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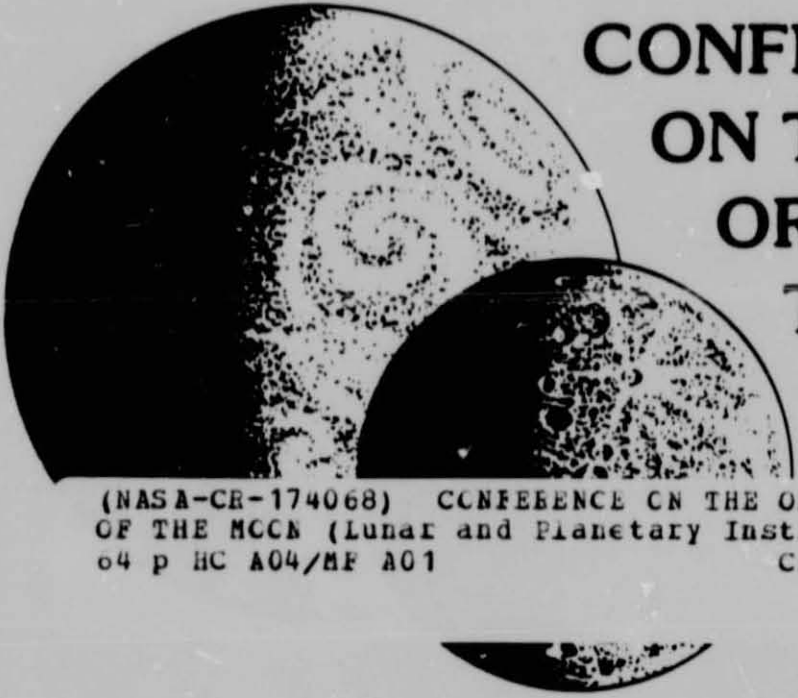
NASW-3389

Papers presented to the

CONFERENCE ON THE ORIGIN OF THE MOON



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Division for Planetary Sciences
of the American Astronomical Society
Lunar and Planetary Institute
National Aeronautics and Space Administration

Kona, Hawaii
October 13-16, 1984

Abstracts and Program for the Conference on the Origin of the Moon

Co-Sponsored by

Division for Planetary Sciences
of the American Astronomical Society

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National Aeronautics and Space Administration

October 14-16, 1984

Kona, Hawaii

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Compiled in 1984

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Lunar and Planetary Institute

PREFACE

This volume contains abstracts that have been accepted by the Program Committee for presentation at the Conference on the Origin of the Moon. This Committee included the conveners and committee members listed below.

Conveners:	William K. Hartmann (Planetary Science Institute), Roger J. Phillips, (Southern Methodist University), and G. Jeffrey Taylor (University of New Mexico).
Committee Members:	William V. Boynton (University of Arizona), Alan Harris (Jet Propulsion Laboratory), L. L. Hood (University of Arizona), Pamela Jones (Lunar and Planetary Institute), Günter W. Lugmair (University of California, San Diego), and Graham Ryder (Lunar and Planetary Institute).

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PROGRAM

LPI TOPICAL CONFERENCE ON THE ORIGIN OF THE MOON

Sunday, October 14, 1984

8:00 - 9:00 a.m.	Registration
8:45 a.m.	Opening Remarks

INVITED REVIEWS

9:00 a.m. - 12:00 noon

Chairman: Michael B. Duke

() Minutes for presentation

(30) Wood J. A.
Review of theories of lunar origin.

(30) Larimer J.
How does lunar bulk material relate to the solar nebula condensation sequence?

(30) Wetherill G. W.
What were lunar accretion dynamics and early cratering history.

(30) Drake M. J.
Is lunar bulk material similar to Earth's mantle?

LUNCH

INVITED REVIEWS - CONTINUED

1:00 - 3:15 p.m.

Chairman: Robert O. Pepin

(30) Taylor G. J.
What were the earliest lunar differentiation events?

(30) Hood L. L.
Is there a lunar iron core?

(30) Burns J.
What was the Moon's ancient orbital history?

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Sunday, October 14, 1984

GEOPHYSICAL CONSTRAINTS

3:30 - 5:30 p.m.

Chairman: Roger J. Phillips

6:00 - 7:30 p.m. SOCIAL

Monday, October 15, 1984

CHEMICAL AND PETROLOGICAL CONSTRAINTS

8:00 - 11:30 a.m.

Chairman: John T. Wasson

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Monday, October 15, 1984

DYNAMICAL CONSTRAINTS

1:00 - 3:15 p.m.

Chairman: Alan Harris

COFFEE BREAK

Monday, October 15, 1984

MY MODEL OF LUNAR ORIGIN I

3:30 - 5:15 p.m.

Chairman: G. Jeffrey Taylor

Tuesday, October 16, 1984

MY MODEL OF LUNAR ORIGIN II

9:00 a.m. - 12:00 noon

Chairman: Torrence V. Johnson

SUMMARY AND OPEN DISCUSSION

2:00 - 5:00 p.m.

Chairman: William K. Hartmann

(30) Sean C. Solomon
Summary: Geophysical perspective.

(30) John Longhi
Summary: Geochemical perspective.

(30) Stanton Peale
Summary: Dynamical perspective.

GEOPHYSICAL CONSTRAINTS

Sunday, October 14, 1984
3:30 - 5:30 p.m.

D1

N85 13710

GEOPHYSICAL AND GEOCHEMICAL CONSTRAINTS FAVORING THE CAPTURE HYPOTHESIS; D.L. Turcotte, Department of Geological Sciences, Cornell University, Ithaca, NY 14853

There appears to be a near consensus that the early fractionation of the moon was the result of melting the outer layer of the moon. This melting can be attributed to the accretional heating of moon. We have carried out calculations of the early thermal evolution of the earth and moon (Turcotte and Pflugrath, 1984) based on the assumption that these bodies accreted independently. The results are consistent with many observations.

We have also applied the concept of geochemical resevoirs to the moon. The rubidium-strontium isotope data for mare basalts can be explained by an early fractionation of the source region. When the initial isotope ratios ε_i are plotted as a function of time we find very good agreement with $d\varepsilon_i/dt = -16$. The fractionation factor f for the system can be obtained from the relation $f = (d\varepsilon_i/dt)\ Q^{-1}$ where $Q = 10^4\ \lambda\ j_{so}/i^*_{so}$ where λ is the decay constant, j_{so} is the initial concentration of the parent, and i^*_{so} is the initial concentration of the daughter. Taking the chondritic reference value $Q = 18$ we find $f = -0.9$. Thus the source region was almost completely fractionated. The good correlation of the data and the reasonable results indicate that the reference isotope ratio i^*_{so}/i_{so} used in defining ε and the ratio j_{so}/i^*_{so} used for the earth are also valid for the moon. There is considerable scatter in the data for the semarium-neodymium isotope system. This can be attributed to either experimental difficulties or to variable degrees of fractionation in the source region. These results are also consistent with the independent accretion of the earth and moon from chrondritic type material.

A primary difficulty with the capture hypothesis is the difficulty of dissipating sufficient energy to allow capture to occur. However, we have shown that if the earth and moon were accreting sufficiently close together accretional capture could occur (Nordman and Turcotte, 1977). If a primary body is increasing in mass the hyperbolic orbit of a secondary body with respect to the primary body can be transformed into an elliptic orbit. Calculations of the capture cross section for accretional capture indicate that a significant window for capture exists.

Nordmann, J.C., and D.L. Turcotte (1977), Proc. Lunar Sci. Conf. 8th, p. 57-65.

Turcotte, D.L. and J.C. Pflugrath (1984), Proc. Lunar Sci. Conf. 15th, submitted for publication.

Dr

N85 13711

LUNAR MAGMA OCEAN AND ITS IMPLICATION FOR ORIGIN OF THE MOON;

Takafumi Matsui and Yutaka Abe, Geophysical Institute, Faculty of Science, University of Tokyo.

It gives one of the most important thermal constraints on origin of the moon whether a magma ocean covering the entire surface of a growing moon can be formed. Accretional heating is probably only one promising heat source for formation of such magma ocean (1). However, so far have not been proposed any accretional models which satisfy the magma-ocean constraint (2). In this paper, we will study a plausible accretional model of the moon using as a constraint the formation of a magma ocean.

Recently, we showed that the surface of a planet growing by planetesimal impacts was heated over the melting temperature of surface materials due to the blanketing effect of an impact-induced atmosphere (3). Using the same calculational scheme for the earth (3) early thermal history of the moon growing by planetesimal impacts can be calculated for various accretional models. Figure 1 shows thermal evolution of moon accreting by planetesimal impacts. It is shown that a magma ocean covering the entire surface was formed in both models. Most important parameters related to surface temperature are safronov number and accretion time. Our results show that very small safronov number is needed for formation of the magma ocean. Safronov number is usually larger than 1 for accretion of planetesimals in heliocentric orbit (4). However, safronov number decreases when the moon's growth is dominated by the proximity of the earth. According to Harris (5), safronov number falls in the range of 0.02-0.1 for the binary accretion case. Therefore, we may suggest that the moon was formed by accretion of planetesimals in geocentric orbits.

