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PRE-MAIN SEQUENCE HEATING OF PLANETOIDS

C. P. SONETT and F. L. HERBERT

The problem of thermal metamorphosis of meteorites, possibly the Moon and Mercury, and perhaps other planetary objects is reviewed. Classical mechanisms of heating include fossil nuclides (especially ^{26}Al), accretional heating, tidal heating, chemical reaction heat, and electrical induction. These various mechanisms involve constraints on the early thermal profiles of the Moon or Mercury. In the case of the meteorites, the primary contenders for a viable mechanism currently are fossil nuclides and electromagnetic induction, or some combination of these. But the issue of energetic mechanisms in the early solar system remains enigmatic. The fossil nuclide hypothesis leads to constraints upon nucleosynthesis while electromagnetic induction places significant constraints upon electrodynamic effects such as solar spin damping.

It has been known for many years that the thermal metamorphosis of many meteorite types required the presence of an extraordinarily strong source of thermal energy at a very early time in the history of the solar system (cf. Wood 1968), presumably prior to the arrival of the Sun onto the main sequence. Isotopic studies suggest that the metamorphosis followed shortly after the original accumulation of parent objects. Cooling rates of parent objects have been established for irons and stony-irons and imply that such objects were of asteroidal and sub-asteroidal size (Wood 1972; Goldstein and Ogilvie 1965). Later fragmentation lead to formation of meteorite fragments and their final dispersal into Earth crossing orbits, capture into the Earth's atmosphere eventually taking place.

H. Brown (1947) was the first to call attention to short-lived radionuclides in early solar system matter while Urey (1961) noted that ^{26}Al (τ 1/2 = 7x10^5 yrs) might have been responsible for meteorite metamorphosis. However, he later noted obvious difficulties of ubiquitous incorporation of ^{26}Al into planets, especially for a cold primitive Moon which he favored at the time. This difficulty still persists for some lunar models. Although other nuclides, notably ^{129}I and ^{244}Pu, have been inferred through the detection of fission Xe and fission tracks (Reynolds 1960; Fleischer, *et al.* 1965; Alexander *et al.* 1971), their original concentration appears to be insufficient as a source of thermal energy. Indications of incorporation of ^{26}Al have recently been found in strong concentration in certain inclusions in the Allende meteorite (Lee *et al.*1976). The inferred ^{26}Al concentration is so large as to make possible the melting of objects only a few km in radius provided that certain rather stringent constraints are adhered to.

In addition to the metamorphosis of meteorites there exists other evidence

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of early heating. On the Moon separation of the highlands from a primeval "magma ocean" appears to have taken place shortly after the formation of the Moon. Whether this actually represents fractionation of a "magma ocean" or of a completely molten Moon is currently the subject of controversy among cosmochemists. Whole Moon melting is the preferred model for formation of an Fe core and ancient dynamo. Whole Moon melting is also consistent with a high abundance of ^{26}Al in the early solar system; nevertheless, the prevailing geochemical viewpoint favors a Moon with an early "magma ocean" having a depth of several hundred km and is also consistent with recent evidence for isotopic closure of the basalt source regions less than 200 million years after formation of the Moon (Drake, Papanastassiou, private communications). The reader should note, however, that this is not consistent with an abundance of short-lived nuclides in the region where the Moon was formed, a problem correctable by the assumption of inhomogeneous accretion or a reduction of the hypothesized ^{26}Al concentration. Inhomogeneous accretion would have to infer that a high radionuclide concentration was laid down preferentially in the lunar mantle and crust.

