SOLAR-WIND HEATING OF ASTEROIDS

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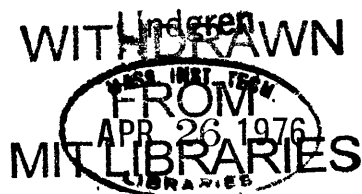DEGREE OF MASTER OF

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Peter Laurence Briggs

Recent observations indicate that a minority of asteroids have undergone considerable metamorphism, possibly during the brief episode of heating that produced many high-temperature meteorites early in solar system history. The validity of postulating an early episode of solar wind heating to account for this metamorphism is considered, and assumptions necessary to solar wind heating hypotheses are reviewed. Thermal histories of model asteroids, some of which indicate the likelyhood of substantial electromagnetically induced heating, are presented for a variety of initial asteroidal and solar conditions. Results of modelling are considered in light of modern observations of the asteroids and lead to speculation about conditions in the asteroid belt at the beginning of planetary history.

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I. Introduction

Many sources have been suggested which might have provided heat to planetary interiors in the course of solar system history, including gravitational potential energy, chemical potential energy, long- and short-lived radioactivity, T-Tauri-like solar winds, tidal forces, collisions and bombardment of planetoids, and solar luminosity. The present appearance of both the major and minor planets, however, seems explicable in terms of thermal histories dominated by only two heat sources, both internal to the planets - heating by gravitational potential energy release (accretion, core formation) and heating by long-lived radioactivity. Observations of the great satellites of the outer solar system also have been explained by the action of these two heat sources (Consolmagno, 1975). The most striking object in the night sky is, curiously, the only large body for which the action of these two heat sources seems unable to produce a thermal evolution compatible with modern observations without invocation of peculiar and extraordinary circumstances in the early solar system (Toksoz and Johnston, 1973). The case of the moon suggests the consideration of a third source of substantial heat in the early solar system. It is now becoming clear that the asteroids, too, show evidence of internal heating which cannot be accounted for by gravitation and long-lived radioactivity alone.

Among the various classes of meteorites is much high

temperature material whose origin is also difficult to understand by considering only these two primary planetary heat sources. For example, the formation of basaltic achondrites requires temperatures at least locally a few hundreds of degrees above $1000^{\circ}C$. The iron meteorites suggest that temperatures of at least $1000^{\circ}C$ (approximate Fe-FeS eutectic temperature) prevailed not just locally, but throughout substantial volumes of some meteorite parent bodies, allowing the segregation/concentration and rather slow cooling of a metallic fraction. The ordinary chondrites (some of which appear to constitute a high temperature metamorphic sequence) have ages within a few tens of millions of years of 4.6 aeons (Wasson, 1974), indicating a brief episode of intense heating near in time to the presumed origin of meteorite parent bodies. The presence of tridymite in stony irons, enstatite chondrites, and irons, and the absence from ordinary chondrites of metastable high pressure phases unrelated to shock all indicate high temperature meteorite formation at pressures of less than 3 kb. (Anders, 1964) - presumably within very small parent bodies only a few hundreds of kilometers in radius.

Although very little was known about the composition of asteroids until recently, it has long been supposed that these various meteorites originated in the asteroid belt, and models of planetary formation have been proposed which link the genesis of meteorites and asteroids. Based on his review of meteorite

research, Wasson (1974) outlined a model history of meteorite parent bodies which includes:

- the condensation of solid particles from a cooling solar nebula

- the end of condensation and the onset of agglomeration of small grains to form 1 - 100 meter-sized planetessimals

- varying degrees of metamorphism of the planetesimals

- cooling of the planetessimals

- accretion of planetessimals into asteroid-sized bodies

- breakup of these larger bodies and the scattering of some fragments into earth-crossing orbits.

Recently our knowledge of the composition of asteroids has dramatically increased as 1) spectrophotometric studies have revealed similarities in composition between asteroid surfaces and some classes of meteorites, 2) a new interpretation of the asteroids' size-frequency distribution has been advanced to accompany these new observations, and 3) diameter and mass data have begun to accumulate, allowing density determinations for the largest asteroids.

The asteroids have been divided into two broad groups on the basis of their surface compositions - a C-type,of surface material resembling the carbonaceous chondrites (about 80% of asteroids belong to this class),and an S-type, of inferred stony-

iron composition (Chapman, 1975a). Chapman has interpreted the size-frequency distribution of asteroids to suggest that a significant minority of asteroids with 50 - 100 km. radii are remnant stony-iron cores of differentiated planetoids (Chapman, 1974). Currently, three asteroid surface compositions can be matched to bulk densities. Ceres, the largest asteroid, has radius $\approx$ 575 km., density $\sim$ 2.6 gm./cc., and carbonaceous surface; Vesta has radius $\approx$ 250 km., density $\sim$ 3.5 gm./cc., and basaltic achondritic surface; Pallas has radius $\approx$ 275 km., carbonaceous surface, and density perhaps slightly greater than that of Ceres (Chapman et. al. 1975). Clearly, Vesta has been strongly heated on a large scale, while there is reason to suspect that Ceres is composed of low density, unmetamorphosed carbonaceous chondrite type C-2 material throughout.

Observations of Ceres and Vesta bring some difficulties to scenarios of meteorite and asteroid development that include metamorphism of planetessimals before accretion of asteroids. If small planetessimals were metamorphosed through part of their volumes, how could mutual collisions have isolated sufficient low density material in the inner asteroid belt to form a body such as Ceres? How can one account for the development of a uniformly basaltic surface on Vesta while most asteroids retained carbonaceous surfaces? How, inside small bodies, could iron have been concentrated into 50 - 100 km. radius cores?

Even if asteroids were heated to metamorphic temperatures

after final accretion, why should neighboring bodies develop so differently (eg. Ceres within 0.4 A.U. of Vesta)? The development of a single generation of asteroid sized bodies would explain the mutual similarity of most asteroid surfaces, but in this case, though the surfaces of most asteroids might resemble carbonaceous meteorites, to suggest that C-type asteroids are the parent bodies of meteorites implies a case of planetary development unique in the solar system.

Although the exact timing of the epochs of condensation, accretion, and nebular dissipation is not known, let us assume that at some time before thermal processing of meteorite parent bodies began, there could be recognized an original population of asteroids composed of mixed high and moderate temperature condensates - partially hydrated ferro-magnesian silicates with some iron sulfide and carbonaceous material, as predicted by models of equilibrium condensation and homogeneous accretion for the region of the asteroid belt (Lewis, 1972,1973). Let us also assume that,although these bodies may have been much more numerous than large asteroids today, planetary accretion in the asteroid belt was somehow terminated when the largest original asteroids had attained radii of not more than ∿ 500 km. (Chapman, 1975a).

By including in solar system history the formation of a suite of condensates similar to that predicted by Lewis for the aster- oid belt, and the subsequent accretion of mineralogically

homogeneous individual asteroids, difficulty arises in finding a heat source to produce a brief episode of intense heating which would produce from the original carbonaceous asteroids both the various known meteorite types and a collection of small bodies resembling the present day asteroids.

The unique and problematic nature of asteroid heating is emphasized when one reviews properties of the major heat sources that could have affected the terrestrial planets. Gravitational energy release upon accretion scales with the fifth power of planetary radius and is negligable for the assembly of asteroid-sized bodies. The impact of large objects on asteroids should result in heating which does not greatly affect the planet-wide heat budget, but remains confined to the near-surface neighborhood of the impact area. A superluminous sun may have heated dispersed material before and/or during accretion of asteroids (although it is difficult to see how types 1 and 2 carbonaceous chondritic material, rich in volatile elements, organic compounds, and hydrated silicates could have survived such an episode), but such a phase is inefficient in heating a rocky planet from the surface inward (Wasson, 1974) and could not have acted on the asteroids in a post-accretional epoch without producing asteroid surfaces of uniformly decreasing metamorphic grade with increasing heliocentric distance, in conflict with spectrophotometric observations (Chapman, 1975b). The long-lived radionuclides which release an amount of energy increasing

with the third power of planetary radius and have been crucial

in controlling the evolution of the larger terrestrial planets,

could not have released energy rapidly enough (at chondritic

abundances) to produce an intense, yet brief, metamorphic

episode within small bodies early in solar system history. If

sufficient concentrations of short-lived radionuclides were

present in some of the pre-asteroidal condensates, their heating

effect might have been substantial if they were buried beneath

thermally insulating rocky material by accretion on a favorable

time scale. Short half-lives insure that heating would have

occurred in a single, brief episode upon planetary formation

(energy release presumably scaling with radius). Many candidate

isotopes have been suggested (eg. Fish et. al., 1960), but

because it can be produced by an intense proton irradiation [sic.]

of nebular gases, Al^{26} has been considered the nuclide most

likely to have been important in the early solar system (Reeves

and Audouze, 1969). The short, 0.72 million year, half-life of

Al^{26} would have allowed a considerable difference in power

generation between asteroids assembled just a few million years

apart, so that accretional timing effects could have led to the

observed irregular distribution of mineralogic types of asteroid

surfaces through the asteroid belt. However, the short half-

life of Al^{26} requires that only about 10^6 years elapse between

irradiation of the nebular gas and the completion of accretion

for effective heating, according to the estimates of Reeves and

Audouze. Further, it is difficult to reconcile the required intense solar wind irradiation with the persistence, rather than the dissipation, of nebular gasses. To date, no significant Al^{26} excesses have been definitely established in meteorites (Schramm et. al., 1970). Though the few meteorites studied do not include the often remarkable Allende, they do include two ordinary chondrites of approximately solar system age (Bruderheim and St. Severin) formed about 7×10^6 years apart (Wasson, 1974) and a sample definitely associated with a high temperature environment (a feldspar inclusion from the Colomera iron).

The most recent observations of the asteroids suggest that whatever was the heating mechanism that heated the asteroids, it must have had the following properties:

- heating which did not scale simply and predominantly with asteroid radius, so that Ceres, the largest asteroid, could survive with a low density ~ 2.6 gm/cc.

- heating which did not scale simply with heliocentric distance (solar photon, proton irradiation) so that there need not be a regular metamorphic gradation (allowing for some mixing) of asteroids with heliocentric distance

- heating which was of short duration so that, for example, Karoonda could form at about 400°K, undergo heating to about 900°K and cool to retain xenon in less than about 2×10^6 years (Lewis and Anders,

1975); also, solar system ages for ordinary chondrites
must be explained

- production, in a few environments, of temperatures
  high enough to permit segregation of metal and
  silicate phases and to produce either planet-wide
  melting of silicates at some depth or enough bassaltic
  material to flood the surface of a small asteroid
  such as Vesta

- heating which was often apparently planet-wide rather
  than surficial, leaving remnant cores, apparently
  differentiated, possibly metallic of 50 - 100 km.
  radius (rather than small, isolated metallic pods)

- heating which left some carbonaceous chondrites
  thermally unaltered since formation.

The above restrictions suggest that some asteroids underwent
heating by a mechanism different from those which prove adequate
to explain the evolution of the larger terrestrial planets.
Sonett et. al. (1968, 1969) proposed that an enhanced solar wind
may have been an important heating mechanism for asteroid-sized
bodies early in solar system history. Because it depends much
more critically on electrical conductivity than on planetary
radius, electrical heating induced in meteorite parent bodies
satisfies more simply than any other single mechanism the require-
ments listed above, while elegantly using the smallest and largest
bodies in the solar system to link planetary and solar evolution

at the beginning of planetary history.