References

(1) Mizutani, H. et al. (1972) Moon, 4, 476-489.
(2) Kaula, W. M. (1979) J. Geophys. Res., 84, 999-1008.
(3) Matsui, T. and Abe, Y. (1984) Lunar Planet. Sci. XV, 517-518.
(4) Safronov, V. S. (1972) NASA Tech. Transl., TTF-677.
(5) Harris, A. W. (1978) Icarus, 34, 128-145.

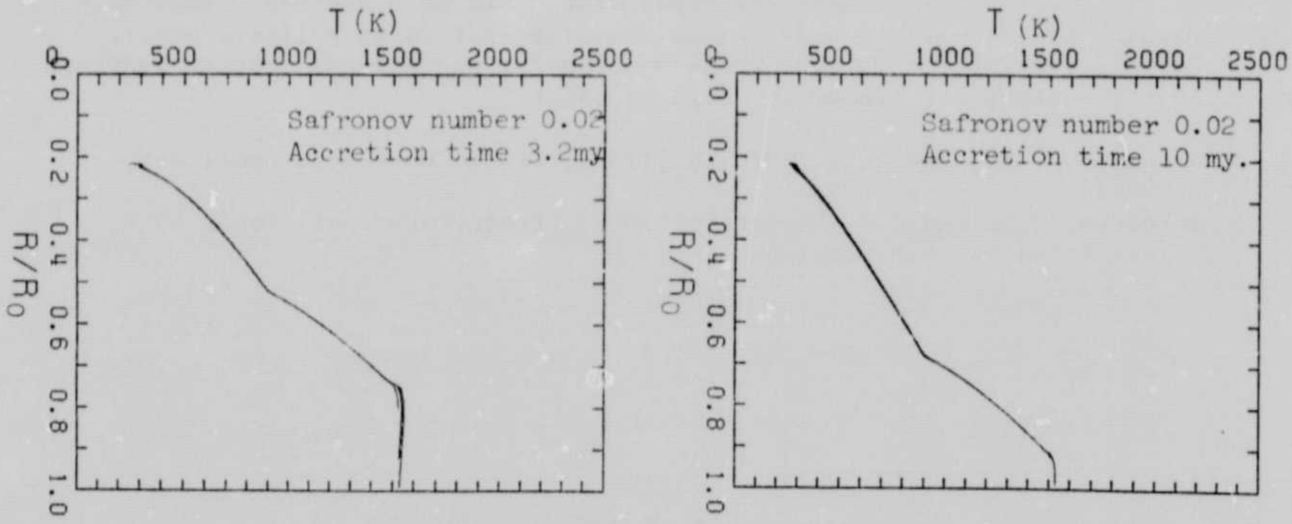


Figure 1.

D3

THE INITIAL THERMAL STATE OF THE MOON; A.B. Binder, Senior NRC Fellow, Johnson Space Center, Houston, TX 77058

The initial thermal state of the moon may depend on its mode of origin. For example, if the moon formed by accretion in geocentric orbit it appears likely that the moon would have had a relatively cool interior and an initially molten zone only a few hundred km deep. If the moon formed by fission from the protoearth, it must have been totally molten initially. Results I have obtained during the past few years all favor the concept that the moon was initially totally molten, this evidence includes:

1) The existence of young (<10^9 year old) thrust fault scarps in the highlands and kbar stress drop, shallow moonquakes both suggest that the thermoelastic stresses in the outer crust are currently in the kbar range. This is expected if the moon were initially totally molten, but not if the moon had a magma ocean only a few hundred km deep.

2) Model studies, which successfully account for all the major characteristics of the mare basalts, indicate that the concentrations of the refractory incompatible elements (Sr, Ba, REE) in the magma at the time the crust and mare basalt magma source region began to form was 15 to 20 times CI values. This result can be converted into bulk moon concentrations using the additional result that the source region and crust formed as the outer 20% of the mass of the moon crystallized. Thus the concentrations of these refractory incompatibles in the bulk moon must be between the limits of 3 to 4 x CI if the moon were initially totally molten and 15 to 20 x CI if only the outer 200 km of the moon was initially molten. A test of these end-member alternatives is provided by the limited heat flow data which suggest that the bulk U and Th (also refratory incompatibles) contents of the moon are also 3 to 4 x CI values. Since it is most likely that the enrichment factor of all the refractory incompatible elements is about the same, these results together suggest that the moon was initially totally molten.

D4 6 **N85 13713**

THE SIZE OF THE LUNAR CORE; C.F.Yoder, Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California 91109.

A 0.2 arc second phase shift in the 18.6 year forced precession of the lunar figure has been inferred from analysis of lunar laser ranging data. The source of the phase shift is either viscous friction at a lunar core-mantle boundary or solid friction caused by tidal flexing of the moon by the earth. Core-mantle viscous coupling will explain the signature if the core radius $R_c \simeq 330$ km. On the other hand, solid friction can account for the signature only if the lunar solid friction $Q \simeq 30$ is abnormally small compared with that observed for, say, Mars ($\simeq$100 - 200). Although the inferred core radius is certainly within the limits imposed by the Apollo seismic experiment ($R_c <$ 500 km), it is significantly smaller than estimates of order 400-500 km from electromagnetic sounding. How accurate is the estimate of the R_c derived from the phase shift? I shall discuss the effect of uncertainties in the frictional coupling mechanism, core density and ellipticity on the inferred core radius. The excitation of lunar free librations by core turbulence vis-a-vis other mechanisms (e.g. cometary or asteroidal impacts) and the influence of changes in lunar precession in the past on lunar dynamo generation will also be examined.

N85 13714 D5

ON THE APOLLO SUBSATELLITE EVIDENCE FOR A LUNAR CORE: C. T. Russell, Department of Earth and Space Sciences, and Institute of Geophysics and Planetary Physics, University of California, Los Angeles, CA 90024

Electromagnetic sounding of the lunar interior is based on the fact that electric currents are induced in a conductor in the presence of a changing magnetic field in the direction as to oppose any change in the magnetic field within the conductor. The length of time for the "new" magnetic field to diffuse into the conductor is a function of both the conductivity of the material and the dimensions of the conductor. Two independent techniques have been used to infer the electrical conductivity of the interior of the moon. The first is the measurement of an incident spectrum of electromagnetic waves in the solar wind near the moon and the separate measurement of the incident plus reflected spectrum on the surface of the moon. The second is the measurement of the distortion of the ambient magnetic field of the geomagnetic tail lobes by the conducting moon. The first technique is most sensitive at high frequencies and short wavelengths where the scattering by the moon is strong. The second technique is most sensitive to the deep conductivity of the moon where time scales are of the order of many hours or more. The first technique has the limitation that two different sensors are used whose calibration might differ slightly. A one percent difference in gain can strongly affect the inferred conductivity profile at depth. The latter technique depends on a single sensor but returns little information about lunar effects on time scales much less than 90 minutes.

Apollo subsatellite measurements reveal a statistically very significant signal corresponding to -4.23×10^{22} Gauss-cm^3 per Gauss of applied field, corresponding to a G-factor of -0.008 ± 0.001. While these measurements do not place any strong constraints on the conductivity of the lunar core as long as it has a conductivity of greater than about 10 mho/m. However, they do constrain the size of this conducting region to be greater than 400 km in radius.

D6

N85 13715

8

LUNAR MAGNETIC HISTORY; S. M. Cisowski, and M. Fuller, Department of Geological Sciences, University of California, Santa Barbara, CA 93106

Intensity normalization results (1) have now been obtained from almost all of the lunar samples for which some type of age determifnation is available. This amounts to about 90 samples. In the absence of intensity determinations of the Koenigsberger-Thellier-Thellier type, these results are likely to remain the most complete data set upon which the history of the intensity of ancient lunar fields must be based in the foreseeable future.

Magnetic contamination either during or after collection has been identified and minimized by a combination of AF demagnetization, thermal demagnetization over the range of the lunar diurnal cycle, along with investigation of multiple samples from single rocks. The IRM_S normalization method then reveals that rocks whose radiometric ages lie between 3.6 and 3.9 B.Y. have magnetizations indicative of being magnetized in far stronger magnetic fields than those having older or younger radioactive ages. By comparison with both terrestrial and lunar samples given thermoremanent magnetization in the laboratory, the strength of the ancient lunar field during this short period of lunar history appears to have been comparable with the present earth's field, i.e. to order of magnitude tenths of an oersted, or tens of A m^{-1}.

The only exceptions to this pattern of normalized magnetic intensity and age are a few samples whose magnetization is very soft and appears to be dominated by a small number of large multidomain particles. These samples characteristically have non-repeatable AF demagnetization curves in both intensity and direction. Although the number of samples with radiometric ages significantly greater than 3.9 B.Y. is limited, stratigraphic classification of the lunar breccias for the Apollo 17 boulders and meteoritic trace metal content correlations suggest that the oldest lunar samples were not magnetized in this strong field. There is a significant absence within the high normalized intensity group of samples exhibiting strong shock features.

The observation that the Mare basalts older than 3.6 B.Y. carry stronger magnetizations than younger mare samples is in excellent agreement with the surface field determinations by the electron reflectance method and with the satellite magnetometer data. There is then some degree of agreement from different approaches that the moon may indeed have had a magnetic field comparable in intensity to the geomagnetic field for a period of about 300 M.Y. between 3.9 and 3.6 B.Y.

