FORMATION OF THE LUNAR CRUST: AN ELECTRICAL SOURCE OF HEATING. C. P. Sonett, Dept.of Planetary Sci.& Lunar and Planetary Lab., Univ.of Ariz., Tucson, Ariz.85721, D.S. Colburn, NASA Ames Res.Center, Moffett Field, Calif.94035, K. Schwartz, 5160 Camino Floral, Santa Barbara, Calif.93111.

It is now generally conceded that the formation of the lunar highlands and the accompanying Ca-Al rich anorthositic rocks resulted from a period of intense heating approximately coincident with the formation of the Moon itself[1,2] The classical source of the required thermal energy is hypothesized to be from rapid accretion of the Moon itself.[3,4,5] Such a model permits the subsequent heating associated with the formation of the maria to take place in a natural manner following the inward drift of the thermal peak and an accompanying increase in temperature due to long-lived radioisotopes, provided however that such isotopes are not first lost to the surface during the initial melting.

Although the accretional hypothesis can explain both the first and second stage thermal events, the large initial heat pulse required for the first melting implies a very short time for the formation of the Moon. For example, for unity emmissivity ($\varepsilon = 1$), a starting temperature $T_o = 100^oC$, and a constant mass flux, $\dot{m} = 10^{-3}$ gm cm^{-2}-sec, a final surface temperature, $T_f = 600^oC$ is attained in $\tau = 56.5 \times 10^3$ yrs. The temperature is increased to 1800^oC for $\dot{m} \sim 10^{-1}$ gm cm^{-2}-sec, implying a time of 560 yrs for $\dot{m}$ constant and 192 yrs for $\dot{m}$ proportional to the gravitational potential. (In the latter case, time is measured from half radius; if started at zero radius, time becomes infinite for this mass law.) Some increase in the temperature attained or alternatively an increase in the permissible time is gained for smaller ε , but this is not a significant aid.

All these calculations are based upon material falling upon the Moon with escape velocity. Lower velocities are anticipated if material is collected from adjacent orbits; only if crossing orbits are admitted will there be a substantial increase in the impact energy, and such orbits seem artificial for a condensing solar system. In any event such impacts would decrete a significant fraction of the material already residing on the Moon, so the net mass flux would be reduced, increasing the accretion time at the expense of final temperature. The background temperature could be raised but this would cause difficulty with simple models for the second (maria) thermal stage.

These difficulties suggest a class of heating based upon eddy currents flowing in the pristine Moon. The source of the electrical induction lies in turbulent magnetic fields carried out from the solar atmosphere by a T Tauri-like plasma outflow, similar in many respects to previous calculations we have done for meteorite parent body heating[6]. The principle difference is that in the present case all currents close in the interior of the Moon, so the heating is independent of solar system background temperature. The requirement for rapid solar spin remains; the magnetic turbulence is modelled by a power law with spectral index -2 reminiscent of the spectrum of periodic step functions similar to sector structure in the present-day solar wind, but the power is 10^6-10^7 times the present value. Magnetic back pressure is accounted for as previously and a strong plasma flow tends to confine the induced fields.

An initial temperature of 300-400^{o}C is required for the process to "ignite" using typical rock conductivities. This permits a heating rate in excess of the losses to space via radiation. The temperature attained is sufficient for a "runaway" to occur and the temperature finally rises rapidly. A typical case for a Moon with an electrical conductivity similar to olivine with a Fa/Fo ratio[7] of 7.6% is shown in Fig.1. More recent conductivity measurements[8,9] would alter the times and the lower temperature limit but the qualitative features of the mechanism would remain.

The conclusions to be drawn are that the anorthositic highland formation can be accounted for by melting of the surface of the Moon during an early heat pulse from electrical induction. This relaxes the accretional time requirement by 2-4 orders of magnitude; the longest duration of accretion and heating is determined by the lunar heat loss rate during the heating and details of the T Tauri parameters entered into the calculation. A heating time of 10^6 yrs seems possible; calculations are in progress to examine the longest time bound permissible.