Although they amply demonstrated the plausibility of substantial solar-wind heating, the few thermal models of asteroids recorded by Sonett et. al. (1969) suffered from the longstanding lack of knowledge of asteroidal composition and from the need to invoke certain ad hoc assumptions. Some data about the composition of asteroids and relevant physical proper- ties of asteroids and meteorites are now available, and permit models of solar-wind induced heating of asteroids to advance beyond pioneering plausibility arguments.

Chapter 1. Model Basis of Solar Wind Heating Estimates

The solar wind moving radially outward from the sun sweeps "frozen in" magnetic flux past planetary bodies so that an observer comoving with a planet may observe a motional electric field. If coupling between a planet and the solar wind plasma is favorable, polarization of the bulk of the planet will result and, if charges can be exchanged between the plasma and the planet's surface, currents may flow through the planet causing ohmic heating of its interior. This is not possible without electrical contact between the solar wind and the planetary surface, eg. if an atmosphere/ionosphere surrounds the planet, or if the planet possesses an internally generated magnetic field strong enough to stand off the solar wind. When the asteroids were newly formed, the major terrestrial planets probably were much larger than the asteroids and very early in their histories may have developed atmospheres and/or active internal magnetic dynamos as byproducts of their self heating upon accretion. Because of their small size and unique composition, the asteroids may be the only solar system bodies in which one should expect to see the effects of heating by an early solar wind. Depending on the assumed pre-main sequence behavior of the sun and the solar wind, electrical heating of some asteroids may have been substantial, and may have been responsible for the brief epoch of intense metamorphism which seems to have affected some meteorites.

1.1 The Early Sun

Before beginning well-behaved main sequence evolution, there is reason to suspect that stars like the sun pass through a phase of a few million years duration during which they eject non-negligible fractions of their initial masses in the form of enhanced stellar winds which carry magnetic flux outward and act to despin young stars. The assumption that the sun had significantly greater mass, magnetic field, and spin rate upon formation than at present is crucial to the effectiveness of solar wind induced heating. Because no direct evidence about the early sun survives, these assumptions are the ones challenged most frequently in objections to solar wind heating. The grounds for such objections are by no means clear, however.

It has long been a curiosity that the planets have so much angular momentum and the sun so little, particularly since it is believed that the sun was formed by the collapse of a portion of the planetary nebula. Simple extrapolation backward in time of the current solar rotational energy loss rate does not resolve this difficulty. The angular momentum distribution of the modern solar system might be explained readily, however, if one assumes that the sun was originally rapidly rotating, but was despun shortly after formation by magnetic torques acting through an enhanced solar wind. Classical treatments of solar winds (eg. Modisette, 1967) indicate that the sun may be despun in emitting a dense solar wind. In considering magnetic

accellerations of stellar winds, Belcher and MacGregor (1975)
have shown that considerable despinning of a young main sequence
star is possible without an enhanced mass flux.

Kuhi (1964), however, has observed six young T-Tauri like
stars,of 0.6 to 4.1 solar masses, not obscured by nebulosity.
All six were rapidly losing mass, presumably before beginning
main sequence evolution. The average mass loss rate observed
was 3.7 x 10^{-8} solar masses per year; the greatest was 5.8 x 10^{-7}
solar masses per year. It is assumed that an epoch of substan-
tial mass loss is a characteristic feature of young solar-type
stars.

Ejection speeds observed by Kuhi ranged from 225 to 325
km./sec. at about 2 to 3 stellar radii. As Kuhi pointed out,
all ejection velocities were less than the relevant escape
velocities. To leave their respective stars, these stellar winds
must be accellerated, perhaps in a fashon similar to a Parker
solar wind. Brief examination of the Parker equations for
radial flow of a stellar wind indicate that in order for a
wind to escape its star, velocity, V_{sw}, at heliocentric distance

$$r = Gm_{+}M/2kT$$

should be approximately

$$V_{c} = (5kT/3\mu m_{+})^{1/2}$$

with k equal to Boltzman's constant, μ the average molecular
weight, m_{+} the proton mass, G the gravitational constant,

M the stellar mass, and T temperature (from Brandt, 1970).
Qualitative comparison to the modern solar wind may be made.
For an early sun with coronal temperature at all similar to the
modern value of $\sim 2 \times 10^6$ $^{\circ}$K (note that Kuhi's observations
seem to indicate coronal thermal speeds not greater than escape
speeds, consistent with Parker's result concerning stellar
masses and temperatures, $GMm_{+}\mu/RkT \lesssim 4$, here both M and stellar
radius, R, increased by factors of between 1 and 2), the solar
wind should be accelerated outward by gravitational confinement
and velocity V_c reached in the neighborhood of the sun, as it is
today at about 20 solar radii.

In considering the early main sequence evolution of rotation
rate for solar-type stars, Belcher and MacGregor (1975) found
that a sun with enhanced magnetic field and spin rate (about
20 times the modern values) had a characteristic spindown time
of only 4×10^8 years and produced a solar wind which was
magnetically accelerated to a large fraction of its terminal
velocity of 4000 km./sec. within 1 A.U. of the sun. With an
enhanced mass loss rate such as observed by Kuhi, however,
magnetic accelerations should not be so spectacular since the
terminal magnetic velocity is inversely proportional to the
third root of mass flux. For example, an order of magnitude
increase over present values of both magnetic field strength
and rotation rate coupled with a mass loss rate for the sun of
10^{-8} solar masses per year would result in a magnetic terminal

velocity of less than 40 km./sec. The present work, therefore,

ignores magnetic accelerations and takes a fixed solar wind

velocity of 400 km./sec. for the assumed T-Tauri stellar wind

at heliocentric distances appropriate to asteroids. It is

assumed that some acceleration of the solar wind occurrs

so that initial ejection velocities similar to those observed

by Kuhi, on the order of 250 km./sec. are increased somewhat

as the solar wind receeds from the sun, approaching a terminal

velocity similar to the modern value. Although the choice of

solar wind velocity does have an effect on heating through the

motional electric field, this effect is not so important to

heating models as are the differences of many orders of magnitude

in electrical conductivity between petrologic subtypes of

carbonaceous chondritic material.

Various values of initial solar rotation rate and solar

surface magnetic field strength are adopted. Durney (1972) and

Roberts (1974) have argued for a rotational dependence of the

solar dynamo. Although there are no data on the magnetic field

strengths of T-Tauri stars (Kuhi merely suggests less than 1000

gauss), surface field strength is assumed proportional to

rotation rate. The effect of solar wind torques on the solar

rotation rate is calculated using the model of Modisette (1967).

Rotation of the sun winds magnetic field lines into a spiral

and the interplanetary magnetic field (mostly tangential due to

$1/r$ dependence compared to $1/r^2$ fall-off of radial magnetic

strength) is calculated at heliocentric distance r from the
solar surface field, B_o, and solar rotation rate ω_o :

$$B_t = B_o R^2 \omega_o / r V_{sw} \; .$$

Initial magnetic field values are selected by requiring that the
sun be despun from its designated initial rotation rate to a
designated final rotation rate (up to 10 times the modern
rotation rate, acknowledging the possibility of later main
sequence despinning) during the T-Tauri episode. Mass loss rate
is varied by using different initial masses and mass loss laws
for the sun. Although duration of the T-Tauri episode is taken
as 10 million years in all models (in qualitative agreement with
Larson's (1973) suggestion of a few million years for a T-Tauri
like epoch of transition between nebular collapse and the
appearance of a star on the main sequence), heating usually
lasts for a much shorter time as planetary interiors become like
short circuts, solar rotation rate and surface field decrease,
and planets adiabatically receed from the sun upon its decrease
in mass. Previous models by Sonett et al. (1969) assumed an
initial stellar mass of 1.5 solar masses and exponential decay
of mass loss rate, spin rate, solar wind speed and solar surface
field strength.

1.2 Solar Wind Heating Model

The model used to estimate electrical heating is essentially
that developed by Sonett and Colburn (1968). Solar wind velocity

and magnetic field vectors are assumed to lie in the ecliptic
plane and to produce an electric field

$$\vec{E}_m = - \vec{V}_{sw} \times \vec{B}_{sw}$$

in the planetary reference frame (Figure 1). This motional
electric field polarizes asteroids and some charge leaks from
the planetary surface completing a circuit through the solar wind
plasma. As data on asteroids are not detailed, it is not
inappropriate to consider an approximate model of solar wind
heating such as this, in which any details of heating on less
than a planetary scale are ignored. Irregularities of the
solar wind flow are ignored, thus there is azimuthal symmetry.
If one assumes a planet with spherically symmetric physical
properties, the equation for interior potential, Ψ, is:

$$\sigma \nabla^2 \Psi + \nabla\sigma \cdot \nabla\Psi = 0,$$

where σ is electrical conductivity. For planets with non-
uniform conductivities, $\sigma(r)$, this equation separates to:

$$\frac{d}{dr}(r^2 \frac{dR}{dr}) + \frac{r^2}{\sigma} \frac{dR}{dr} \frac{d\sigma}{dr} - n(n+1)R = 0$$

and

$$\frac{d}{d\chi}[(1-\chi^2) \frac{d\Theta}{d\chi}] + n(n+1)\Theta = 0,$$

with $\chi = \cos\theta$. Within the planet, physical solutions involve
odd order Legendre polynomials and numerically determined
radial functions, R:

$$\Psi(r,\theta) = \sum_{\substack{odd \\ n}} A_n R_n(r) P_n(\cos\theta).$$

Current flowing through the planet produces a torroidal magnetic field surrounding the planet which may act to stand off some of the solar wind. In assuming complete azimuthal symmetry, previous models have calculated a planetary current which was uniform over both dark and light hemispheres of the planet. The induced magnetic backpressure on the solar wind was then calculated from Ampere's law as that due to the planetary current in an infinite thin wire passing through the planet's poles. This magnetic pressure is then assumed to deflect a fraction, k, of the plasma so that the planet simply experiences a reduced motional electric field, $\tilde{E}_m = (1-k)E_m$. The present work assumes that a similar deflection of the solar wind occurrs, but that current flows only through the sunward hemisphere of the planet. This is justified as follows. Whatever the currents within the planet, they must flow through the planet's surface, as closed current loops within the planet are forbidden in this steady-state model. Srnka (1975) has shown that photoelectrons are expected to be the dominant contribution to a plasma sheath over the planet's surface which controls the flow of electrons between the solar wind and the planetary surface. Furthermore, the cylindrically symmetric equations of electromagnetic heating are eventually coupled to a spherically symmetric treatment of heat transfer to produce a planetary thermal history. For asteroids of initially uniform composition, electrical conductivity will be much more strongly dependent on temperature than any other internal parameter. If temper-

ature variations are entirely radial, interior current flow
across the plane of the terminators requires that charges move
along paths that are not minimum impedance paths in their
progress between points on the sunward plasma sheath. It is
expected that, in response to the potential difference between
poles, the dark hemisphere of the planet will develop polarization
on a time scale short compared to the planetary rotation time
(Brecher et al. 1975), but that currents and heating on the
dark side should be negligible compared to those of the sunward
hemisphere. Thus, plasma deflection is about 1/3 that of the
Sonett model, and the loss factor, k, is calculated from a
slightly different expression from that given by Sonett et al.:

$$knm_+V_{sw}^2 = \mu(0.31\ \sigma E_m a(1-k))^2/2$$

with μ magnetic permeability, n plasma number density, and a
planetary radius. On the equator, this represents a balance
between solar wind dynamic pressure and the magnetic backpressure
produced by the total planetary current flowing through a thin
wire of length comparable to the planetary diameter which
intersects the equatorial plane at the average position of
points in the sunward semicircle (3/5 the distance from the
subsolar point to the planet's center). Away from the equator,
both the solar wind dynamic pressure and the planetary crossection
through a small circle parallel to the equator vary as $\cos^2\theta$,
so that there is no angular dependence in the k-factor expression.