The origin of this field remains a mystery. None of the various speculations are convincing. Suggestions of an early solar system field are not consistent with the low magnetization of the oldest samples. Models based upon a close approach of the moon to the earth have to account for the 300 M.Y. approach. Lunar dynamo models must explain why this dynamo which must operate in so small a core can operate so efficiently.

We conclude that it is now hard to escape from the idea that there was a relatively strong ancient lunar field between 3.9 and 3.6 B.Y. Moreover it is curious that the existence of this field coincided with the termination of the heavy bombardment of the moon and mare basalt extrusion.

(1) Cisowski, S. M., Collinson, D. W., Runcorn, S. K., Stephenson, A. and Fuller, M. (1983) Proc. Lunar Planet. Sci. Conf. 13th, in Journal of Geophysical Research, 88, p. A691-A704.

N85 13716

D7

MAGNETIC CONSTRAINTS ON EARLY LUNAR EVOLUTION REVISITED -- LIMITS ON ACCURACY IMPOSED BY METHODS OF PALEOINTENSITY MEASUREMENTS;

Subir K. Banerjee, University of Minnesota, Dept. Geology and Geophysics, Minneapolis, MN 55455. Present address: University of California, Dept. Geology and Geophysics, Berkeley, CA 94720.

Lunar internal magnetic field variation can provide a strong constraint for early lunar evolution. However, the magnetic carriers in lunar samples are most unusual, ultrafine grains (100-10,000 Å) of iron either free or in intimate contact with troilite (FeS). Thus it is impossible to carry out conventional paleointensity experiments requiring repeated heating and cooling to 770°C without chemical, physical or microstructural changes. Therefore, alternative, non-thermal methods of paleointensity determination have been sought, the two anhysteretic remanent magnetization (ARM) methods of Banerjee and Mellema (1) and Stephenson and Collinson (2), and the saturation isothermal remanent magnetization (IRMs) method of Cisowski et al. (3).

I have investigated the experimental errors inherent in these alternative approaches to estimate the accuracy limits on the calculated paleointensities. In the light of these built-in errors, a review of the up-to-date lunar paleointensity data yields the following conclusions: (1) It is most likely that lunar surface field was between 1,000 and 5,000 nT during its total history, (2) There is suggestive but not convincing evidence that the field was as high as 100,000 nT at 3.9 b.y. ago, (3) It is unlikely that the 3.9 b.y. high field epoch was preceded by a weak ($\leq$ 1,000 nT) field lasting between 4.0 and 3.9 b.y.

It should also be pointed out that recent discussions about the past polar wander of lunar spin axis assume a strictly axial dipolar magnetic field to have been present at the 4.0-3.9 b.y. period when it is simultaneously claimed that the lunar magnetic field was at its weakest strength ever ($\leq$ 1,000 nT). This may or may not be a contradiction in terms of dynamo field generation.

References

(1) Banerjee, S.K. and Mellema, J.P. (1974) Earth Planet. Sci. Lett., 23, p. 177.
(2) Stephenson, A. and Collinson, D.W. (1974) Earth Planet. Sci. Lett., 23, p. 220.
(3) Cisowski, S.M. et al. (1975) Proc. Lunar Sci. Conf. 6th, p. 3123.

D8

N85 13717

IMPLICATIONS OF LUNAR PALAEOMAGNETISM FOR THE ORIGIN OF THE MOON.

S.K.Runcorn, School of Physics, University of Newcastle upon Tyne, Newcastle upon Tyne NE1 7RU, England, UK.

Lunar palaeomagnetism raises three issues relating to the origin of the Moon: the early formation of a fluid iron core, the nature of primeval heat sources in the Moon and the existence of a primeval satellite system. The remanent magnetization of the Apollo samples was interpreted as evidence for an internally generated lunar magnetic field (1). The three independent methods of determining palaeointensities (the Thellier,ARM (2) and IRM methods (3)) are now in general agreement that the field was about 1 G 3.9 b yr ago declining exponentially to .02 G 3.2 b yr ago. Palaeomagnetic directions of crustal strata have been determined from the Apollo 15 and 16 subsatellite magnetometer observations by Coleman, Russell and Hood (4). The question whether these are randomly directed such as would be expected from local magnetization processes or are proof of the existence of an early core dynamo field is one of the key issues of lunar science. On the core dynamo hypothesis the mean magnetic field would have been a dipole along the axis of rotation: the north magnetic pole positions so calculated from the observational data can be grouped into 3 bipolar groupings along 3 axes different from the present lunar rotation axis (5). I argue that these groupings refer to different times: Pre-Nectarian 4.2 b yr, Lower Nectarian 4.0 b yr and Upper Nectarian-Lower Imbrian 3.9 b yr. The successive reorientations of the Moon with respect to its axis of rotation are the result of the creation of the multi-ring impact basins. As these basins lie close to palaeoequators of corresponding age, it is inferred that the bodies which impacted the Moon were in orbit about the Moon near its equator rather than asteroids (5). The use of the Bingham statistical distribution shows that this (6) association is highly significant. Because each group consists of between 6 and 10 multi-ring basins it is concluded that there were 3 large satellites, each of which broke up as they passed through the Roche limit at 10^8 year intervals as a consequence of tidal friction. In fact it is shown that the successive movements of the palaeomagnetic pole through 90° are required by Euler's principle of rotation of solid bodies. The direction of the incoming impacting bodies can be determined from the asymetry of the basins and the results (Wilhelms(7)) show directions roughly parallel to the palaeomagnetically determined equators of corresponding age. Some of this evidence can be interpreted as implying that the satellites were in retrograde orbit but in any case their existence around the Moon until 3.8 b yr ago sets a considerable constraint on the evolution of the early Earth-Moon system. The creation of the basins by bodies coming in at about 2 km/second in contrast to the former view that the bodies were asteroids or comets, requires them to be of substantial size so that a strong component of solar system material should be present in the lunar regolith. Although the presence of a lunar core was long ago suggested and there are now various different, although individually not conclusive arguments, the fit of the palaeomagnetic data tothe dipole hypothesis is strong evidence for the existence of a molten lunar iron core and implies a powerful heat source present in the earliest history of the Moon.

(1) Runcorn S K (1970) Proc.Apollo 11 Lunar Sci. Conf,p.2369-2387. (2) Stephenson A, Runcorn S K, & Collinson D W (1975) Proc.Lunar Sci.Conf.6th, p.3049-3062. (3) Cisowski S M, Collinson D W, Runcorn S K, Stephenson A & Fuller M. (1983) Proc.Lunar Planet.Sci.Conf.13th, in Journal of Geophysical Research,88, A691-A704. (4) Hood L L (1980) Proc.Lunar Planet.Sci.Conf.10th, p.1879-1896 & Proc.Lunar Planet.Sci.Conf.12B, p.817-830 (1981). (5) Runcorn S K (1983) Nature, 304, 589-596. (6) Runcorn S K (1984) Phil.Trans.R.Soc. (7) Wilhelms D E.Prof.Pap.

CHEMICAL AND PETROLOGICAL CONSTRAINTS

Monday, October 15, 1984
8:00 - 11:30 a.m.

N85 13718 D9

CONSTRAINTS ON THE ORIGIN OF THE MOON FROM MOLYBDENUM AND OTHER SIDEROPHILE ELEMENTS;

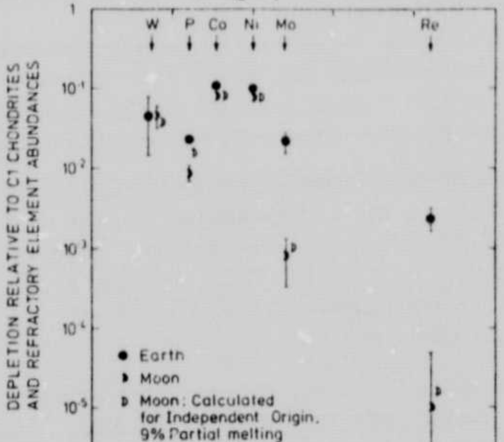
H.E.Newsom, Max-Planck-Institut für Chemie, Saarstrasse 23, D-6500 Mainz, F. R. Germany, and Institute of Meteoritics, University of New Mexico, Albuquerque, NM 87131, USA (present address).

New data on the concentration of molybdenum in the mantle of the Earth (1) and in lunar rocks confirm that most siderophile elements in lunar crustal rocks and lunar basalts derived from the interior have significantly lower concentrations than in the Earth's mantle and much lower concentrations compared to chondritic meteorites (Fig. 1). Our data confirm the low Mo concentrations reported by Taylor et al. (2). The Mo/Nd ratio in lunar samples (0.0016) is a factor of 30 lower than the Mo/Nd ratio in terrestrial samples (0.043, ref. 1), and a factor of 1,200 lower than in C1 chondrites (1.94). Different but correlated depletions of Co and P have been found in different lunar samples (3). The Mo data appear to be correlated with the P and Co depletions. The variations in siderophile contents seem to be real (3), not just due to experimental error, and may be explained by small variations in the segregation of metal, possibly on a global scale.