Other suggestions of early heating episode(s) come from examination of the Mercury imaging experiment on Mariner 10 (Murray *et al.* 1974). Scarps are seen which are consistent with thermal contraction. These lines of evidence suggest an early differentiation of the planet which may require an external source of heat. Early differentiation of Mercury is suggested by the apparently heavily

TABLE 1

CANDIDATE PRE-MAIN SEQUENCE SOURCES OF ENERGY FOR DRIVING PLANETARY METAMORPHOSIS

Source	Asteroidal Parent Objects	Moon: Core	Moon: "Magma Ocean"	Mercury
Electrical induction(1)	+	+	+	+
Short-lived nuclides(2,3,4,5,6)	+	Whole body melting(if ^{26}Al is homogeneously distributed)		+
Accretion(7,8,9,10,11)	-	-	+	+
Adiabatic compression(3,12)	-	-	-	-
Solar insolation(13,14)	-	-	-	+
Tidal dissipation(15,16)	na	?	?	?
Chemical reaction heat(17)	?	?	?	?
Evaporative formation from earth(18)	na	+	+	na

1Sonett,C.P.,et al.(1972)
2Brown, H. (1947)
3Urey, H. (1961)
4Reeves, H. and Audouze,(1968),
5Fish,R.,Goles,G.and Anders,E.(1960)
6Lee,T., et al.(1976)
7Wood,J. (1968)
8Sonett, C.P.and Colburn,D.S.(1970)
9Nakamura,Y.et. al. (1973)
10Toksoz, N.,et al.(1972)
11Wetherill,G. (1975)
12Bainbridge, J. (1962)
13Cameron, A.G.W.(1973)
14Wasson,J.T. (1974)
15Kaula, W.M. (1963)
16Wones, D.R. and Shaw, H.R. (1975)
17Urey, H. and Donn, B. (1956)
18Essene, et al. (1970)

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cratered surface showing details implying early bombardment of a fractionated crust. Such early differentiation may have involved the whole planet; this would imply a strong source of primordial heating (Siegfried and Solomon 1974). If it is assumed that Mercury formed at its present distance from the Sun, the above imputed heat source could have arisen from solar insolation. It is possible that together with accretion this would have been sufficient to trigger differentiation, thus obviating the need for initial endogenic radioactivity or electrical heating (discussed later).

Candidate pre-main sequence sources of energy for driving planetary metamorphosis are shown in Table I. The references are intended only to be indicative of key contributors to each of these hypotheses. The table is divided into asteroidal parent objects, Mercury, and two model Moons.

Chemical reaction heat has been discussed by Urey and Donn (1956) in connection with planet differentiation, but we are not aware of any conceptual connection with recent equilibrium or non-equilibrium condensation models. Solar insolation (except perhaps for Mercury) is a poor candidate generally as a source of planetary heating because it depends upon a superluminous Sun. The solar luminosity is large at the beginning of a Hayashi contraction (Hayashi and Nakano 1965) where the radius of the solar nebula is measured in tens or hundreds of AU, but is not more than several times that of the present Sun at the time of onset of nuclear burning. In the Larson (1973) model, only short segments of Hayashi (convective) contraction appear, and the Sun never attains a highly luminous phase. Even for the Hayashi model the superluminous period is very early, likely prior to formation of a strong, central condensation (the Sun) and condensation of planetary protomatter. Adiabatic compression of gas spheres containing the planets as central condensations has been studied by Urey (1961) and by Bainbridge (1962). Although planets are thought to be secondary condensations likely including some gas, the sphere radius required for a gravitational collapse (Jeans criterion) is far too large in order to attain a large temperature rise. Furthermore, rather special timing would be required to form in this manner a lunar "magma ocean" in this manner, especially for basalt source region isotopic closure and a cold core. Although tidal dissipation has been suggested for the Moon and studied by several workers (cf. Kaula 1963; Wones 1975), it is a special mechanism not generally applicable in the solar system, *e.g.*, the asteroids. On the other hand, it could provide an important source of heat for the Moon when the latter is in close orbit around the Earth. A variant for the Moon is formation in orbit from matter volatilized from the Earth (Essene *et al.* 1970). This model has severe geochemical difficulties and also is not pertinent to other objects in the inner solar system.