Finally these calculations support the hypothesis that the Sun passed through a T Tauri-like phase prior to arrival onto the main sequence, but subsequent to or in conjunction with the formation of the planets. This is consistent with the known high spin rate of early stellar objects[10], and the existence of paleomagnetism in some meteorites which suggests the presence of a magnetic field of 0.1-1 gauss in the early solar system[11-15]. Further, the ubiquitous presence of magnetic fields on the Moon[16] providing an alternate route of magnetization to the dynamo hypothesis[17] in itself demands the existence of a magnetic field of the same order of magnitude. Such a field is entirely consistent in magnitude with that required for lunar crustal heating, fits quite well the field strength postulated for the seat of the current system hypothesized for heating of meteorite parent bodies. Conjecture is contained in these comments that the Sun was endowed with a quadrupole dynamo, for in that way a magnetic field of constant polarity could be maintained in the equatorial plane of the Sun while a solar wind was flowing, thereby supplying the background field for imprinting paleomagnetization.

BIBLIOGRAPHY

1. J.A.Wood, J.S.Dickey, U.B.Marvin, and B.N.Powell (1970) "Lunar Anorthosites", Science, 167, 602.
2. J.A. Wood (1970) "Petrology of the Lunar Soil and Geophysical Implications" J.Geophys.Res. 75, 6497.
3. C.P. Sonett and D.S.Colburn (1970) "The Role of Accretionally and Electrically Inverted Thermal Profiles in Lunar Evolution", The Moon, 1, 483.
4. J.A. Wood (1972) "Thermal History and Early Magnetism in the Moon", Icarus, 16, 229.
5. M.N.Toksöz, S.C.Solomon, J.W.Minear, and D.H.Johnson (1972) "Thermal Evolution of the Moon", The Moon, 4, 190.
6. C.P.Sonett, D.S.Colburn, K.Schwartz and K.Keil (1970) "The Melting of Asteroidal-Sized Bodies by Unipolar Dynamo Induction from a Primordial T Tauri Sun", Astrophys.Spa.Sci. 7, 446.
7. Y.Kobayashi and H. Maruyama (1971) "Electrical Conductivity of Olivine Single Crystals at High Temperature", Earth Plan.Sci.Lttrs. 11, 415.

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8. A. Duba and I.A.Nichols (1973) "The Influence of Oxidation State on the Electrical Conductivity of Olivine",Earth Plan.Sci.Lttrs. 18, 59.
9. A.Duba (1972) "Electrical Conductivity of Olivine",J.Geophys.Res.,77,2483.
10. R.P.Kraft (1972) "Evidence for Changes in the Angular Velocity of the Surface Regions of the Sun and Stars",in The Solar Wind,eds. C.P.Sonett, P.J. Coleman,Jr., and J.M.Wilcox, NASA SP-308.
11. A. Brecher (1972)"Memory of Early Magnetic Fields in Carbonaceous Meteorites", in Symp.on the Origin of the Solar System, p.270 (CNRS).
12. S.K.Banerjee and R. B. Hargraves (1972) "Natural Remanent Magnetizations of Carbonaceous Meteorites and the Magnetic Field of the Early Solar System", Earth Plan.Sci.Lttrs. 17, 110.
13. R.F. Butler (1972)"Natural Remanent Magnetization and Thermomagnetic Properties of the Allende Meteorite",Earth Plan.Sci.Lttrs. 17, 120.
14. V.I.Potcharev and E.G.Guskova (1962)"The Magnetic Properties of Meteorites" Geomag.and Aeron.7, 626.
15. F.D.Stacey, J.F.Lovering, and L.G.Parry (1961)"Thermomagnetic Properties, Natural Magnetic Moments, and Magnetic Anisotropies of Some Chondritic Meteorites",J.Geophys.Res. 66,1523.
16. C.P.Sonett and S.K.Runcorn (1973)"Electromagnetic Evidence Concerning the Lunar Interior and Its Evolution",The Moon 8, 308.
17. S.K.Runcorn and H.C.Urey (1973)"A New Theory of Lunar Magnetism",Science 180, 636.

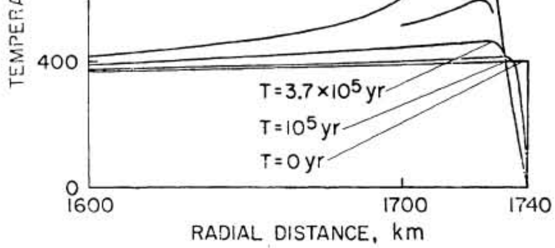

Fig.1. Development of thermal spike for a moon accumulating in 37,600 yrs at constant mass rate from a solar nebula at 0°C. Final accretional temperature is 400°C, ε=1, solar spin rate centrifugally limited at 198 times the present value and photospheric magnetic field 23 gauss. The runaway property is demonstrated by the primary rise taking place in the last 10^5 yrs. Temperatures well above 1200°C are easily obtained shortly after the last time entry shown.