As discussed by Newsom (4) the siderophile element data are consistent with theories for either a terrestrial or an independent origin for the Moon. Wänke et al. (3) suggest that the Moon formed from the Earth's mantle (depleted in siderophile elements, e.g. ref. 5), and segregation of metal within the Moon further lowered the concentrations compared to the Earth's mantle. From the terrestrial siderophile element concentrations, the concentrations in the lunar samples can be reached by segregation of only 0.15% metal at 10% partial melting. For total melting of the silicates as much as 1% metal is required to achieve the observed W, P, Mo and Re lunar depletions.

For an independent origin of the Moon, segregation of a small metal core could explain the observed concentrations of siderophile elements in lunar rocks (4). Starting with chondritic concentrations and assuming a metal content of 5.5% at 9% partial melting of the silicates, the calculated depletions match the observed depletions. Metal contents less than 5.5.% can explain the depletions of W, Mo and Re if equilibrium occurred at smaller degrees of partial melting (6). For a 2% core about 1% partial melting is needed.

The Mo data support evidence from other siderophile elements that the Moon almost certainly contains a metal core or pools of segregated metal. A terrestrial origin is indicated if the core is less than 2 wt% because the siderophile element depletions could not be obtained by such a small core alone. An independent origin is likely, but not required, if the lunar core is greater than 2 wt%, because the siderophile element depletions could then be explained by purely lunar processes. Determining the actual size of the lunar core will be a key step in answering the riddle of the lunar origin.



Ref.: (1) Newsom and Palme (1984) Earth Planet. Sci. Lett. in press. (2) Taylor et al. (1971) Proc. 2nd Lunar Sci. Conf., 1083. (3) Wänke et al. (1983) in Lunar Planet. Sci. XIV, 818. (4) Newsom (1984) EOS 65, 369. (5) Ringwood and Kesson (1977) The Moon 16, 425. (6) Newsom and Drake (1982) Nature 297, 210.

D10

N85 13719

NICKEL-COBALT SYSTEMATICS AND THEIR BEARING ON LUNAR ORIGIN;

A.E. Ringwood and S. Seifert. Research School of Earth Sciences, Australian National University, Canberra, A.C.T. 2601 Australia.

The earliest metal phases to crystallise from the least-fractionated low-Ti mare basalts contain about 30% Ni and 2 to 7% of Co. Experimental investigations of partitioning of Ni and Co between primitive lunar basaltic magmas and metal phases are currently in progress (1). Preliminary results show that the metal phase crystallizing near the liquidus of Green Glass (185 ppm Ni, 70 ppm Co) would contain about 40% Ni and 2.3% Co. It seems, therefore, that if a lunar core does exist, as suggested by the results of (2), it is relatively rich in Ni (30-40%) and Co (2-7%). This composition presents a remarkable contrast to that of the earth's core which is estimated to contain about 6% Ni and 0.3% Co.

One explanation for the differing densities of earth and moon is that both bodies accreted independently in the same neighbourhood of the solar nebula from a common mixture of metal and silicate particles. Enrichment of metallic phase in the earth is attributed to a physical fractionation process. Hypotheses in the category (eg. disintegrative capture,Fe silicate fractionation based on magnetic properties or on differential ductility of metal and silicates) fail to explain the very different chemical compositions of terrestrial and lunar cores and can therefore be rejected.

Another class of hypotheses maintains that the moon accreted independently in the solar nebula and was produced from a mixture of high temperature, intermediate temperature and low temperature condensates together with condensed metal phase. These batches were fractionated by unspecified mechanisms and assembled in desired proportions to form the moon. These hypotheses are subject to certain cosmochemical constraints: (a) metal phases condensing in the nebula do not contain more than 13% Ni and 0.7% Co (3). (b) they imply a particular relationship between the Ni content of the metal and the $MgO/(MgO+FeO^*)$ ratios of coexisting silicates (manifested in chondrites as Prior's Second Law). Thus a metal core containing 30-40% Ni implies a lunar mantle with $MgO/(MgO+FeO^*)$ molar of about 0.5. This is far beyond the limits permitted by the moon's physical properties; (c) known cosmochemical processes are ineffective in fractionating cobalt from nickel; hence the bulk lunar Ni/Co ratio is probably close to the primordial ratio of 21. The abundance of cobalt in Low-Ti basalt is almost identical to that in terrestrial oceanic tholeiite and it seems likely that this similarity extends to their respective source regions. Acceptable lunar models consistent with observed Ni-Co metal/silicate distribution coefficients and also possessing a bulk chondritic Ni/Co ratio appear to require even higher concentrations of Ni in the lunar mantle (>1500 ppm) and in the lunar core (>40% Ni) than are indicated by the Green Glass equilibria.

These conditions are very difficult, if not impossible to satisfy in terms of existing models by which the moon was formed as an independent "planet" in the solar nebula. They are readily explained if the moon was formed from material possessing similar Ni and Co abundances to the earth's mantle and subsequently differentiated a very small (< 0.5% by mass) Ni-rich core as suggested independently by Wänke, Ringwood and Newsom.

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N85 13720 D11

ABUNDANCES OF Ni,Cr, Co, AND MAJOR ELEMENTS IN THE SILICATE PORTION OF THE MOON: CONSTRAINTS FROM PRIMARY LUNAR MAGMAS.

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The lunar volcanic glasses are samples of primary magmas derived by partial melting of the Moon's mantle. The twenty-seven varieties of glass define three linear arrays having nearly constant Mg/Si ratios. The low-Ti magmas in each array approach the chondritic Ti/Al ratio. In addition, the Ca/Al ratio in these low-Ti magmas trends toward the chondritic value as one proceeds from array I through array III. Using the chemistries of these primary magmas, as well as the assumption that the Moon possesses chondritic Ca/Al/Ti/Mg ratios, the silicate composition of the Moon has been estimated (Table). The results have the following implications:

(A) In agreement with [e.g. 1-4], the silicate portion of the Moon is enriched in FeO by a factor of ~ 2 compared to the Earth's upper mantle at present.

(B) In agreement with [e.g. 2,3,5,6], the Moon is not strongly enriched in the refractory lithophile elements relative to either chondrites or the Earth's upper mantle.

(C) The Mg/Si ratio of the Moon lies outside the range exhibited by chondritic meteorites but is similar to that within the Earth's upper mantle.

(D) According to the Co vs. (FeO + MgO) systematics [2] in lunar volcanic glasses, the Co/Mg ratio in the silicate portion of the Moon is identical to that in the Earth's upper mantle at present (~ 8x less than chondritic value).

(E) The abundance of Ni (as NiO) in the Moon's silicate-portion is ~ 250 ppm. This is a factor of 8 less than in the Earth's upper mantle at present and 60x less than in H-group chondrites. In agreement with [7,8], this abundance of Ni requires the presence of a metallic core within the Moon. The distinctly non-chondritic Fe/Ni ratio (i.e. 650 vs. chondritic value of 18) suggests that the Moon's metallic core is Ni-rich. This fact, in combination with the high FeO-abundance in the lunar silicate (Table), may present formidable obstacles for the in situ depletions of P and W required by the 'binary planet' hypothesis [e.g. 9]. For a 'modified Earth-fission' hypothesis [2] to be consistent, the mantles of the Earth and Moon must have segregated FeO-rich [10] and Ni-rich cores, respectively, subsequent to the fission event.

SILICATE PORTION OF THE MOON

SiO_2	41.3 - 42.7 wt.%	FeO	16.3 - 16.7	Ni	250 ppm
TiO_2	0.18 - 0.19	MnO	0.23	Co	90 ppm
Al_2O_3	3.50 - 3.65	MgO	33.6 - 35.0		
Cr_2O_3	0.33 - 0.43	CaO	2.80 - 2.91		

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GE ABUNDANCES IN THE LUNAR MANTLE AND IMPLICATIONS FOR THE ORIGIN OF THE MOON