The problem of heat transport in a planet is unfortunately difficult to treat numerically. Although subtle proscesses may be at work and great thermal complexity may be real, planetary temperature fields can only be modeled conveniently as spherically symmetric. Spherical thermal symmetry imposes an important constraint on electrical heating, as the planetary surface temperature (and thereby surface layer electrical conductivity, $\sigma(T)$) must be specified. Whatever the interior conductivity, currents must pass through the impedance of the surface layer (in implicit spherical symmetry, this is no more than the general restriction that current at r cannot be greater than $((r + \delta r)/r)^2$ times the current at $r + \delta r$).

At some point in the calculations, one must assume that heating rates, and currents, are spherically symmetric. Toward this end, the light/dark hemisphere asymmetry in heating is removed by assuming that model asteroids rotate with unspecified periods of several hours (i.e. rotation time much greater than polarization response time).

1.3 Planetary Interior Parameters

1.3.A. Initial Temperature

Thermal models of asteroids may be generated from two logical starting points. Temperature may be set to some uniform value throughout the body (as done in this study, implying accretion before the T-Tauri episode), or temperature may be set to some equally ad hoc initial profile, presumably decreasing from the

interior toward the surface (as though solar wind heating were
in effect during accretion, perhaps more realistic, but
but difficult to model with any certainty).
Fortunately, these two initial conditions are really quite
similar in that they both lead to electrical conductivity values
which increase with depth. Both are also subject to the same
restrictions of surface impedance. In the first case, energy
deposition per unit volume will be initially uniform, heat loss
occurring only at the surface. The planetary interior will
warm and its heating rate j^2/σ, will decrease. As the planetary
interior becomes more like a short circut, heating as would
result from the second case is approached.

The equation for interior potential predicts that electric
fields will eventually become greatest at shallow depths of
lower electrical conductivity. For this reason, internal
temperatures have a tendency to become uniform, and are somewhat
self regulating because temperature and heating rate feed back
upon one another via electrical conductivity. To display
most clearly the effect of electrical heating, asteroids are set
to initially uniform interior temperatures not greater than
300 $^{\circ}$K. A departure from the models of Sonett et al. (1969)
which called upon a hot circumstellar nebula to produce planetary
base temperatures of 500 $^{\circ}$C, these low initial temperatures are
compatible not only with the presence of a low pressure nebula
of low or moderate temperature (Arrhenius and De, 1973) but

also with both the survival of carbonaceous asteroid surfaces and type C-1 and C-2 material, and the prevalence of radiative equilibrium conditions between asteroids and a sun of luminosity comparable to the present.

1.3.B. Electrical Conductivity

Four electrical conductivity functions are used to model the interaction of types C-1, C-2, C-3-V and C-3-O chondritic material with the solar wind. These functions are based partly on observations of carbonaceous chondrites and partly on observations of terrestrial and lunar rocks.

Surface temperatures of rotating black bodies in equilibrium with the modern sun are about 165 ^{O}K in the inner asteroid belt, somewhat lower in the outer belt. A sun an order of magnitude more luminous than the present would not quite double these temperatures. Therefore, conductivities of carbonaceous material over the low temperature range (100 to 300 ^{O}K), taken from Brecher et al. (1975),are critical for reasonable estimates of solar wind induced heating, and are used here for the first time.

The electrical conductivities of only two carboaceous chondrites have been examined above room temperature - Allende, type C-3-V (Schwerer et al., 1970), and Mighei, type C-2 (Briggs, unpublished data). Above room temperature, Allende shows activation energy increasing with temperature (0.29 eV on 100 to 400 ^{O}C, and 0.95 eV on 400 to 700 ^{O}C). This increase of activation energy with temperature is characteristic of a

variety of terrestrial igneous and metamorphic rocks (Park-homenko, 1974) and some lunar rocks (Duba and Ringwood, 1973).
Mighei has shown behavior very similar to Allende over a more
limited temperature range (up to 350 ^{O}C). Although there are
general similarities between the electrical conductivities of
carbonaceous chondrites and terrestrial rocks above room
temperature, Allende and Mighei suggest that carbonaceous
material shows somewhat individual behavior. Activation
energies and transition temperatures are both rather lower
for the meteorites than for most terrestrial and lunar samples.
Because of the unique compositions and textures of carbonaceous
chondrites, it is reasonable to suspect that the high temperature
electrical conductivities of different petrologic subtypes might
show behavior rather similar to one another but different, as
a group, from terrestrial samples of more conventional structure
and mineralogy.

High temperature continuations of low temperature electrical
conductivities for C-1 and C-3-O material are assumed to be
similar to that of Allende. The adopted conductivity functions
are shown in Figure 2. Presnall et al. (1972) found an increase
of two orders of magnitude in the electrical conductivity of a
synthetic basalt upon melting. Some increase in conductivity
upon melting is also assumed for the chondritic material, although
values of electrical conductivity are restricted to $\leq 10^{2.5}$
Ω^{-1}/m.. High magmatic conductivities are justified in part

by the very high conductivities observed in chondritic material

below melting temperatures; also there may be a contribution to

conduction by ionic species not present in a chemically pure

synthetic basalt.   Note from Figure 2 that at high temperatures

the conductivities of different petrologic subtypes merge.   This

is in qualitative agreement with Parkhomenko's observation of

somewhat convergent high temperature conductivities of terrestrial

rocks with a great disparity in room temperature conductivities.

Fortunately, as Sonett et al. (1969) have suggested, the high

temperature conductivities of silicates are somewhat less critical

to solar wind heating calculations than are low temperature

values.   For the molten Fe-Ni-S phase, an electrical conductivity

of 10^3 Ω^{-1}/m. is adopted; this value is almost completely

inconsequential in heating models of asteroids with cores.

For silicate materials, the effect of temperature on

electrical conductivity is much greater than that of pressure.

For example, experiments reported by Parkhomenko (1974) show an

increase of only about 0 - 25% in isothermal conductivity of

basalt at pressures from 0 - 500 bars and temperatures from

20 - 800 $^{\circ}$C.   Although the same author cites   a greater

change in room temperature conductivity with increasing pressure

(a factor of 2 - 3 variation, pressures up to 800 bars) for

rocks of granular texture, the electrical conductivity of

carbonaceous material is assumed to be pressure independent.

1.3.C. Thermal Conductivity

Thermal conductivity is taken to be independent of temperature in all models of asteroids. Toksoz and Johnston (1974) have discussed the negligible consequences of this simplification in the case of lunar-sized bodies. Although the small sizes of asteroids compared to the moon will allow more rapid conductive cooling, this is more than compensated for by the very short duration assumed for the T-Tauri heating episode compared to thermal response times for large asteroids. Further, uncertainty, even up to a factor of perhaps 2, in thermal conductivity is not too damaging on timescales of a few million years, since many parameters indicative of cooling rates are uncertain (eg. temperatures for Xenon retention are not well known (Lewis and Anders, 1975); cooling rates of some iron meteorites are uncertain by up to ±40% (Goldstein and Short, 1967)). Experiments by Schatz and Simmons (1972) have shown that the thermal conductivity of a variety of minerals decreases by about a factor of 2 over the temperature range 500 to 1500 $^{\circ}$C. Fortunately for the cases of C-1 and C-2 material which contain considerable serpentine, serpentine dehydrates to olivine (with thermal conductivity about double that of serpentine) in just the temperature range where the conductivity of serpentine might otherwise be most rapidly decreasing. The value of thermal conductivity used throughout is that of serpentine, 2.4×10^5 erg/cm-$^{\circ}$K-sec. (Diment, 1969). This value is in the upper range

of conductivities measured for several ordinary chondrites by
Alexeyeva (1960).

1.3.D. Heat Capacity

The value of silicate heat capacity used throughout is
7.33×10^6 erg/gm.-$^\circ$K. This value is in the middle of a
narrow range of values reported for five ordinary chondrites by
Alexeyeva (1958), and is essentially identical to the heat
capacity of serpentine found by Diment.

1.3.E. Other Heat Sources

To display most clearly the effect of solar wind heating
during the T-Tauri episode, other sources of heat are excluded
from the present models, except insofar as various initial
temperatures may reflect the effect of solar luminosity. Long-
lived radionuclides do not produce significant heating on time
scales of interest here. Short lived radionuclides are not
considered because so great a variety of concentrations and
concentration gradients could be postulated ad hoc for individual
asteroids without demonstrably overstepping the bounds of
possibility. One of the interests of the present work is to
avoid peculiar ad hoc assumptions about the early solar system
that will serve to elucidate nothing but asteroid evolution.

1.3.F. Simulation of Melting

To date the only experimental melting study of a carbon-
aceous chondrite is that of Kushiro and Seitz (1974) who melted
samples of Allende at pressures up to 30 kb.. At the pressures

encountered in asteroids, 0 - 3 kb. , they found that the silicate phase of Allende began to melt at 1225 to 1240 ^{O}C (dry, 0 to 3 kb.) and 1225 to 1125 ^{O}C (water saturated, 0 to 3 kb.). At their highest temperature, about 1350 ^{O}C, the silicate phase of Allende was incompletely melted, about 25% molten. Similar values of melting temperature have been reported for ordinary chondrites (Wasson, 1974). For purposes of modelling heat transport in asteroids, silicate melting temperatures of 1300 ^{O}C (dry) and 1175 ^{O}C (wet, for C-1 and C-2 material with significant water contents) are adopted, with latent heat of melting 400 joules/gm. (Toksoz and Johnston, 1974). Although the silicates may not be completely molten, it is assumed that at or above these temperatures, heat transport in the silicates is dominated by the free percolation of the fluid fraction.

Kushiro and Seitz noted that the Fe-Ni sulfide phase of Allende tended to aggregate at temperatures above 1000 ^{O}C, and by 1350 ^{O}C had formed spherical globules. In the present calculations, it is assumed that given time scales much longer than those available in the laboratory, the aggregation of the metal sulfide phase and its segregation from the silicates will take place much nearer the eutectic temperature. At 1000 ^{O}C, 80% of a metal sulfide phase of chondritic composition should be molten; therefore, 1000°C is taken as the melting tempeture of the metallic phase. It is further assumed that above 1000 ^{O}C, C-1, C-2, and C-3-O material behave like Allende, with appro-

priate volume fractions of metal, silicate and carbon (amounts

of carbon to effect reduction of iron taken from Clarke et al.,

1970 and Mason, 1963).