Accretion is generally thought to be responsible for melting of the outer parts of the Moon (Wood 1972; Wood *et al.* 1970; Sonett and Colburn 1970; Toksoz *et al.* 1972; Wetherill 1975; Wetherill 1976). The mechanism is especially attractive because of its apparent simplicity, and it has therefore been rather broadly discussed. The normative model requires accretion in several times 10^3 years; otherwise heat loss through radiation decreases the entrained heat to below that required for melting. This model has been combined with some heating for long-lived radioactives to yield conditions appropriate for formation of basalt source regions, but the time scale is inconsistent with 200 million year source region isotopic closure. Wetherill has recently proposed a variation of this by employing large impacts with relatively large energy; thus heat is deposited very deep and screened from radiative losses (Wetherill 1975; Wetherill 1976). Wetherill's model is consistent with Safronov's accumulation time for the Moon (Safronov 1972). However, accretion cannot be used for heating of asteroidal parent objects for the threshold radius is approximately 1000 km, under the admittedly restricted assumption of impacts having velocity not exceeding escape (Sonett 1974).

Electrical induction as a means of joule heating of planets has been studied extensively by Sonett and co-workers (c.f., Sonett 1974; Herbert *et al.* 1976), and more recently in application to asteroids by Briggs (1976). The special conditions introduced by formation of a plasma sheath about small objects and the consequent attenuation of one form of this mechanism has been investigated by Srnka (1976). Electromagnetic induction depends upon certain properties of the pre-main sequence Sun commonly held to be characteristic of T Tauri-type stars. Both the spectroscopic information regarding gas outflow and model calculations are not in a satisfactory state (Kuhi 1964; Herbig 1970). Nevertheless, a popular viewpoint does prevail that the pre-main sequence Sun did pass through a T Tauri period.

It is a general property of massive stars of early spectroscopic type that their spin rates are large (Struve 1930); a sudden break in rotational speed is apparent for spectral types later than F5V (Kraft 1967). The suggestion follows that later-type stars are endowed with a turbulent atmosphere (emission features in the H and K lines of Ca are used to infer a chromosphere) which drives a solar wind. The associated magnetic field permits magnetic de-spinning. In support of this hypothesis is the fact that magnetic fields are generally found in association with rotating massive objects. Unfortunately, line-broadening due to turbulence precludes the detection of magnetic fields of magnitude less than about 1000 gauss in the atmospheres of T Tauri stars (Kraft 1972).

Electrical induction is based upon the supposition that the pre-main sequence Sun passed through a T Tauri phase and at that time solar conditions included a surface magnetic field of 10-100 gauss. (Note that a magnetic field is an aid in de-spinning the Sun). (Alfven 1954; Hoyle 1960). (However, McCrea (1963) has suggested that since stars tend to form in close association, mutual tidal interaction might be a source of de-spinning; it should be noted in this context that Ostriker (1964) has calculated the fission limit for a spinning polytrope to be 0.26 ω_B where ω_B is the rigid body breakup speed; in any event, sufficient central object spinning must be retained for planet formation). Under these conditions a strong electromagnetic field would be set up in the interplanetary cavity. Planetary objects in such an environment would be subject to electrical induction. That this is substantially more than a supposition is shown by the Apollo magnetometer which detected a very large transverse electric (TE) mode in the Moon excited by the forcing field of the solar wind (Sonett *et al.* 1972).

Detailed calculations of the joule heating taking place under hypothesized T Tauri electromagnetic conditions show that melting of objects in the inner solar system can take place with varying efficiency depending upon the solar distance and the bulk electrical conductivity assumed for the rocky matter. Additional parameters important for excitation by the electric field are the temperature in the interplanetary cavity into which the object will radiate, the strength of the magnetic field, accretional time, and the solar wind ram pressure.

Electromagnetic heating can be combined with other heating mechanisms such as accretion or short-lived radioactives to yield increasingly complex thermal profiles in objects as variable as the Moon or asteroids. All of these profiles are developed in less than several million years, and for small objects in less than 5×10^4 years. Thus, for purposes of the long term thermal evolution, the process is essentially instantaneous and the profiles derived are termed "zero age." They form the initial conditions for the usual heating via long-lived radioactives (Sonett 1971; Herbert *et al.* 1976).