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Regardless of the origin of the moon, metal segregation must have occurred within the moon in order to account for its low siderophile element abundances relative to the earth or chondrites (1) Evidence of variability of siderophile elements in the moon may provide additional clues on the origin of the moon Germanium is a strongly siderophile element whose bulk distribution coefficient indicates that it is not fractionated during igneous processes on the moon Thus, variability in absolute Ge abundances in mare basalts and pristine highland rocks, rather than elemental ratios, can be used to infer lunar mantle abundances and processes We have compiled literature data for Ge abundances in mare basalts and pristine highland rocks (Fig 1) For some landing sites, samples with > 12 ppb Ge were considered to be extreme outliers and are not included The Apollo 15 samples are enriched in Ge by a factor of 2.5 over the Apollo 12, 16, and 17 samples Other siderophile element variations have been found in the moon For example, variations in the (P/Nd) and (Co/MgO+FeO) ratios from landing site to landing site have been found (2) Based on the data in Fig 1, our best estimate of the average Ge abundance in the silicate portion of the moon is 3.52 ppb The moon is depleted, relative to chondritic abundances, by a factor of 38,000 normalised to Si Two possible explanations for the observed variations in Ge abundance in the moon are (a) more metal may have segregated from some regions of the moon than from others, or (b) Ge-bearing material may have been added later in the evolution of the moon The Ge concentrations in Apollo 12, 16, and 17 materials could be produced from the Ge concentrations in Apollo 15 materials by 0.09% metal segregation, assuming D(Ge) of 1283 (3) Palme (4) suggested that the target material at the Apollo 16 and 17 landing sites had different indigenous Ni and Co abundances, and concluded that the Apollo 17 material could be produced by segregation of 0.03% metal from the Apollo 16 material The segregation of this metal should cause the Apollo 17 material to be depleted in Ge by a factor of 3 compared to the Apollo 16 material However, the Ge abundances of the Apollo 16 and 17 samples are roughly the same The material added later in the evolution of the moon could be infalling meteoritic material, remelting of cumulate layers, or pieces of a cold primordial core which has been displaced into the mantle For example, plagioclase grains in norite 78235 are enriched in both incompatible elements (Ba and Yb) and siderophile elements (Co and Cr) over plagioclase in anorthosite 15415 (4) Palme et al (5) explain these conflicting data by assuming a mixture of a highly evolved KREEP liquid with a component enriched in Mg, Cr and siderophile elements such as Ni and Co Herbert (6) has shown that relaxation of an inverted density distribution in the mantle, caused by fractional crystallisation of olivine and pyroxene from the magma ocean, could displace upward a cold primordial core Also segregation of metal during core formation would displace such a core Based on Ge abundances, the Apollo 15 material could be produced from the Apollo 12, 16, and 17 materials by addition of 0.31% of material of terrestrial mantle composition, or 0.01% of material of C1 composition Since terrestrial mantle and chondritic material have different siderophile element signatures, it may be possible to distinguish among these alternatives for the material out of which the moon formed The available Ge data confirm some of the previously suggested element variations in lunar samples The siderophile element signature of a primordial silicate core could provide an additional clue to the origin of the moon

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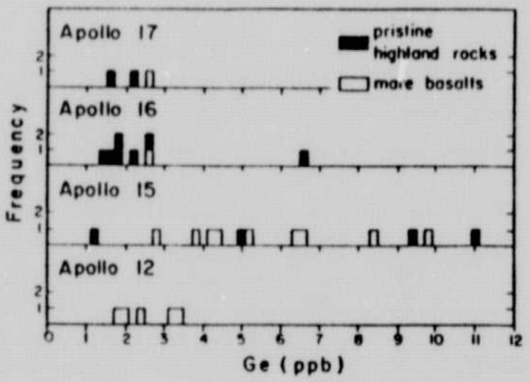

N85 13722 D/3

Is Phosphorus Predictably Incompatible in Igneous Processes?

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Siderophile element abundances have been central to recent models for core formation in the Earth and Moon and the origin of the Moon (e.g. 1,2,3). It is important to identify siderophile elements whose behavior in igneous processes is predictable, so that primary mantle abundances can be deduced by subtracting out the effects of igneous processes (2). W, Mo, and P appear to be well correlated with La or Nd in terrestrial and lunar samples, and therefore to have behaved as lithophile incompatibles during igneous processes (1,2,3). The model of (4) for core formation in the Moon is consistent with initially chondritic abundances of W and Mo, but requires subchondritic P, and suggests that P was depleted due to volatility. Data compiled by (1) suggests that P and La are correlated for lunar samples. However, it is possible that the correlation they observe is partly due to mixing of a primitive and a KREEP component, rather than incompatibility.

Rare occurrences of P-rich silicates suggest that P is not always incompatible. Phosphoran olivine (with up to 4% P_2O_5) occurs in pallasites (5,6), where it might have formed by reaction between P-bearing metal and olivine (7). Olivine grains containing up to 0.7% P_2O_5 have recently been found in fine-grained mm-sized objects in type 3 ordinary chondrites (8), which suggests that P-bearing silicates might have been present in early solar system materials. Phosphoran olivine and pyroxene occur in silicate inclusions within iron-carbon alloy from Disko Island (9). These minerals contain up to 2.7 wt.% P_2O_5 and show P silicate crystal/liquid distribution coefficients (D_P) on the order of 0.5-1.0. Low fO_2, rapid cooling, or high bulk P_2O_5 coupled with low SiO_2 content might have led to P compatibility in the Disko rocks, and low fO_2 might also have been an important factor in the case of pallasites. If low fO_2 leads to P compatibility, then P-rich silicates might have formed during core formation, and hidden reservoirs of P-rich silicates might exist. The apparent depletion of P in the Moon observed by (4) could be due to the existence of such hidden reservoirs.

We have begun an experimental study to determine P olivine/liquid distribution coefficients. Preliminary experiments were conducted at fO_2=FMQ, with the following starting composition: SiO_2 28.43, TiO_2 6.83, Al_2O_3 6.62, FeO 33.53, MnO 0.39, MgO 10.26, CaO 9.14, Na_2O 0.27, K_2O 0.02, P_2O_5 4.45. In isothermal runs (held for 24 and 27 hours at 1250 and 1206°C) average D_P was slightly high (0.03-0.07). However, in a run held 49 hours at 1081°C the average D_P was less than 0.003, which indicates that the equilibrium tendency is toward very low D_P. A series of experiments at cooling rates ranging from 20 - 400°C/hr gave the following results. (1) D_P increases with cooling rate. D_P as high as 0.43 was observed for crystals formed during quenching from 1198°C to room temperature. (2) Isothermal annealing at temperatures ranging from 1038-1180°C led to loss of P from olivine. P gradients (P_2O_5 contents ranging from 0.2-1.3 wt.% over a distance of 0.1 mm) were observed in crystals homogeneous in Fo. (3) The effect of annealing is temperature dependent, reflecting the dependence of diffusion rate on temperature. Experiments with lower P_2O_5 contents and at lower fO_2 are planned. We have also measured P_2O_5 contents of late pyroxenes in several Apollo 11 basalts, which crystallized at fO_2=IW or lower. Some pyroxenes that grew in interstitial immiscible liquids rich in FeO and P_2O_5 show high D_P. However, FeO-rich outer zones of large pyroxene crystals have very low P_2O_5 contents. This indicates that low fO_2 is not sufficient to cause high D_P. The crystals that grew in the immiscible liquids might have grown very rapidly in closed systems.

Our preliminary results indicate that P can be compatible with olivine during rapid cooling, but is not during isothermal crystallization with long growth times, and tends to be expelled during annealing. It is therefore not likely that P is compatible under any widespread igneous conditions, and the incompatible behavior of P in lunar crustal rocks can be safely assumed. In addition, low fO_2 is insufficient to cause P compatibility, so it is unlikely that P-rich silicates formed during the early evolution of the Earth or Moon. These results indicate that P is depleted in the Moon as suggested by (4). Our conclusions may not apply to phosphoran olivine in pallasites or ordinary chondrites, because these minerals might not have formed by igneous processes.

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D14

N85 13723

MEGAREGOLITH THICKNESS, HEAT FLOW, AND THE BULK COMPOSITION OF THE MOON

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The Moon's bulk composition is a major constraint on its origin. Bulk density alone shows that the Moon is depleted in metallic FeNi relative to the Earth or to chondrites of comparable MgO/FeO (e.g., H chondrites). Depletions of minor-trace volatile elements are also obvious from geochemical data. The simplest assumption would be that in terms of nonsiderophile, nonvolatile elements the Moon is not much different from the silicate portions of the Earth or chondrites. But heat flow data [1] have been interpreted to imply that the Moon's U content is about 46 ng/g, i.e., about 2x that inferred to be in the Earth's mantle, and 3x that of H chondrite silicates. It is difficult to envisage a nebular process that would fractionate refractory lithophiles like U from major lithophiles like Si. Thus, a disparity in U/Si implies a disparity in provenance of parental materials, i.e., origin. However, previous studies have suggested that (a) the two sites where lunar heat flow was measured are unrepresentative, because their megaregolith layers are unusually thin [2]; and (b) heat flow is about 1.4x greater than steady-state models imply, mainly because roughly half of the Moon's mass is convection-free (conductively cooled) lithosphere [3; also implicit in 2].

Our models further assess effects of megaregolith on lunar thermal evolution. We confirm that the two measured sites are probably unrepresentative, with heat flows about 25% higher than regional averages, due to focussing of heat flow towards regions with thin megaregolith. These effects are much smaller than originally suggested [2], because we make more realistic assumptions about lateral differences in megaregolith thickness, and about the difference in thermal conductivity of megaregolith vs. bedrock. Numerous lines of evidence indicate that the megaregolith is generally 2-3 km thick under highlands (which cover about 83% of the total lunar surface), and <1 km thick under maria. In most of our models, megaregolith thickness is assumed to be roughly 6x greater over highlands than over maria. In previous models [2] this ratio ranged from 10 to 1000. Based on sparse data for porosity among lunar rock types, and the correlation between thermal conductivity and porosity [1], we assume that megaregolith conductivity is roughly 20 kiloerg s^{-1} cm^{-1} K^{-1}, and bedrock conductivity is roughly 7x greater. In previous models [2] the ratio of these parameters ranged from 10 to 1000. We also find that insulation by megaregolith exacerbates the problem [4] of reconciling modest temperatures inferred for the (present) mantle with a high rate of heat production; an upper limit of 30 ng/g for the bulk-Moon U content can be derived from this constraint alone.

