DIFFERENTIATION OF THE GALILEAN SATELLITES: ARE THEY REALLY IRON POOR? William B. McKinnon. Department of Earth and Planetary Sciences and McDonnell Center for the Space Sciences, Washington University, Saint Louis, MO 63130; mckinnon@wustl.edu.

Introduction: The internal structures of Jupiter's large moons — Io, Europa, Ganymede, and Callisto — can be usefully compared with those of the terrestrial planets, but it is evolutionary paths to differentiation taken (or not taken) by these distant and divergent worlds that are in striking contrast to that presumed to have governed the terrestrial planets and differentiated asteroids. Several aspects are important: 1) time scales; 2) the role of large impacts; and 3) long-term vs. short-term radiogenic heating.

Background. The large moons of Jupiter, Io, Europa, Ganymede, and Callisto, are all considered to be differentiated, although Callisto only partly so [1]. The evidence comes from interpretation of their second-degree gravity fields, as measured by *Galileo*, and assumes hydrostatic (though rotationally and tidally distorted) bodies. In the case of Ganymede independent corroboration comes from its intrinsic dipole magnetic field, which implies a dynamo in a liquid metallic core. Europa has an induced magnetic field, which is interpreted as requiring a conducting, saline aquasphere ("ocean") at depth — again consistent with a differentiated interior [2]. And Io is so intensely tidally heated that there is little question that it is a differentiated body. Only Callisto is deemed to be incompletely differentiated (~20–40% ice-rock separation), yet it too has an induced magnetic field and thus an internal aquasphere.

The terrestrial planets accreted over several 10s of Myr, based on the latest radiometric chronologies, and in doing so suffered catastrophically energetic impacts [e.g., 3]. Early magma oceans, if not global melting, must have resulted. Metal from rock differentiation in such an environment was facile. Even smaller asteroids were able to differentiate, apparently due to heat release due to the disintegration of short-term radionuclides, principally ^{26}Al and ^{60}Fe [e.g., 4]. Neither of the these mechanisms or processes can be called upon to explain the differentiation of the Galilean satellites, however.

Time Scales. The Galilean satellites are a byproduct of the formation of Jupiter. Jupiter formed within the lifetime of the gaseous solar nebula, which based on astronomical studies of nearby (analogous) protostars, had a lifetime in the 1–10 Myr range [e.g., 5; see 6]. The leading model for giant planet formation in our Solar System is the *core accretion–gas capture* model, in which a rock-ice-gas planet accretes by normal processes in the solar nebula until a mass threshold is crossed and nebular gas and entrained solids rapidly flow onto this planetary "core," inflating it to giant planet status [e.g., 7]. Under such circumstances the proto-giant planet may then open a gap in the solar nebula and terminate its accretion — or nearly so as nebular material continues to flow across the gap at a much reduced rate. An accretion disk forms about the nascent giant planet from this material, and satellites can then form (accrete) from this end-stage solar bequest, augmented by larger solar planetesimals that are captured into the disk [8,9] (though it should be noted that many details remain to worked out [10]).

As such, the accretion time scale for formation of the Galilean satellites is extended far beyond the intrinsic dynamical time scales in the protojovian disk. Accretion can last as long as the solar nebula exists to feed the protojovian disk, and as long as newly formed satellites can survive against gas drag and tidal-torque induced inward migration [8,9]. These time scales can be considerable (>1 Myr) for these so-called *gas-starved* accretion disks [8]. The solids entrained in the nebular flow across the gap would necessarily be relatively small, perhaps <1 m diameter [8], and should be compositionally representative of Jupiter's formation zone, and thus likely similar to the smaller carbonaceous bodies of the mid-to-outer asteroid belt (see [6,11] for discussion).

Extended formation times are required if bodies the size of the Galilean satellites (i.e., Callisto) are to form undifferentiated or nearly so. This gives sufficient time to radiate accretional energy to space (provided the accretional heat is not deeply buried). For the atmosphereless case, which applies to gas-starved accretion disks, the accretion time must exceed ~few x 10^5 yr [12]. While strictly speaking this argument applies only to Callisto, the gas-starved disk model posits that all the Galilean satellites grew more-or-less simultaneously, from a diminishing solar inflow [9], so they should have all formed on similar time scales, and thus likely accreted in relatively cool state. Cool is relative to the protojovian disk background, however, so Europa and especially Io should have seen somewhat elevated initial temperatures (but still well shy of rock or metal melting).