Chapter 2. Thermal Models of Asteroids

Before considering thermal evolution models, an informative preliminary calculation may be made. For asteroids of uniform electrical conductivity (i.e. uniform mineralogy and temperature throughout), the equation for interior potential simplifies and heating rates are initially uniform throughout the body. In this case, the parameter which most strongly influences heating is electrical conductivity. The great difference in low temperature conductivities between different petrologic sub-types of carbonaceous chondrites gives some indication of the relative ease of electrically heating various carbonaceous asteroids.

If the initial heating rate for a body is $\gtrsim 10^2$ $^{\circ}$K per million years, considerable changes in internal temperature and conductivity are possible, and time dependent thermal modelling is necessary to determine the final condition of the asteroid. An initial heating rate of only a few degrees per million years, however, indicates virtually no change from the initial state of the asteroid during the T-Tauri episode. In fact, for asteroids with initially low heating rates, the characteristics assumed for the T-Tauri episode will work to decrease both the motional electric field and the heating rate with time if solar wind velocity remains stable as solar fields weaken, solar spin decays and asteroids recede from the sun.

Figure 3 shows initial heating rates for asteroids of

varying electrical conductivities, 10^{-9} to 10^{-3} Ω^{-1}/m., exposed

to solar winds developing a range of motional electric fields,

10^{-3} to 10^{+2} volt/m.. Electrical conductivities of C-1, C-2,

C-3-V and C-3-O material between 150 and 300 ^{O}K are indicated.

In some cases, planetary heating may be limited by the solar wind

power available over the planetary target area; solar wind

velocity of 400 km./sec., solar mass loss rate of 10^{-8} solar

masses per year, and asteroid heliocentric distance of 2.5 A.U.

are assumed. Small bodies with high crossection to mass ratios

have higher solar wind power limited maximum heating rates than

larger bodies of the same conductivity. Arrows in Figure 3

indicate solar winds carrying magnetic fields of 1.0 and 0.1 oe.

at 2.5 A.U..

It is clear from Figure 3 that C-2 bodies are not signifi-

cantly heated at motional fields of up to 1 volt/m., C-1 bodies

at up to 10 volt/m.. If one follows Chapman's implication that,

after 4.5 aeons of mutual collisions, asteroid surface and

interior compositions are similar, and thus that about 80% of

observable asteroids are composed of unmetamorphosed material

resembling C-2 chondrites, then one may suspect that if the

solar wind was the primary source of heat for metamorphism in

asteroids, most of the original asteroids must have been too

electrically resistive to be substantially heated. Conversely,

the solar wind is constrained - motional electric fields cannot

have been strong enough to produce metamorphic temperatures in

a majority of asteroids. The following selected models serve to illustrate this.

Figures 4, 5, and 6 show thermal histories of initially cold, 165 ^{O}K, C-1,2, C-3-V and C-3-O asteroids respectively. The radii are 500 km., approximately the radius of Ceres, and Chapman's estimate of the greatest radius in the population of original asteroids. The solar surface field is initially 28 oe.; initial solar mass is 1.25 solar masses. Mass loss rate is held constant throughout the T-Tauri episode at 0.25 x 10^{-8} solar masses per year, somewhat modest compared to Kuhi's observations.

The heating history model of Figure 4 is typical of very resistive, cold C-1 and C-2 bodies. Electromagnetic heating is insignificant through the entire T-Tauri episode. Variation in mass loss rate, eg. a linearly decreasing mass loss rate, produces no important changes. After 10 x 10^6 years, the interior of the asteroid should be heated to ~20 ^{O}K above initial temperatures by long-lived radioactivity (MacDonald, 1959), not included here. The survival of many such unmetamorphosed C-2 asteroids is in agreement with modern observations of the asteroids.

Figure 5 presents the heating of a C-3-V asteroid. Excepting mineralogy, all initial conditions are identical to those of Figure 4. The higher conductivity of C-3-V material produces a striking change in thermal evolution; electromagnetic

heating, rather than long-lived radioactivity, controls the interior temperatures. Within 0.5×10^6 years, most of the interior has warmed enough to liquify water. At 1.5×10^6 years, core formation has begun, and by 3.0×10^6 years, peak temperatures are attained. At radii of 0 to 50 km. temperatures are high enough to mobilize iron sulfide, and the water-saturated solidus at 3 kb. of Allende is barely exceeded. It is unlikely that the core of an Allende-type body would be wet enough to melt, but the possibility of basaltic material mixed with some iron out to $\sim$ 50 km. radius is not excluded. After 3.0×10^6 years, no further heating occurs, but stored heat cannot diffuse outward from the core to melt iron much beyond $r \sim$ 60 km.. If no carbon reduction of FeO occurs, a pure metal sulfide core of 20 km. radius overlain by strongly metamorphosed silicates is possible. If reduction by Allende's 0.29 wt.% carbon occurs, the metallic fraction will be slightly larger. The deepest 100 km. of this asteroid reach metamorphic temperatures of > 1000 $^{\circ}$K. To a radius of about 275 km., the few hydrated silicates originally present should be dehydrated (Clarke, 1966). Water from this reaction, and any other free water may be collected in a cold trap in the asteroid's outer few km.. After solar wind heating, much of the asteroid outside the core area, $r \gtrsim$ 100 km. could well have rather low mechanical strength characteristic of unmetamorphosed chondritic material. Subsequent collisions which erode all but the inner 50 to 100

km. of the asteroid, as proposed by Chapman, are not in conflict with this thermal model. High temperatures in the central portion of the asteroid suggest the removal of carbon and are not inconsistent with the development of S-type bodies.

Figure 6 presents the development of a thermal profile quite similar to that of Figure 5 in a cold C-3-O asteroid under the same initial conditions as Figures 4 and 5. This composition is raised to metamorphic temperatures in about 1/10 the time required to heat the C-3-V asteroid. Thus, even if the T-Tauri episode were of very brief duration, it would still be possible to strongly heat some types of asteroids. Between 0.3 and 0.5 x 10^6 years, a modestly warm body reaches peak temperatures. High temperatures necessary for the mobilization of iron are reached at $r \lesssim 125$ km., slightly greater than the upper limit to the size of S-type asteroids (Chapman et al., 1975). A core of pure metal sulfide $r \sim 45$ km. may be produced without carbon reduction of iron (by 0.58 wt.% C) if metal concentration is complete. A stony-iron core of $\lesssim 100$ km. radius is possible if metal does not percolate through silicate material with complete ease. One may suspect that subsequent thermal evolution will be controlled by the removal of the asteroid's outer layers in collisions.

One interesting feature of these heating models is the curvature of the temperature vs. depth curve - concave upward

in contrast to familiar radioactivity-heating models which have concave downward T vs. depth, z, profiles. Because d^2T/dz^2 is positive, electromagnetic heating produces elevated core temperatures without strongly heating entire asteroids. Because a hot core is a small volume fraction of a large asteroid, heat flow from a core cannot possibly heat silicates and concentrate iron at radii much greater than the original core radius. This feature may explain the observation that S-type asteroids do not have radii greater than about 100 km., and lends indirect support to Chapman's estimate that the original asteroids had radii $\lesssim$ 500 km..

Evidence of stable paleomagnetization in carbonaceous chondrites has been presented by Brecher and Arrhenius (1973). Brecher and Arrhenius (1976) conclude that paleofields on the order of 1 oe. must be invoked to account for this magnetization and suggest two possible sources for so strong a field, 1) solar wind "frozen in" fields, 2) interstellar fields enhanced by nebular collapse. The latter is possibly the more reasonable alternative, but these authors conclude that the overall magnetic properties (eg. anisotropy) of carbonaceous material was established as a primary feature during accretion in the presence of magnetic fields.

Figures 7 and 8 present thermal models of 500 km. C-2 asteroids in solar winds carrying peak fields of 0.5 oe. in the asteroid belt. The initial solar surface field is considerable, 338 oe.; initial solar mass is 1.15 solar masses, and mass

loss rate is constant. A C-2 object with base temperature 165 ^{O}K is heated barely to 0 ^{O}C in 10 x 10^{6} years. A second C-2 asteroid, identical except for an assumed base temperature of 30 ^{O}C, heats dramatically in the strong ($\lesssim$ 20 volt/m.) motional electric fields associated with magnetic fields $\lesssim$ 1 oe., Figure 8. Within 0.2 x 10^{6} years silicates are dehydrated at r $\lesssim$ 200 km. and both wet melting temperatures of silicates and the metal sulfide mobilization temperature are exceeded at r $\lesssim$ 150 km.

If solar wind-borne fields $\lesssim$ 1 oe. were responsible for the paleoremnance in carbonaceous chondrites, an interesting constraint on the temperature of pre-asteroidal material arises. If C-2 bodies are to be unheated in solar winds carrying 1 oe. fields, they must accrete at temperatures below the ice/water transition in C-2's, T $\lesssim$ 250 ^{O}K. In fields an order of magnitude smaller (Figures 4,5,6 with peak fields $\sim$ 0.05 oe.) C-2 asteroids must accrete at temperatures $\lesssim$ 350 ^{O}K to avoid strong heating.

Chapter 3. Summary

The fact that thousands of thermal models have been generated in the past to explain the histories of only a small number of planetary-sized objects is striking. Certainly, thermal models must be regarded with some suspicion. Presentation of numerous, redundant models from the same computer program would not lend the few representative models presented here any greater relationship to reality. Certain features of asteroid evolution and meteorite formation which are difficult to reconcile with the action of long-lived radioactivity alone do, however, seem to be explicable in terms of solar wind - induced heating.

The foregoing models are quite representative of solar wind heating of asteroids under a variety of rather similar solar wind conditions. Differences in low temperature electrical conductivity between petrologic subtypes of carbonaceous chondrites are so great that conductivities control heating. The possibility of strongly heating some asteroids while leaving others unheated is clear. Furthermore, it is C-2 (and C-1) bodies that survive the T-Tauri episode unheated, in agreement with modern observations of asteroids. Although the model bodies presented had final heliocentric distances of 2.5 A.U., asteroids at 3.5 A.U. heat similarly, although somewhat more slowly, (solar wind power limits drop by only a factor of 2 between 2.5 and 3.5 A.U., and magnetic field strengths

decrease somewhat less, by a factor of $\sim$ 2.5/3.5).

When solar mass loss rates $\sim$ 10^{-8} solar masses per
year are assumed, only modest enhancements of solar surface
field and solar spin rate (to $\gtrsim$ 10 times present values) are
needed to produce significant solar wind heating of some
asteroids. Temperatures high enough to allow the formation
of any type of meteorite (if other local environmental factors
are favorable) may be achieved.

In addition to the survival of unmetamorphosed C-2
bodies, the development of an excess of S-type bodies of
50 - 100 km. radius also seems particularly compatible with
solar wind heating. In high conductivity asteroids of less
than 500 km. radius, core size does not decrease simply with
asteroid radius (at least down to radii of about 100 km.).
Smaller asteroids stand off less solar wind and have, in effect,
higher solar wind power limits to heating. For example, a
100 km. C-3-O body may develop temperatures greater than
1000 $^\circ$C over half its radius and reach silicate melting
temperatures over one fourth its radius. After the end of the
T-Tauri episode, such asteroids may follow the straightforward
cooling histories of Fricker et al. (1970), or may undergo
collisions, cool more rapidly and appear as differentiated
remnant cores of asteroids.