One of the two sites (Ap 15) is probably further unrepresentative because it is in an exceptionally U-rich region of the Moon. It is probably not mere coincidence that measured heat flow is 50% greater for the Ap 15 site than for the Ap 17 site [1]. Correcting the Ap 17 measurement for the effect (+25%) of locally thin megaregolith, our estimate for present global mean heat flow (Q) is 11 erg s^{-1} cm^{-2}, which is only 0.6x as great as previously estimated [1]. If present heat production is 0.7x present heat flow [2, 3], a Q of 11 erg s^{-1} cm^{-2} implies a bulk-Moon U content of 20 ng/g, only 0.43x that previously suggested [1]. This estimate is equally consistent with derivation of the Moon by depletions of FeNi and volatiles from the Earth, or from chondritic silicates. The Moon's bulk composition is less exotic than generally assumed.

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N85 13724 D15

THE BULK-MOON MGO/FEO RATIO: A HIGHLANDS PERSPECTIVE

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The main observational constraints on the origin of the Moon involve its orbital parameters, its thermal history, and its bulk composition. The first two of these are now known to excellent and fair precision, respectively. The bulk composition is still a matter for enlightened speculation, but some aspects can be constrained well enough to have genetic significance. The ratio MgO/FeO, more commonly expressed as mg (= molar MgO/(MgO+FeO)), evolves during igneous fractionation in ways that are well understood. The simple fact of the Moon's proximity to the Earth suggests similar provenance of parental materials. However, bulk density alone shows that the Moon is depleted in metallic FeNi relative to the Earth. Depletions of minor-trace volatile elements are also obvious from geochemical data. The simplest assumption would be that in terms of nonsiderophile, nonvolatile species such as MgO and FeO the Moon is compositionally similar to the silicate portion of the Earth. The mg ratio of the Earth's upper mantle is about 0.896, and clearly >0.86. But most estimates of the mg ratio of the bulk Moon are <0.82, implying that the Moon and the Earth come from fundamentally different batches of material.

Compositional data for nonmare (highlands) samples suggest that the Moon's mg ratio is higher than generally estimated. Geochemically representative highlands soils have mg ratios of 0.66 (Apollo 16), 0.69 (Luna 20) and 0.73 (ALHA81005). These soils are mixtures of unrelated pristine nonmare rocks, of which there are at least three groups: Mg-rich rocks, ferroan anorthosites, and KREEP. Other than Mg-rich rocks, virtually all pristine rocks have mg <0.65. Thus, assuming the mixing process that sampled Mg-rich materials was random, the average mg of Mg-rich parent magmas was probably at least 0.70. More direct evidence can be derived from the Mg-rich rocks themselves. Nine of them (about 1/4 of the total) have bulk-rock mg >0.87. Two (15445 "A" and 67435 "PST") contain Fo_{92} olivine. Production of melts that crystallized Fo_{92} olivine implies that the mg ratios of source regions in lunar mantle were commensurably high.

Assuming that the parent melts formed by equilibrium ("batch") partial melting, this constraint can be quantified as:

$$mg(\text{system}) = (f \cdot mg_l + (1-f) \cdot mg_x \cdot A)/(f + (1-f) \cdot A)$$

where the subscripts are l = liquid and x = crystals; f = the degree of partial melting; and $A = X_x^{Mg+Fe}/X_l^{Mg+Fe}$. For any given value of K (defined as $[Fe/Mg]_x/[Fe/Mg]_l$), mg_l and mg_x are interdependent. Literature data indicate that K for olivine is in the range 0.26-0.36, and K for low-Ca pyroxene is close to 0.30. A is probably never <<2; an extreme lower limit would be 1. During partial melting, as f increases beyond a certain threshold, the crystalline framework of the rock breaks down, and the buoyant melt tends to rapidly separate from the residual crystals. This critical f is probably <0.4, and almost certainly <0.5; 0.6 would be an extreme upper limit. Plugging these sorts of values into the above equation, it can be shown that source regions of melts parental to Fo_{92} olivines must have mg >0.84, and much more realistically >0.86. For example, assume K = 0.3, f = 0.5, and A = 2. Then mg_x (the olivine Fo content) = 0.92 implies mg_l = 0.78, and mg(system) = 0.875. If K = 0.3, f = 0.5, but A = 1, mg(system) still = 0.851; if K = 0.3, A = 2, but f = 0.6, mg(system) still = 0.861. The constraint cannot be eased much by invoking a different K, either.

Assume for the sake of argument that the Fo_{92} olivines are flukes. Widespread Mg-rich melts evidently had mg_l >0.70. If during their genesis K = 0.3, f = 0.4, and A = 2, the system mg must have been at least 0.839. The Moon's bulk composition is less exotic than generally assumed.

D16

N85 13725

BULK COMPOSITION OF THE MOON IN THE CONTEXT OF MODELS FOR CONDENSATION IN THE SOLAR NEBULA; Kenneth A. Goettel, Dept. of Geological Sciences, Brown University, Providence, Rhode Island 02912

The compositions of the terrestrial planets may be governed in part by variation with heliocentric distance of the composition of condensates in the solar nebula, with due account taken of the effects of mixing and possible addition of volatile-rich material. Equilibrium condensation in the nebula produces material at two temperatures with a density equal to that of the moon: high-temperature, refractory-rich material or low-temperature, fully-oxidized material. Either composition is grossly discordant with lunar geochemical data, although extensive devolatilization of the latter composition could perhaps result in an viable composition. Furthermore, to account for the composition differences between Earth and moon, nebular condensation models for the moon presumably require formation of the moon remote from the Earth, with subsequent capture. Capture models for the origin of the moon appear implausible because of dynamic difficulties and particularly because of the oxygen isotope systematics that suggest formation of the moon was intimately associated with formation of the Earth. Therefore, double-planet (formation in geocentric orbit) or fission models for lunar origin appear more plausible. Recent siderophile trace-element data (1) suggest that either of these two models may be viable if segregation of a small metal core occured within the moon. The focus of the present paper is not to argue for either of these models, but rather to address an implication that is common to both.

The FeO content of the moon, about 13%, is substantially higher than the present FeO content of the Earth's mantle, about 8%. If the moon formed by fission from the Earth's mantle, then the conclusion that the Earth's mantle must have been much richer in FeO at the time of fission appears firm; there do not appear to be viable mechanisms to fractionate FeO so markedly during fission or to add FeO to the moon after fission and not add FeO to the Earth as well. If the moon formed independently in geocentric orbit, then the FeO contents of the two bodies should be similar, because both would be accreting from the same source of silicate material and it is very difficult to envision a process that would so markedly fractionate FeO between Earth and Moon. Therefore, Earth's mantle at the time of lunar formation probably had an FeO content quite similar to the present FeO content of the moon. This conclusion, if valid, has profound implications in two areas: 1) the differentiation history of the Earth's mantle and core, and 2) the processes responsible for governing the bulk compositions of the terrestrial planets. Reduction of the FeO content of the mantle requires growth of the core either by addition of FeO or by addition of Fe from disproportionation of FeO. If the Earth initially contained more FeO then Earth should also have higher abundances of other volatiles; this conclusion applies whether the FeO was produced by reaction of H_2O with Fe in the nebula or produced in the Earth by addition of volatile-rich material to metal-bearing material. If Earth had more FeO than previously thought, then the composition differences between Earth and Mars are less than previously believed. This suggests that condensation temperature and heliocentric distance may have been less important in governing planetary compositions and other mechanisms, including iron/silicate fractionation may have been more important. The implications of this model for the compositions of the moon and the other terrestrial planets will be discussed.

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N85 13726 D17

PETROLOGIC CONSTRAINTS ON THE ORIGIN OF THE MOON: EVIDENCE FROM APOLLO 14.

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All the theories for the origin of the Moon ultimately must be able to explain the diversity of lunar rock types and their distribution across the lunar surface. The diversity and distribution of these rocks that are fundamental characteristics reflecting the processes involved in lunar origin, including accretionary mechanisms, primordial differentiation, and subsequent melting events.

The Fra Mauro breccias at Apollo 14 contain distinctive suites of mare basalts and highland crustal rocks that contrast significantly with equivalent rocks from other Apollo sites. These contrasts, which are outlined below, imply lateral heterogeneity of the lunar crust and mantle on a regional scale. This heterogeneity may date back to the earliest stages of lunar accretion and differentiation.

Highlands Highland crust at the Apollo 14 site is represented by clasts of magnesian troctolite and anorthosite (Ol >Fo75; Plg >An92; ± En, Di, Sp), alkali anorthosites (Plg <An87; ± Pig, Aug), ilmenite gabbro/norite (Plg = An84; ± Aug, Pig, Ilm) and granite (Qtz, Kspar, Plg, ternary Feldspar). These rocks are unusually rich in alkalis and the incompatable elements. Similar rock-types and compositions occur at the nearby Apollo 12 site, but not at the other, more distant Apollo locations. Ferroan anorthosite and magnesian norite are both rare in the Apollo 14 highland crust, in contrast to Apollo 16, the archtypical highland site.