Large Impacts. By a similar argument, large, ice-melting impacts must be avoided in general, if Callisto is to emerge only partially differentiated. The Galilean satellites ostensibly grew from the sweep up of smaller debris that entered jovian orbit from the outside, and so

would not have experienced the violent end-stage accretion that affected the terrestrial planets (i.e., many large protoplanets on crossing orbits). Accretional velocities should have been close to satellite escape speed, which would have minimized accretional heating (all other things being equal). Accretion of smaller bodies also works in the right direction, but it is not clear if they were small enough. Even 10-m class bodies, accreting over 1 Myr, could bury a considerable amount of heat (this depends on the amount of impact stirring) [6]. Water ice is relatively easy to melt by shock [13], and late accreting ice-rock impactors on the Galilean satellites should have completely melted their ice fractions.

Short-lived Radiogenic Heating. Callisto again sets bounds, this time on the potential contribution of short-lived radiogenic heating to satellite evolution. If accretion began too early, then heat released by the decay of ^{26}Al and ^{60}Fe should have melted Callisto's ice fraction. Although one could take Callisto to be no more than 20% differentiated, a strict lower limit to Callisto's formation time presumes 100% ice melting. Starting from 100 K, and assuming an ^{60}Fe/^{56}Fe ratio between 2.8 x 10^{-7} and 10^{-6}, I find that Callisto *completed* its accretion no earlier than 2.6 to 3.0 Myr after t = 0 (CAI condensation in the inner solar nebula) [14]. While certainly compatible with the nebular time scales above, the implication for the other satellites is that short-lived radiogenic heating is at best a modest early power source.

Discussion. If the power sources above were not sufficient, then differentiation of the Galilean satellites falls to long-lived radiogenic and tidal heating. There is no question that this would have been sufficient for Io and Europa, even without tidal heat, as the ice fraction in a uniform primordial Europa (25-30% by volume) would not have been great enough for solid-state ice convection and efficient heat transport (and ice buffering of internal temperatures is not even an issue for Io). For Ganymede the story is different, and if Callisto is only partially differentiated then explaining a differentiated Ganymede is more difficult. This is an old problem [15]. Establishment of the Laplace resonance between Io, Europa, and Ganymede later in Solar System history is a potential solution [16], but if the Laplace resonance is primordial [17], then Ganymede's present state (complete separation of ice from rock) has no obvious explanation. Nominally, a primordial origin for the resonance brings Io to the threshold of rock-metal differentiation (Fe-FeS eutectic melting) after the protojovian nebula dissipates [6] and pushes Europa well past the threshold. Enhanced tidal flexing and dissipation result.

Without tidal heating, long-term radiogenic heating should bring a rock-metal satellite interior from a cold start (~250 K) to the threshold of differentiation in ~1 Gyr [e.g., 2]. This may best apply to Ganymede, or Europa if the Laplace resonance is *not* primordial. Solar composition rock implies a S/(Fe + S) ratio by weight of 23% [18], close to the Fe-FeS eutectic (at appropriate pressures). The rocky component of these worlds is likely highly oxidized, however [19,20], implying relatively low Mg#s (by terrestrial standards), lower amounts of Fe metal available for core formation, or even oxidized Fe_3O_4 as a potential core component. The latter may be important, as an Fe-S-O melt wets silicate grains readily [21], and thus can easily percolate downward, Elsasser style, to form a core.

If the Fe-alloy melt is not oxygen-bearing, core formation is delayed until sufficient melt accumulates or solid-state silicate convection begins, in which melt can accumulate in deformation bands [e.g., 22]. Regardless, FeS is predicted to be the dominant metallic phase in the rocky component [see, e.g., 23], so complete "melt out" (100% core formation efficiency) may require internal temperatures to be overdriven by tidal heating. Ganymede, and possibly Europa, may retain residual FeS in their rock mantles. Despite published claims [e.g., 24], structural models indicate that the Galilean satellites may not be iron poor at all.

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