In this study, no models reached basalt melting
temperatures at radii of about 275 km., the radius of Vesta.

Heating models suggest that this unique asteroid is not
simply a remnant core of 275 km. radius. Perhaps proto-
Vesta was evolving much like other high conductivity asteroids
when a collision stripped away an unconsolidated, cool
outer zone and/or disrupted the body allowing liquid silicates
to reach the surface or near surface. If Vesta is not
composed of basalt and iron throughout, but rather, consists
mostly of unmelted silicates, it may not have the high mechan-
ical strength attributed to remnant iron core type bodies, so
that its survival may be analagous to the survival of Ceres -
the asteroid has survived breakup simply by chance and,
therefore, like Ceres, appears unique. Such a scenario is
completely ad hoc, and in this respect is not to be favored
over postulating a peculiar concentration of Al^{26} or other
short-lived nuclide for proto-Vesta. It would be somewhat
surprising, however, if Vesta were melted (not merely
metamorphosed) throughout.

Similarly, no models suggest the development of a
body resembling Ceres. It is possible that currents might
flow in a C-3 or C-4 layer of material overlaying a C-2
asteroid, thereby thermally altering that layer, but there is
no reason to believe in such a construction for proto-Ceres.

Models of an early solar wind carrying magnetic
fields $\lesssim 10^{2.5}$ oe. all indicate the survival of primitive C-1
and C-2 material during the metamorphism of C-3 material, in

accord with the modern observation that C-2 bodies are
common in the asteroid belt whereas C-3 asteroids are rare
(Chapman et al. 1975). Because electrical conductivity is
so crucial to solar wind heating, one can confidently suggest
that proto-S bodies had bulk composition an order of magnitude
or more less resistive than C-2 material. The modern distri-
bution of asteroid surface compositions through the asteroid
belt probably reflects, roughly, the original distribution of
asteroid compositions. Apparently bodies accreting in the
inner belt incorporated high-temperature, high-conductivity
minerals more frequently than did bodies in the outer belt.
This is in qualitative agreement with the view that the
different petrologic subtypes of carbonaceous chondrites
represent different mixing ratios of high-temperature and
low-temperature fractions. Note here that inhomogeneous
accretion is not indicated for asteroids. Although the
accretion of volatile-rich C-1 andC-2 material over proto-
asteroids would lead to the near uniformity of surface
composition observed today, such electrically insulating
surface layers would have prevented solar wind heating of
asteroids.

The hypothesis of solar wind induced electrical heating
of asteroids requires that the sun form with enhanced mass
(1 + $\sim10^{-1}$ times the present mass) and surface magnetic field

($\sim$ 10 times the present field). These requirements are surprisingly modest. Postulating such an early sun may explain not only the heating of selected asteroids, but also the thermal histories of the oldest meteorites, the paleo-magnetization of meteorites and, on a larger scale, the modern angular momentum distribution of the solar system.

Appendix

Although many heating and cooling models of asteroid-
sized bodies have been presented previously, eg. Fricker et
al. (1970), this section is appended to illustrate the
characteristics of combined solar wind and radionuclide
heating. Heating by long-lived radionuclides alone, Figures
9 and 10, is compared with the combination of heat sources,
Figure 11.

The straightforward models of this section may bear a
relation to reality for asteroids that have remained intact
since formation. Unfortunately, heating by long-lived radio-
activity occurs on time scales of 10^9 years, 10^3 greater than
solar wind heating time scales; on such a long time scale, the
probability that any but the largest asteroids may be disrupted
in a collision with another asteroid is nonnegligible if an
enhanced initial population is assumed (Chapman, 1975a).
Internal temperatures of an asteroid will be substantially
reduced very quickly following a disruptive collision which
breaks an asteroid into two or more substantial fragments. The
variety of high temperature meteorite types with essentially
solar system ages suggests that early heating and fragmentation
of meteorite parent bodies may have been widespread indeed.

In all but the largest asteroids, long-lived radioact-
ivity alone produces lower peak temperatures than does solar
wind heating. Figure 9 shows peak temperature profiles in

·500, 400, 300, and 200 km. radius asteroids heated only by
long-lived radionuclides in chondritic abundances; melting
temperatures of dry and water-saturated Allende samples at
3 kb. are indicated, as is the Fe-FeS eutectic temperature.
Only asteroids of >400 km. radius are expected to melt
silicate or metal phases. Smaller asteroids, ∿300 to ∿400
km. radius, reach metamorphic temperatures in $\lesssim$ 1 x 10^9
years after asteroid formation. Electrically resistive
bodies of this size class should have melted neither silicate
nor metal fractions, but might have produced meteorites with
both mineralogic and textural metamorphic features. Electri-
cally resistiveasteroids of $\lesssim$ 250 km. radius do not warm
sufficiently to produce interesting geologic effects - even
dehydration of hydrous silicates is not expected. C-1 and
C-2·asteroids in this smallest size class are expected to be
almost unaltered since formation - except for the effects of
collisions (providing, of course, that significant concen-
trations of short-lived radionuclides were not incorporated
into these asteroids).

Figure 10 shows a 4.6 billion year thermal history for
a·500 km. asteroid heated by chondritic abundances of long-
lived radionuclides alone. The Fe-FeS·eutectic is reached
only after 800 x 10^6 years, and peak core temperatures,
between the wet and dry melting temperatures of Allende

samples, are reached at 1500×10^6 years - this contrasts
with the very few millions of years required to reach peak
temperatures during an effective solar wind heating episode.
By about 2.5 billion years, any metal in the core of a 500
km. asteroid begins to solidify; by 3.5 billion years, core
materials have cooled below rare gas retention temperatures.

Figure 11 shows a thermal evolution complimentary to
that of Figure 10 - an asteroid heated by long-lived radio-
activity after strong heating in a T-Tauri episode. Solar
wind heating is represented by the initial thermal profile
labeled SW. After 150 million years, the core has been
substantially cooled and solidified. During the next 850
million years, if the asteroid remains intact, the core
region is reheated; peak temperatures great enough to melt
dry silicates are reached in the inner 150 km.. The sub-
sequent cooling history, very similar to the case involving
radioactive heating alone, leads to a modern thermal profile
indistinguishable from that case.

Consideration of long-lived radioactivity does nothing
obvious to explain the more unusual asteroids. An object
such as Vesta, perhaps the most difficult asteroid to "produce"
from models might have been generated if a large asteroid
suffered a great, but not catastrophic collision within the
first billion years of solar system history. So small a

