the center was cold. These constraints can be compared to time scales recently derived from retention of Iapetus' global figure [8,9].

Short-lived Radionuclides: Structural models of Callisto indicate that it is ≈0.50 rock+metal by mass and ≈20% differentiated, if the rock+metal is partially hydrated and oxidized [1,10]. From this and solar abundances [11], early radiogenic heating can be calculated. Figure 1 illustrates the heat retained by a primordial ice-rock mixture of Callisto's composition once all the ^{26}Al and ^{60}Fe have burnt out. There is uncertainty in the primordial 60Fe abundance, but this is not a crucial point. If Callisto accretes too early in solar system history, then all its ice should have melted, and it would have a core similar to that of Ganymede. As far as we can tell from Galileo gravity measurements, it does not.

Expanding the vertical scale in Fig. 1 to Fig. 2 brings up a more nuanced view of the effects of early radiogenic heating. The horizontal bars indicate the total temperature changes that obtains as function of accretion time relative to the CAI (calcium-aluminum inclusion) condensation time in the inner solar system. I conservatively assume that the initial temperature of Callisto ice-rock is 100 K, i.e., accretional heating is ignored.

The following time constraints can be derived:

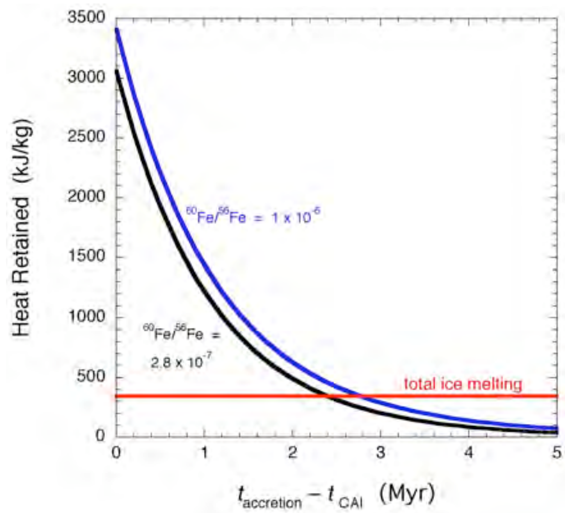

Fig 1. Total heating available, as a function of Callisto's time of accretion. There is plenty of short-lived radiogenic heating *potentially* available to melt Callisto's ice.

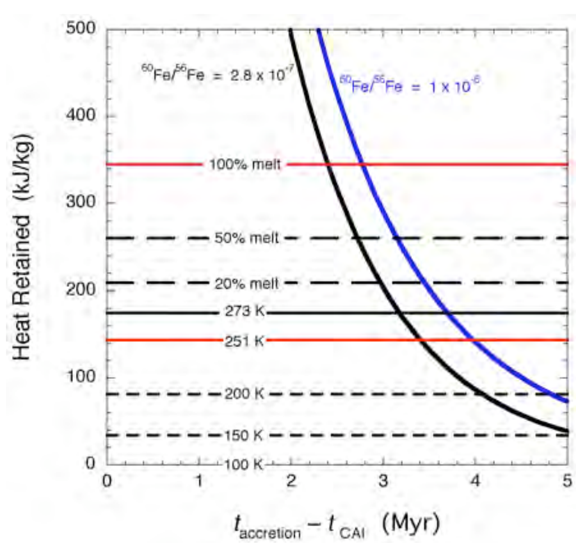

Fig 2. Total temperature change, as a function of Callisto's time of accretion. Note that these times refer to the *completion* of Callisto's accretion.

1) A *hard* lower limit on Callisto's accretion time from total (100%) ice melting is 2.4–2.8 Myr after CAI condensation.

2) If Callisto's limited differentiation (≈20%) is due to ice melting, then accretion must have finished no later than 3–3.5 Myr after CAI condensation.

3) If runaway differentiation at T =251 K must be avoided [7], then accretion must have finished no later than 3.4–4 Myr after CAI condensation.accretion time.

Implications. 1) If Jupiter formed by direct gravitational collapse in the solar nebula (i.e., as a giant gaseous protoplanet), then satellite formation must be delayed at least 1.4 Myr to complete Callisto's accretion at greater than2.4 Myr.

2) If Galilean satellites formed by slow feeding across a tidal gap opened by Jupiter [12], then the solar nebula must persist until ≥ 2.4 Myr

3) If Callisto assembled from large (>100-km diameter) protosatellites in an extended disk [13], then these protosatellites themselves must have accreted after 2.4 Myr to avoid melting and differentiation (which would be inherited by Callisto)

4) It is possible that the deep interior ice of Callisto melted due to radiogenic heating from ^{26}Al and ^{60}Fe decay, while the later accreting exterior remained cool. This could explain 20% differentiation while avoiding runaway differentiation

5) Differentiation driven by ocean formation [10], but without a thermal runaway, favors less restrictive lower limit on accretion time of 3.4 Myr

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