PRIMORDIAL THERMAL HISTORY OF GROWING PLANETARY OBJECTS.
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It is often suggested that planetary objects (terrestrial planets and Galilean satellites) had initially molten mantles, probably before the long-lived radioactive elements released enough energy to increase significantly their temperature. Moreover, the primordial heating can contribute also to the present thermal flux of terrestrial planets. Following Schubert et al. (1), such a contribution can explain from 1/4 to 1/3 of the present heat flux of the Earth: if it is so, also the primordial amount of long-lived radioactive elements can be less than the amount generally hypothesized.

To obtain primordial thermal profiles it is necessary a physical model of the late stages of planetary formation. Safronov (2, 3) and Kaula (4) studied such problem in the framework of an accumulation theory, underlining that the thermal profile critically depends on the mass distribution of the impacting bodies whereas little depends on the accumulation time. The Kaula model gives for the Earth temperatures much higher than the melting ones, because it is underestimated the convective heat transport (5). In our simulation we have accepted the general treatment of the problem suggested by Safronov (2), but we have ameliorated the following points:

Energy balance of the impact. The propagation of shock waves in different media has been analysed deducing the amount of energy irreversibly trapped $E_r$ as a function of the distance $r$ from the impact center. We have obtained that $E_r = C r^{-n}$, where $n = 4.4 - 4.6$.

Projectile penetration depth. The projectile penetration is critical in order to evaluate the depth at which the energy irreversibly trapped is buried in the target. In the adopted impact velocity range (from 3 km/s for Galilean satellites to 15 km/s for the Earth) the obtained depth ranges from 1 to 2.5 radii of the projectile (6). Taking into account that the radius of the largest planetesimals is of the order of 0.1 of the radius of the growing embryo (2), it is clear that the depth of the burst strongly affects the efficiency of energy burial.

Heat transport. The differential equation for heat flow has been solved numerically using the algorithm suggested by Toksöz et al. (7). The convection has been treated as in (4) but the employed numerical techniques improves the precision so temperature...
higher than the melting one is never reached and the convective layer regularly increases with time.

Heat sources. In addition to the accretional heating, radioisotopic and adiabatic compression heating have been taken into account. However the last two sources give contribution generally negligible except when accumulation time is long.

Results can be shortly summarized as follows: Earth. The obtained primordial temperature profile lies below the Kaula one (fig. 1). In a wide region (±1000 km) convective motions set in and the heat transport becomes so efficient that the temperature profile exactly lies on the melting curve. Mars. The time scale for accumulation is generally longer than the Earth one. The temperatures are generally lower than those of the Earth and depends on the assumed accumulation rate. The molten layer is narrow (±500 km) and more deeply located with respect to the Earth (fig. 2).

Ganymede and Callisto. Assuming that these satellites were formed by accumulation of planetocentric planetesimals in a time scale of the order of 100 - 1000 years (8), we obtain an initial thermal profile with temperatures high enough to melt dirty ice in a shell ranging from 0.75 to 0.95 satellites radii (fig. 3). The initial temperature profile is also different from the ones assumed by (9). In spite of the extremely high transport efficiency in liquid water, the initial thermal profile of Ganymede and Callisto are different in contrast with the previous suggestion of Cassen et al. (10).

Fig. 1 Thermal profile for the Earth at the end of the accumulation. Accumulation time is $1.2 \times 10^8$ y. $R$ is the final radius of the planet.
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Fig. 2 Thermal profile for Mars. Accumulation time is $3.5 \times 10^8$ y. When a longer accumulation time is assumed ($1.5 \times 10^7$ y) the central temperature increases up to 1000 K and a wider convective zone is obtained.

Fig. 3 Thermal profile for Ganymede (G) and Callisto (C), also with the same accretion time ($100$ y), different results are obtained. In both cases the abrupt change in the slope at $.95 R_\odot$ is due to the onset of convection.

REFERENCES

(1) Schubert, G., Cassen, P. and Young, E. (1979) Icarus 36, 192-211.