volume fraction of a large asteroid would have been molten
at that time that "turnover" of the "crust" seems quite
impossible. A very particular collision might, however,
strip away some of the cool, friable outer portions of the
asteroid, create fractures of planetary scale, and mobilize
molten core material to form a flood basalt surface. Even
such an ad hoc scenario, however, seems difficult without
solar wind preheating of proto-Vesta. Ceres, if composed
of C-2 material overlain by a veneer of metamorphosed
material, remains somewhat puzzling.
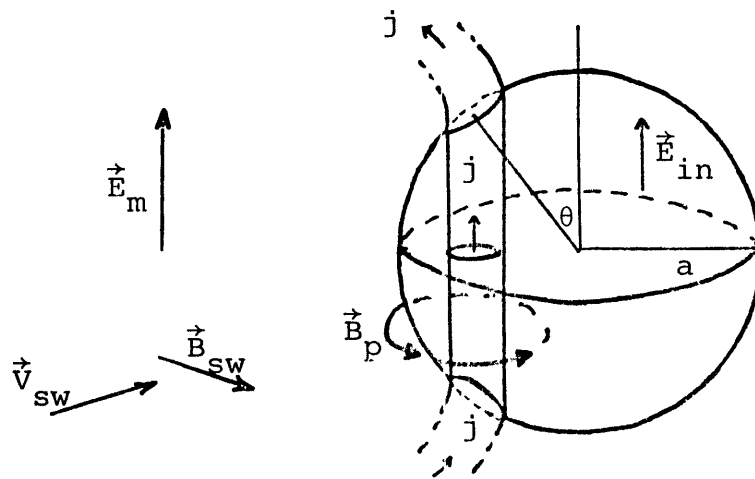
FIGURE 1.
Model geometry of solar wind - asteroid interaction. Solar wind passing at velocity V_{sw} and carrying "frozen in" magnetic field B_{sw} produces apparent motional electric field E_m. Currents, j, flow in the planet producing planetary magnetic field B_p which may stand off some solar wind so that reduced field E_{in} affects the planet.
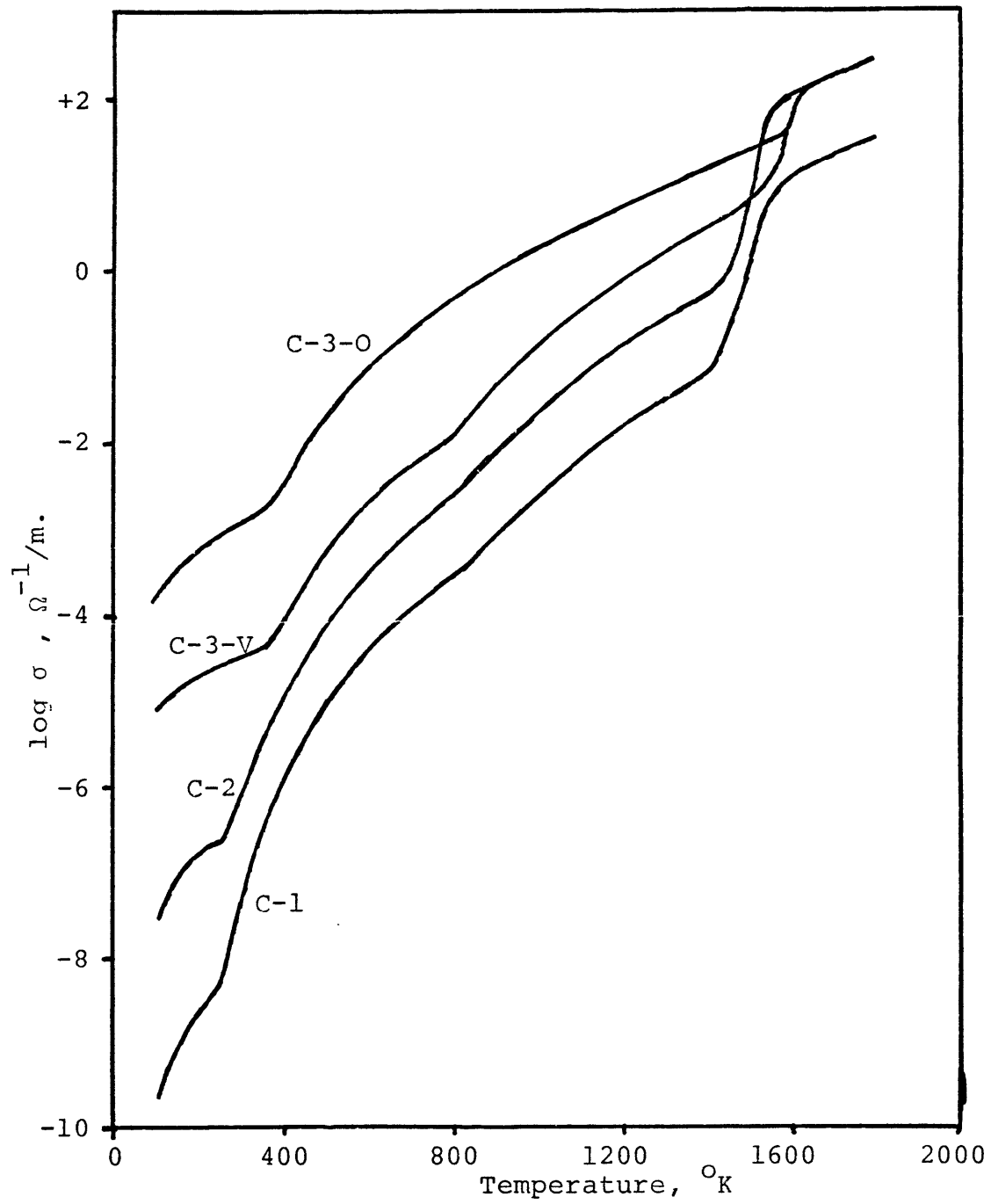
FIGURE 2.
Electrical conductivity functions adopted for C-1, C-2,
C-3-V, and C-3-O material.
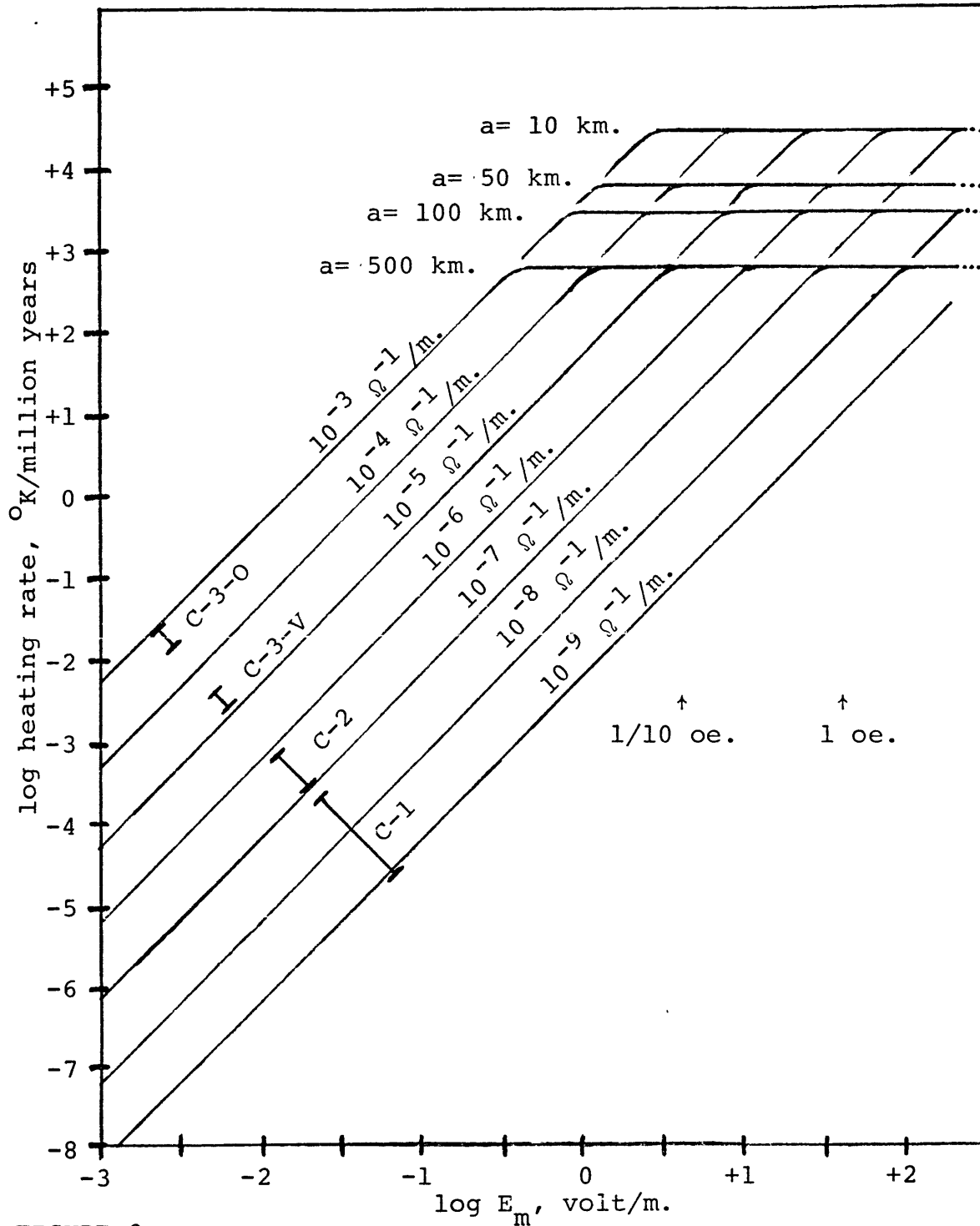
FIGURE 3.
Initial heating rate as a function of conductivity and motional electric field.