Asteroidal heating has lately been modelled using new information on the bulk electrical conductivity of chondritic meteorites (Briggs 1976). Difficulties are still present in these data because of fugacity control and metamorphosis in the laboratory, but the differences highlight the specific condi-

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tions required for asteroidal parent body metamorphosis and generally reasonable solar system conditions can be found which lead to the required thermal profile.

A key aim in examining the inductive heating hypothesis has been to find qualitative relationships between formative conditions and resulting geophysical evolution, so as to be able to deduce causes for observed evolutionary features. Since the Moon is the best understood object likely to have been strongly affected by inductive heating, the principal object of our investigation has been the Moon.

In particular, the relatively thin (several hundred km) "magma ocean" thought to have been present early in the Moon's history is a natural outcome in situations where the body is relatively large and the induction frequency is high (TE mode induction) or where there is an outward positive electrical conductivity gradient (surface heating is then due to TM mode induction). The latter case can come out about through significant accretional heating, for example.

A more elusive set of conditions is required for formation of a core early in the life of the Moon. There, a combination of a relatively low accretional rate and relatively low induction frequency is required. In addition, the accumulation of the Moon while the induction takes place further complicates the problem. Internal melting with resolidification due to the pressure dependence of the solidus is a pervasive feature of these models. The occurrence of internal melting suggests that some fractionation outwards of long-lived radioactives will take place. In such cases the "zero age" profile of the Moon will have a strongly depleted concentration of radioactives below some depth determined by the parametrization of the Sun and the assumed bulk electrical conductivity function (Herbert *et al.* 1976).

Early calculations for Mercury restricted to the TM mode showed that because of the closeness of this planet to the Sun, strong heating would take place and full melting could be expected under reasonable parameter constraints (Sonett *et al.* 1968). However, further work on this problem is required. The other terrestrial planets--Earth, Mars, and Venus--have not been investigated; for these objects the problem may well be more complex. These planets are endowed with an atmosphere and, in the case of Earth, a strong, intrinsic magnetic field. The early history of the Earth is nearly obliterated and though information on Mars and Venus is scant, these planets appear to have been differentiated. This could have taken place without inductive heating. It therefore appears, because of the more easily interpretable prehistory of meteorites, the Moon, and Mercury, that the main study of primitive thermal profiles will be primarily restricted to these objects for a time at least.

It should be noted that electromagnetic induction intrinsically contributes to the possibility of explaining the magnetization of meteorites and of the Moon since a key requirement for inductive heating is the presence of a magnetic field of order 1 gauss at 1 AU. Curiously this turns out to be the field strength required for meteorite magnetization (Butler 1972; Brecher 1972; Stacey *et al.* 1960; Weaving 1962; Pochtarev and Gushova 1962). In the case of the Moon the problem remains somewhat more enigmatic since the source of the field may be internal. Presently there is no evidence for a metallized core, though this matter is not resolved (Wiskerchen *et al.* 1976b; Goldstein *et al.* 1976). In the absence of a core, the condition for early isotopic closure of the basalt source region is satisfied.

Unless the exotic scheme of impact magnetization were to explain the surface magnetization of the Moon, it seems likely that an early external field would be needed. This is satisfied by the induction hypothesis, though the topology of the field is quite specialized. In particular, to retain the same polarity for time sufficent for imprinting the field is not consistent with the present sector structure of the solar wind; a quadrupole field for the Sun would surmount this difficulty and would be qualitatively consistent with a rapid ro-