Mare Basalts Ten (10) compositionally distinct varieties of mare basalt have been documented at the Apollo 14 site. Seven of these are low-Ti, high-Al mare basalts; others include low-Al basalts similar to those from Apollo 12, and high-Al, very low-Ti (VLT) glass spheres. High-Ti basalts are not found. The low-Ti basalts are all enriched in alkalis relative to other low-Ti basalts and have compatible trace element (Co, Ni, Sc, V, Cr) abundances intermediate to normal low-Ti basalts and high-Ti basalts. Incompatible elements vary widely, e.g., La varies from 8x to 100x chondrite. These and other trace element abundances and ratios (e.g., La/Lu, Lu/Hf, Ti/Sm, Sc/Sm) span the range observed between VLT, low-Ti, and high-Ti mare basalts from other Apollo and Luna sites. These data suggest an interfingering of low-Ti and high-Ti basalt source regions, or alternatively, that these distinct source regions never developed in the lunar mantle beneath Apollo 14. They also suggest, like the crustal data, that the mantle under this part of the moon is enriched in alkalis.

Discussion Current theories requiring a moon-wide crust of Ferroan Anorthosite are based largely on samples from Apollo 16, where all but a few samples represent the FAN suite. However, at the nearside sites, FAN is either scarce (A-15) or virtually absent (A-12, A-14, A-17). These sites are dominated by troctolites and norites of the Mg-suite and, to lesser extent, alkali anorthosites (A-12, 14 only). Two possibilities exist: 1) a thick crust of FAN never formed on the western lunar nearside. Instead, a thin protocrust may have been succeeded directly by later intrusive suites; or 2) large basin-forming impacts such as Procellarum could have removed much of whatever FAN crust did exist.

The younger intrusive suites demand a variety of origins, including the assimilation of KREEP and the diapiric rise and remelting of early, Mg-rich cumulates. However, none of the processes discussed above accounts for the LIL-enriched nature of the western lunar nearside. This enrichment is evidenced by: 1) orbital gamma-ray data showing high K, U, and Th in this region; 2) the common occurrence of enriched rock types such as alkali anorthosite and granite at Apollo 12 and 14; 3) the 'enriched' character of "western" Mg-suite rocks noted by Warren et al. (1983); 4) the abundance of KREEP in soils and breccias; and 5) the 'enriched' character of Apollo 14 aluminous mare basalts. Wasson and Warren (1980) have addressed asymetrical fractionation in the magma ocean as a possible explanation.

We suggest another possibility: the accretion of a large mass of material (e.g., 0.1-0.2 moon masses) late in the crystallization history of the magma ocean. Besides adding fresh, primordial material, this would remelt a large pocket of crust and mantle, thereby allowing a second distillation to occur in the resulting "magma sea". This late accretion of large bodies of primary composition would have contributed significantly to large-scale heterogeneity in the lunar crust and mantle. As emphasized by Palme et al. (1984), the chemistry of the highlands crust virtually requires a large meteorite component. Therefore, it would appear that meteorites may have played a much bigger part in crustal evolution than simply metamorphosing the rocks and creating the lunar landscape. The large variety of rocks with no apparent common parentage demands an unusual set of circumstances - i.e., different processes, not just variations on a theme.

D/8 N85 13727

ORIGIN OF THE MOON: CONSTRAINTS FROM VOLATILE ELEMENTS*. Melanie E. Kreutzberger**, Michael J. Drake, John H. Jones, Lunar and Planetary Laboratory, University of Arizona, Tucson, AZ 85721. **Present address: University of Michigan.

Fission of the Moon from the Earth following core formation is a hypothesis for the origin of the Moon (Ringwood, 1979). Supporting arguments include the low density of the Moon corresponding to the density of the Earth's mantle and the low volatile content of the lunar rocks vs. those of terrestrial origin. Vapor pressures of the alkali elements and their oxides increase in the following order: Na, K, Rb and Cs. The Moon should, therefore, be more depleted in Cs relative to Rb, Rb relative to K, and K relative to Na than the Earth if the fission model is correct. Analyses of lunar mare basalts and terrestrial mid-ocean ridge and other young basalts indicate that this behavior is not observed; for example, the Moon shows a higher Cs/Rb ratio than the Earth--i.e., it lies between chondrites and the Earth.

It is possible that monovalent alkali elements might be lost from silicate materials in a different order than that inferred from elemental and oxide vapor pressures, as a result of differences in the way they are bound in silicate materials. To test this hypothesis we conducted a series of experiments to investigate alkali loss at high temperatures. A synthetic basalt of composition $Di_{75}An_{25}$ containing approximately one wt.% each of Na, K, Rb, and Cs was prepared. The mixture was ground under acetone, fused twice at 1400°C, and quenched to form a homogeneous glass. The glass was used as our starting material. Experiments were conducted using the wire loop technique at 1 atmosphere and 1400°C and 1050°C in air, allowing volatile loss as a function of time to be determined. The resulting glass beads were then analyzed using the scanning electron microprobe.

Analyses indicate that the behavior of volatiles dissolved in a silicate melt is similar to that inferred from elemental and oxide vapor pressures. At 1400°C (superliquidus), Cs is most readily volatilized, followed by Rb, K, and Na (see figure). The mass of the glass beads is not a major factor in the rate of volatile loss. At 1050°C, no significant loss of volatiles was detected after 1 week.

These results are consistent with previous experiments by Gibson and Hubbard (1972) on 12022. We conclude that alkali element ratios in the Earth and Moon are not readily interpreted in terms of the Fission hypothesis.

*Research conducted in conjunction with the Tucson Lunar Origin Consortium.

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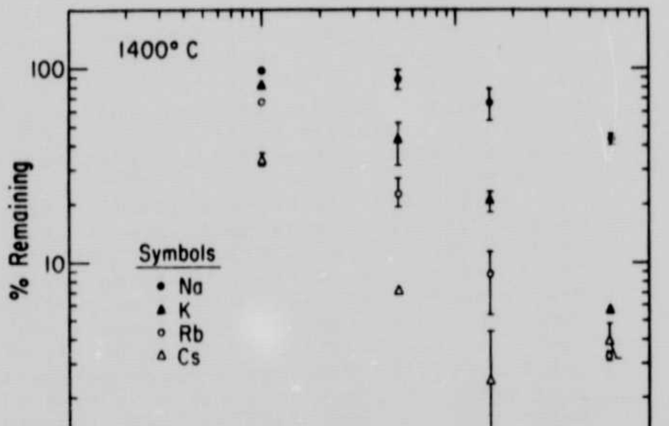

D19

N85 13728

VOLATILE ELEMENTS IN AND ON LUNAR VOLCANIC GLASSES: WHAT DO THEY TELL US ABOUT LUNAR GENESIS ?

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Lunar volcanic glasses exist in many different varieties (1,2) (at the moment about 23 have been identified), and there are good reasons to believe that they have originated from a deep lunar interior source, giving the opportunity to probe the composition of these regions. One of the most important observations, namely the presence of surface correlated elements (e.g. 3-7), has caused some interest because of the implications on the chemistry of the deep lunar interior.Most of these elements (like F,Na,S,Cl,Cu,Zn, Ga,Ge,Br,Cd,In,Sb,I,Tl,Pb) are clearly volatile. Since the lunar interior has been thought to be depleted in volatile elements when compared to the earth (8), the detection of a possible source of volatiles is of importance. Models of the origin of the moon have been developed,based on the assumption that the moon is depleted in volatiles. Although this seems to pose some problems to the fission theory (deriving the moon from the earth's mantle). a fission model involving devolatilization has been discussed (9). Recently the surface correlated elements have been interpreted to indicate that the moon has some reservoirs that are enriched in volatiles, and that the deep lunar interior is not depleted in volatile elements.Delano and Livi (1) suggest three different scenarios for the origin of these elements:early differentiates from a magma ocean, a deep undifferentiated source (heterogenous accretion of the moon?), or cosmic xenoliths with random distribution in the lunar interior. Of course, a lunar interior which is not depleted in volatiles has important implications on the origin of the moon.So it would be of interest to know something about the amount of volatiles present in the lunar interior. Since most of these elements are abundant only in the form of very thin surface layers on the glasses, and since the glasses themselves do not show a similar enrichment,the source should be of rather limited extent. Also the driving mechanism of lunar volcanoes must have been quite different from the terrestrial mechanism, making the lunar eruptions rather 'bubbling' than really 'explosive fountaining'. This is implied also by the absence of large bubbles including volatiles (and the driving gas, like on earth). The total absence of water on the moon (in all samples, including volcanic glasses) precludes the presence of water also very probably in the lunar interior. However, water is a very vigorous driving gas for volcanoes on earth.None of the other volatile compounds which may have formed (10),is equally capable of launching melts with great energies.The rather limited amounts of these compounds (halides etc.) have condensed fast on the quenched glasses. From the condensation behaviour of the volatile compounds (10),which leads to heterogenous condensation,we may conclude that comparing element ratios of surface correlated elements gives little sense.Thus it seems as if the "volatile reservoirs" are of rather limited extent,and that they do not enlarge the volatile content of the bulk moon significantly.

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D20 N85 13729

THE I-PU-XE AGE OF THE MOON.