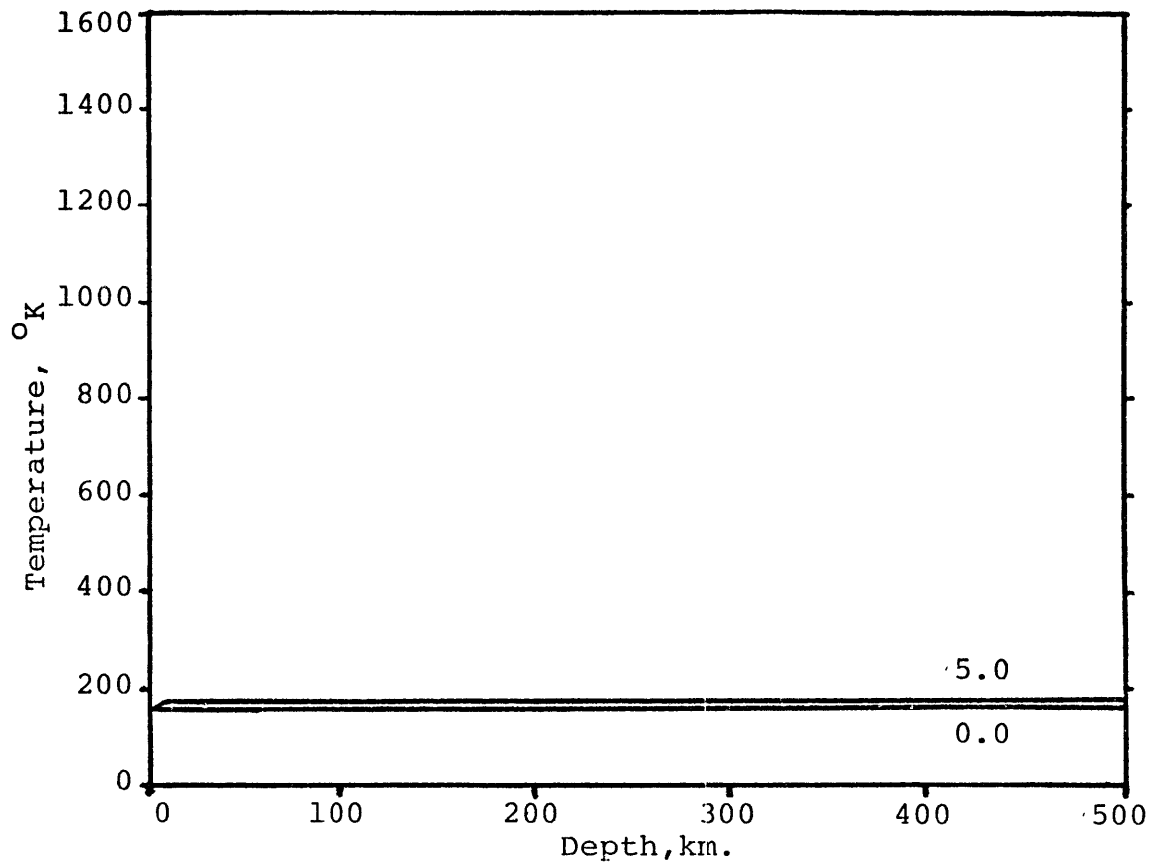
FIGURE 4.
Solar wind heating of C-2 asteroid, base temperature 165 ^{O}K. Initial solar field 28 oe., initial solar mass 1.25 present solar mass. Numbers on thermal profiles indicate time in millions of years after the beginning of T-Tauri episode.
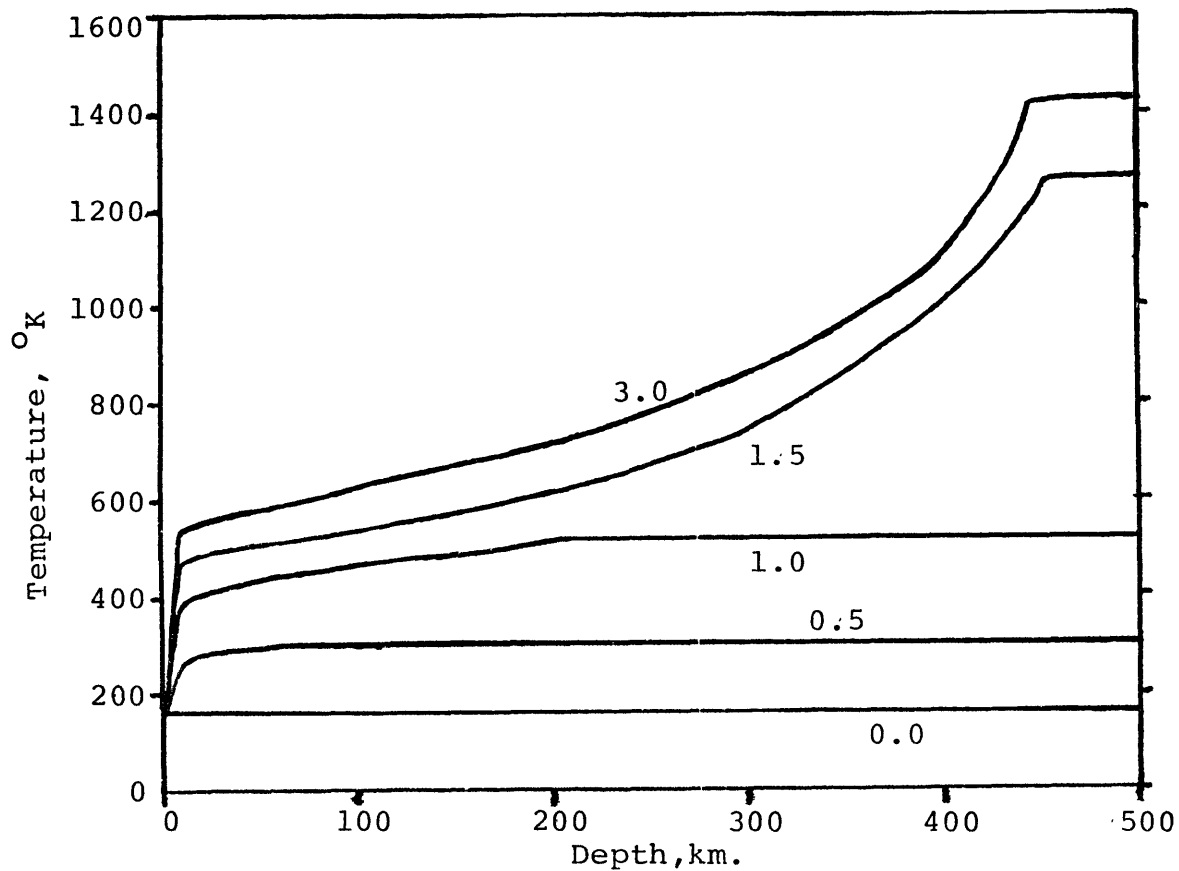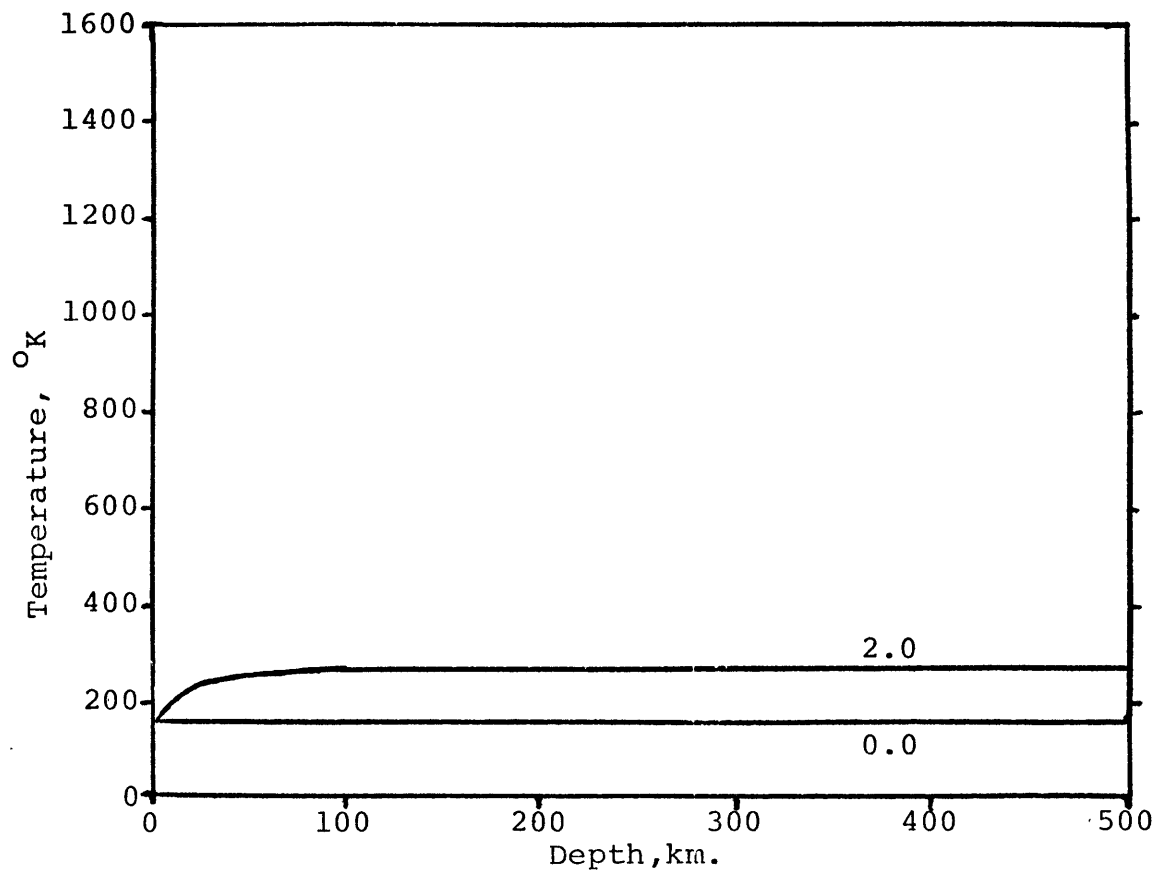
FIGURE 5.
Solar wind heating of C-3-V asteroid, base temperature 165 $^{\circ}$K. Initial solar field 28 oe., initial solar mass 1.25 present solar mass. Numbers on thermal profiles indicate time in millions of years after the beginning of T-Tauri episode.
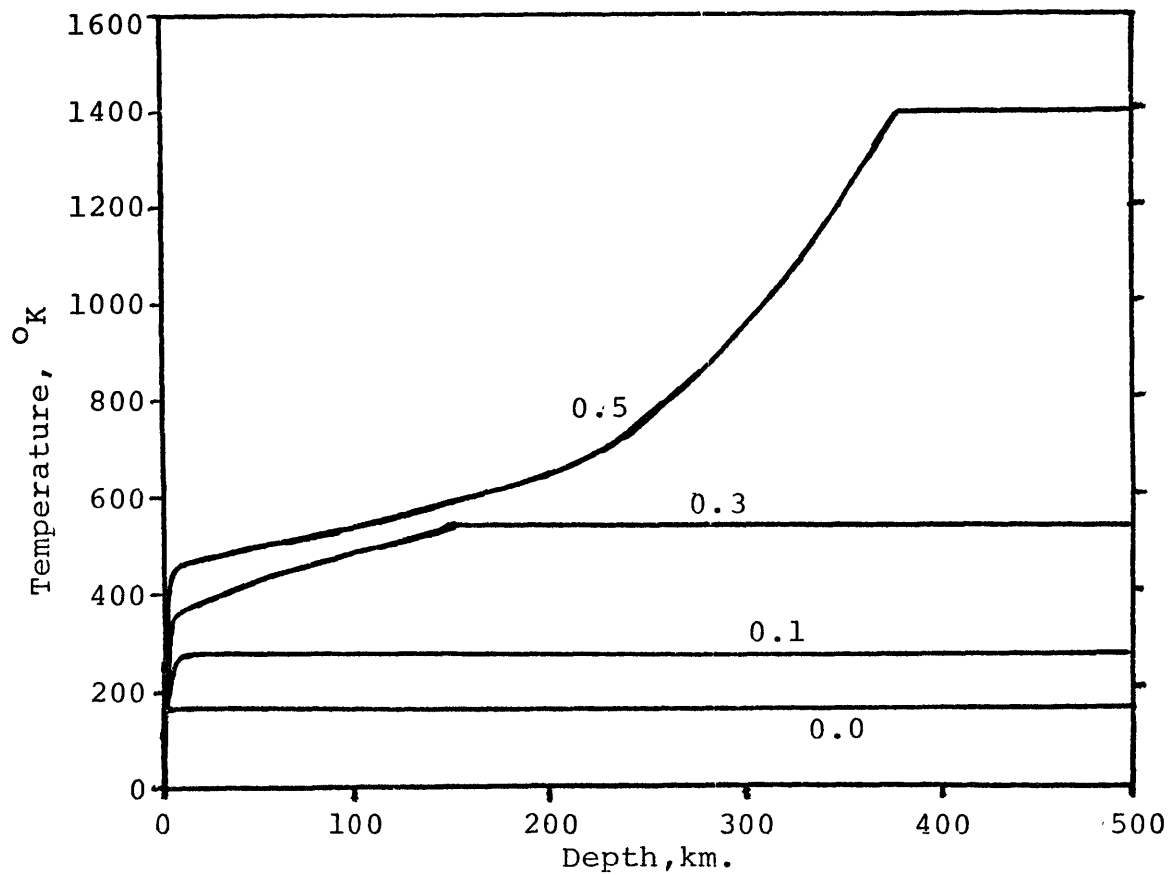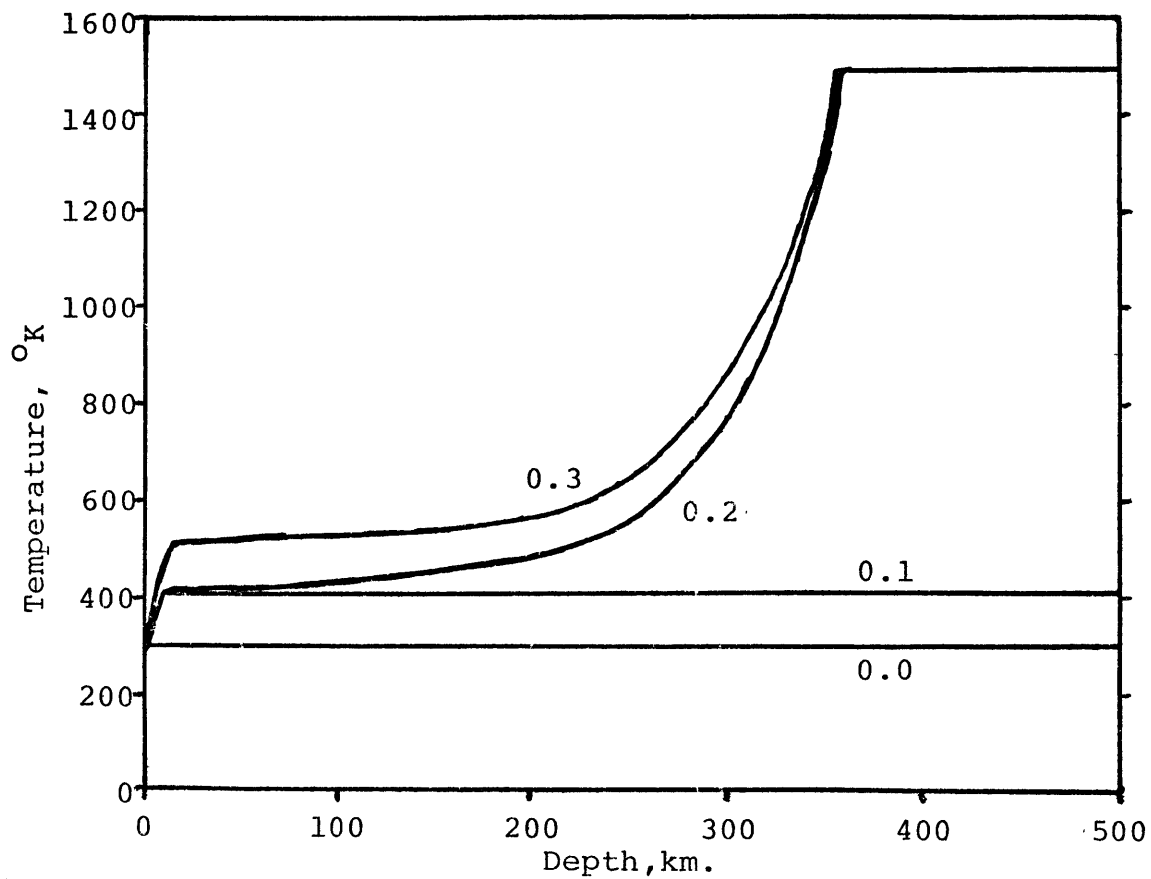
FIGURE 6.
Solar wind heating of C-3-O asteroid, base temperature 165 °K. Initial solar field 28 oe., initial solar mass 1.25 present solar mass. Numbers on thermal profiles indicate time in millions of years after the beginning of T-Tauri episode.
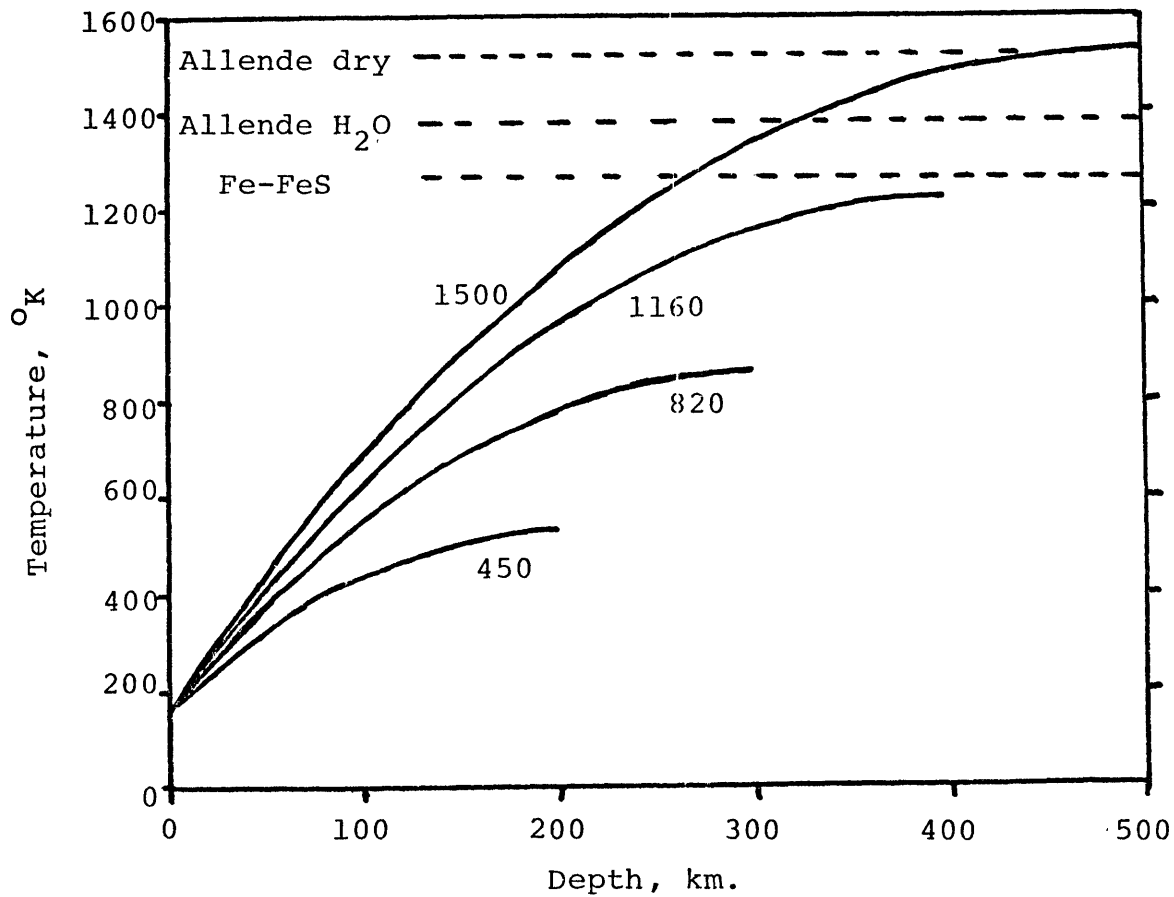
FIGURE 7.
Solar wind heating of C-2 asteroid, base temperature 165 °K. Initial solar field 338 oe., initial solar mass 1.15 present solar mass. Numbers on thermal profiles indicate time in millions of years after the beginning of T-Tauri episode.