TABLE 2

PRINCIPAL COSMOGONIC PROPERTIES ASSOCIATED WITH ELECTROMAGNETIC INDUCTION

SUN	Pre-main sequence mass flux $\sim 10^{-8} M_o$/yr High spin $\omega = 25\text{-}50\ \omega_o$ Magnetic field 10-100 gauss Post-Hayashi phase, possibly after onset of nuclear burning Possible quadrupole solar magnetic field
INTERPLANETARY CAVITY	Plasma flow 10^8 times present value
ELECTROMAGNETIC FIELD	Spiral magnetic field outgrowth of solar rotation and plasma speed Electric field $E = V_s \times B = 20$ volts/m Magnetic field ~ 1 gauss at 1 AU Significant magnetic turbulence spectrum
SOLAR NEBULA	No requirement for heating via TE mode (heating by eddy currents) 300-500°C for heating via TM mode using characteristic conductivities of strongly metamorphosed rock (e.g., model lunar enstatite) Uncertain but much lower for heating carbonaceous chondrite matter
TIME PERIOD FOR INDUCTION	From 0.1 to several times 10^6 yrs -- well within model pre-main sequence post-nuclear times for 1 M_o star
SOLAR LUMINOSITY	Not more than several times L_o according to evolutionary models during nuclear pre-main sequence time (Hayashi, Ezer and Cameron, Larson)

TABLE 3

COMPARATIVE COSMOGONIC IMPLICATIONS OF ELECTRICAL INDUCTION AND SHORT-LIVED ISOTOPIC THERMAL ENERGY SOURCES

ELECTRICAL

(a) Supports T Tauri hypothesis for 1 M_o star
(b) Provides background field for meteorite & lunar magnetization if the solar field is quadrupolar
(c) Consistent with magnetic braking of solar spin
(d) Can be scaled between asteroidal parent objects and Moon and Mercury
(e) Dual modes (TE and TM) for selective crustal and core heating of planetary size objects
(f) Removes short time accretional heating constraint for lunar "magma ocean"
(g) Can be "mixed" with other heat sources such as accretion and radioisotopes

RADIOISOTOPE(S):

(a) Link to very active Sun but inconsistent with lack of depleted giant neutron cross section isotopes in lunar matter
(b) Evidence for injection from another local star
(c) Cannot be scaled between asteroids and Moon if "magma ocean" isolation time is correct
(d) By itself does not lead to a complete self-consistent cosmogonic model

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tation, as would the present sector structure superimposed upon a small bias field (Herbert *et al.* 1976b). Table II summarizes the principal cosmogonic parameters associated with electromagnetic induction.

Current models for early planetary metamorphosis which conceptually include planets and asteroids appear to be limited to fossil radionuclides and electromagnetic induction (See Table III). Other models shown in Table I appear not to satisfy constraints which are common to large and small objects. Nevertheless, it is far too early to rule conclusively on just how objects were heated. Considerable further work by way of model calculation is required for electromagnetic hypotheses if a common set of parameters is to be found. Lastly, a combination of electromagnetic induction and fossil nuclide heating is also plausible but speculative. On the other hand, the evidence for radionuclides is still sporadic.

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DISCUSSION

PELLAS: What type of temperature gradient do you get inside an asteroid of 300 km in radius?

SONETT: Electrical heating can arise from either the time dependent interplanetary field (eddy currents) or from the electrical field, VXB. The thermal profiles resulting from induction are strongly time dependent. A 300-km asteroid subject to electrical heating will increase in temperature throughout with the near surface gradient steepening with time, depending finally between joule heating and radiation losses of the surfaces (See Sonett et al. 1970, Astrophysics and Space Science, for a study of 300-km objects). Eddy current heating tends to favor the outer part of the object because of skin depth effects but even here the limited gradient which can be very steep is restricted by radiative losses (see Herbert et al. 1976, Icarus, 28, 489).

SINGER: Could you explain why Al^{26} content turns off the inductive heating?

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SONETT: With heating, the planet's core becomes very conducting electrically. Thus, most of the ohmic losses tend to take place in the more resistive crust as a planet evolves in time. Initially the two sources, electrical and ^{26}Al are additive, but the ^{26}Al speeds up the development of the highly conducting core. The core becomes a "short circuit" with little ohmic loss. Thus electrical heating is not actually turned off, but tends to favor the crust from which heat is easily lost through the surface by radiation. These remarks are restricted to unipolar induction. (See Sonett et al., Astrophysics and Space Science 1970).

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