FIGURE 8.
Solar wind heating of C-2 asteroid, base temperature 303 °K. Initial solar field 338 oe., initial solar mass 1.15 present solar mass. Numbers on thermal profiles indicate time in millions of years after the beginning of T-Tauri episode.

FIGURE 9.

Peak temperatures produced in asteroids of various sizes by long-lived radioactivity. Numbers on thermal profiles indicate time in millions of years after asteroid formation. Important melting temperatures are indicated.
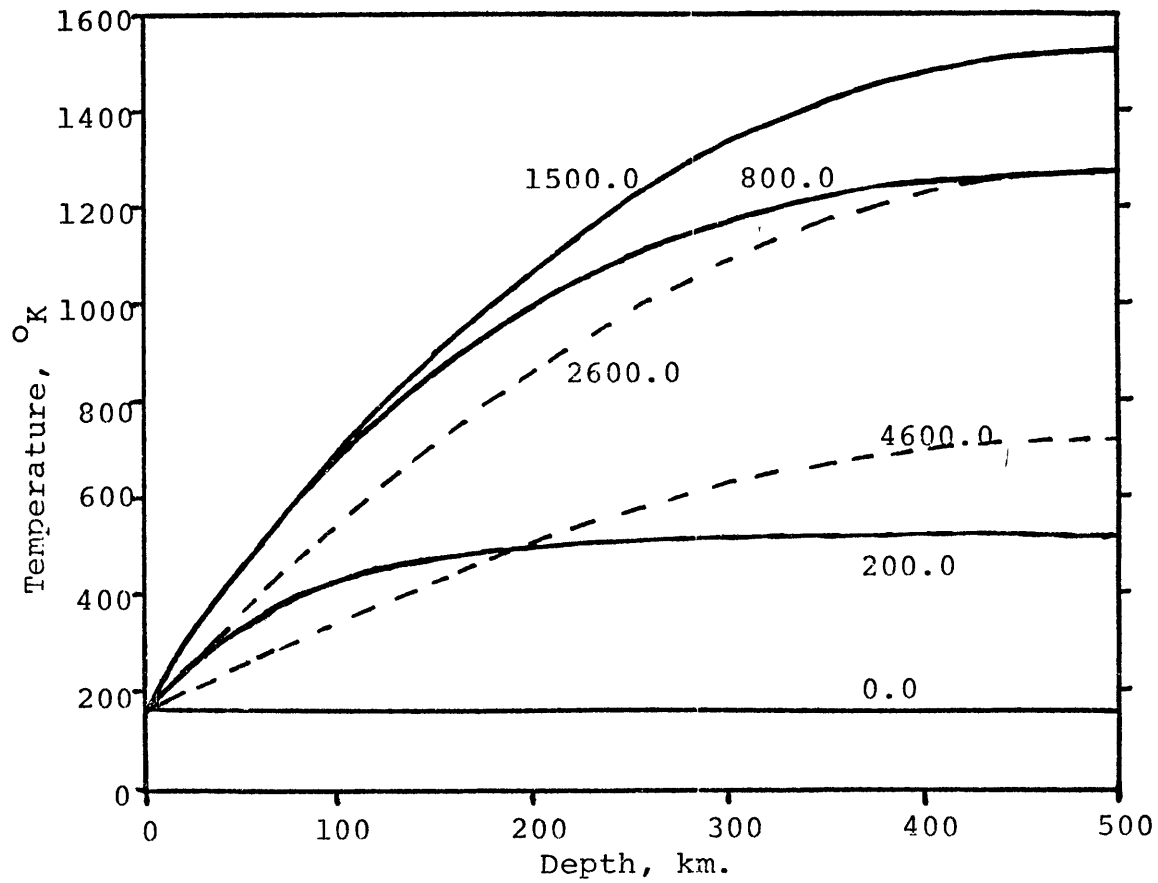
FIGURE 10.
Heating of a C-3 asteroid by long-lived radioactivity, base temperature 165 °K. Numbers on thermal profiles indicate time in millions of years after the formation of the asteroid.
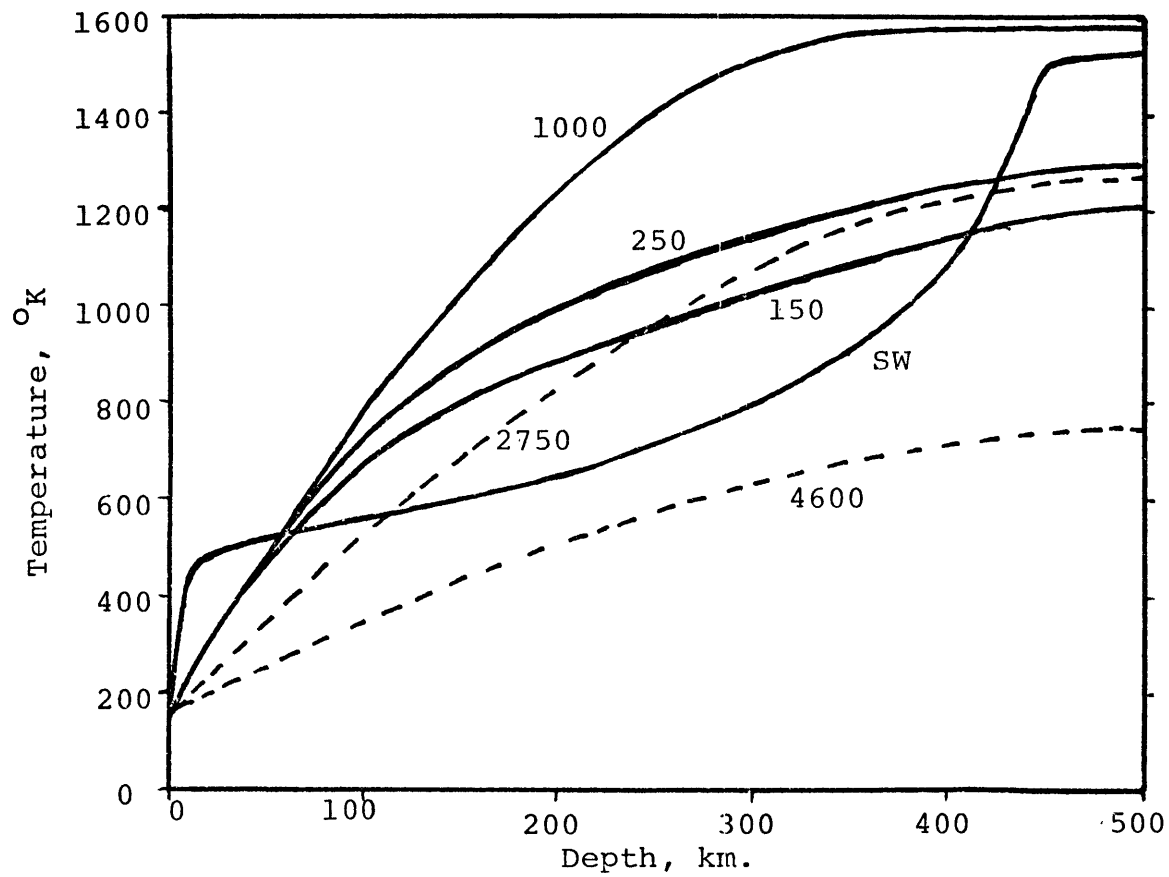
FIGURE 11.
Heating of a C-3 asteroid by solar wind induction and long-lived radioactivity. Base temperature, 165 $^{\circ}$K. Numbers on thermal profiles indicate time in millions of years after the onset of heating.

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