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Rb-Sr analyses of some lunar samples indicate that the Moon is close to the age of primitive meteorites [1], but are only reliable to within about 100 m.y. A potentially more precise chronometer is the I-Pu-Xe system. ^{129}I has a 17 m.y. halflife and decays to ^{129}Xe; ^{244}Pu, with an 82 m.y. halflife, produces ^{131}Xe-^{136}Xe in fission. The ^{129}I/^{244}Pu ratio has a halflife of 21 m.y.

The experimental observations: Gas-rich lunar highland breccias contain xenon that is surface-correlated and has an isotopic composition matching that of ^{244}Pu fission, with variable contributions from ^{129}I [2, 3]. The exact method of incorporation of this surficial component is not known, but the gas probably comes from degassing of the bulk Moon (rather than some smaller reservoir), since the presence of this component is a global lunar phenomenon [2]. The ^{129}Xe/^{136}Xe ratio of the gas incorporated into a given sample seems to be time-ordered. This is proportional to the relative rates of decay of ^{129}I and ^{244}Pu if production, release and re-incorporation are closely coupled [3]. From this, we can calculate the ^{129}I/^{244}Pu ratio at the time of incorporation, which, in principle, allows us to calculate the time of incorporation onto the host surfaces. The ratios ^{129}I/^{127}I and ^{244}Pu/^{238}U at the time of formation of primitive meteorites are fairly well known [4]. The I/U ratio of the Moon, however, is poorly constrained, since iodine is difficult to measure, making this the most uncertain part of the procedure. S. R. Taylor estimates the present-day I/U of the Moon to be .01 or less (personal communication). Using this value, we get a xenon incorporation time of about 45 m.y. after xenon closure in the most primitive meteorites. If we assume an uncertainty of a factor of two in the lunar I/U ratio, the corresponding uncertainty in the age of the host grain surfaces is about 20 m.y.

The implications: Various authors have calculated the xenon retention time for the Earth to be 50-100 m.y. (after primitive meteorites) on the basis of the isotopic composition of the Earth's atmosphere [5] or of certain mantle samples [6]. The formation time we have computed for the Moon is near the older edge of this range. These calculations are consistent with xenon retention for the Moon beginning anywhere from several times 10^7 years before it began on Earth to about 10^7 years after.

How do these conclusions constrain models for the Moon's origin? The model that has the most rigorous chronological constraints is the earth-fission model (and its variants). Xenon retention for the Earth could have begun as late as the event that gave birth to the Moon. For the Moon, it is hard to imagine that xenon retention could have begun before re-accretion of the fissioned (and initially dispersed?) material, particularly if that material got hot enough to account for the depletion of the volatile elements [7]. Thus, if fission models are correct, xenon retention in the Earth certainly began no later than in the Moon, and possibly began earlier. Therefore, the I-Pu-Xe system is only marginally consistent with a fission origin. If further study confirms that the I/U ratio of the Moon is .01 or less, or if gas-rich lunar highland breccias with higher ratios of ^{129}I to ^{244}Pu are found, it would be difficult to explain the results in an earth-fission model of lunar origin.

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TESTS OF THE LUNAR FISSION HYPOTHESIS; S.R. Taylor, R.S.E.S. Australian National University, Canberra.

The progress of science depends on the construction of testable hypotheses. Following the Apollo sample return, the concept that the moon was fissioned from the Earth after core separation has become the most readily testable hypothesis of lunar origin, since direct comparisons of lunar and terrestrial compositions can be made. The following differences, in order of decreasing certainty, have been established:

(a) The moon is depleted in volatile elements relative to the Earth, which in turn is depleted relative to primitive solar nebula abundances. Depletion factors range from 2-4 for Rb/Sr and K/U to over 50 for the most volatile elements (e.g. Bi, Tl)[1].

(b) The FeO content[2] of the bulk moon (13%) is higher than that of the terrestrial mantle (8%) making the bulk lunar Mg/Mg+Fe atomic ratio = 0.81. When ≈2% Fe is removed by a lunar core the Mg/Mg+Fe value of the lunar mantle (0.84) is still lower than that of the terrestrial primitive mantle plus crust value of 0.89.

(c) The silicate portion of the moon is depleted in siderophile elements relative both to the Earth and to solar nebula abundances[3]. The presence of a small core (≈2% of lunar volume) accounts for some of this depletion if the moon was fully molten following accretion. Removal of Ni and Co by olivine and orthopyroxene crystallisation in the deep interior can also deplete the source region of the mare basalts in these elements.

(d) Two observations indicate that the moon is enriched in refractory elements relative to the Earth and solar nebula abundances. Heat flow values indicate U abundances of at least 33 ppb[4]. The Al content of the 60-100 km thick highland crust together with the additional budget for the mare basalt source regions requires bulk lunar Al_2O_3 contents of about 6% consistent with the cosmic Al/U ratio for those refractory elements[5]. These compositional differences are collectively sufficient to rule out simple versions of the fission hypothesis. More complex versions must incorporate the following processes:

   (i) Depletion of volatile elements. This process is limited by the absence of such effects from the volatile REE elements, Eu and Yb. The alkalies are depleted less than the very volatile elements, although volatility effects should produce constant depletion factors[1].

   (ii) Fission must occur when the Mg/Mg+Fe ratio of the terrestrial mantle is 0.80, 10% lower than the present value[6].

   (iii) Enrichment or selective condensation of refractory elements.

These problems introduce so many ad hoc adjustments to the fission hypothesis that it becomes untestable.

Further constraints may be obtained from attempting to date the volatile-refractory element fractionation. Meteorites record metal-sulfide-silicate and volatile-refractory element fractionation close to 4.56 Ae. Mechanisms for large scale separations, required on a planetary scale, of volatile elements occur via strong solar winds in the T Tauri phase during the very early stages of solar nebula evolution, within about 10^6 years of the arrival of the sun on the main sequence[7]. Meteorite evidence records early loss of gas[8] so that a population of fractionated planetesimals is left in the inner solar system. Sweep-up of these into planetary bodies takes of the order of 10^8 years[9].

Two methods for dating the lunar volatile depletion may be derived from the volatile-refractory pairs Rb-Sr and I-Pu. Lunar initial ratios are close to or lower than BABI, implying very early separation of Rb from Sr[10,11]. If the terrestrial initial Sr ratio is also close to BABI, then fission must occur close to 4.56 Ae rather than 10^8 years later (terrestrial Rb/Sr ratio = 0.031). The moon has acquired excess Xe from 17 m.y. ^{129}I and 82 m.y. ^{244}Pu[12]. If the moon fissioned from the Earth following accretion over 10^8 years, then the volatilization required to remove K, Rb, Pb, Bi, Tl, H_2O, etc., will remove Xe, and so Xe derived from I or Pu should be rare in the moon. If the moon accreted from a separate group of fractionated planetesimals, which underwent metal and volatile element fractionation at To, then ^{129}I and ^{244}Pu can be present in the precursor planetesimals. The comination of chemical and isotopic problems suggests that the fission hypothesis is no longer viable, and separate terrestrial and lunar accretion from a population of fractionated precursor planetesimals provides a more reasonable explanation.

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DYNAMICAL CONSTRAINTS

Monday, October 15, 1984
1:00 - 3:15 p.m.

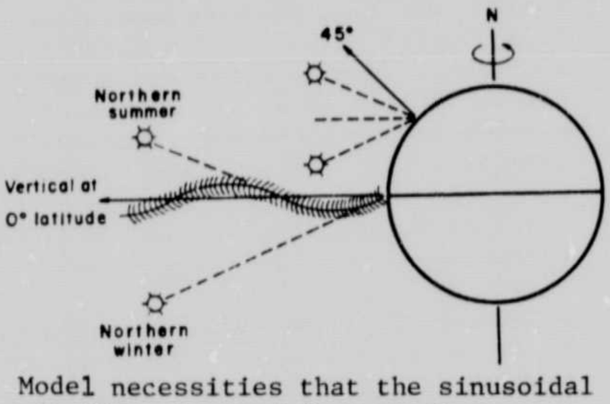
D22

CONSTRAINTS ON LUNAR ORIGIN: EVIDENCE PRESERVED IN PRECAMBRIAN STROMATOLITES:

J.P. Vanyo, Department of Mechanical and Environmental Engineering, University of California, Santa Barbara, CA 93106

In that growth rate and structure of many living organisms are directly influenced by solar radiation and often by conditions in an aquatic environment, these organisms should be expected to respond to various earth-moon-sun relationships. The bio-geological period of major interest for theories of lunar origin is prior to the beginning of the Cambrian some 0.57 billion years ago, but in the Precambrian, life forms were restricted to subaqueous unicellular algae and bacteria. Fossils of such organisms are abundant in the geological record. Their existance is also evidenced by abundant fossilized structures (stromatolites) consisting of many thin layers of usually darker algae-bacterial growth alternating with layers of usually lighter sediment-precipitate. The earliest of these have been dated to 3.5 billion years ago, spanning most of the earth's history and predating many postulated lunar origin times. Although stromatolites are forming in isolated locations today, their preservation dropped off sharply with the advent of burrowing and grazing worms in the Cambrian. In shape the laminated structures vary from nominally horizontal mats, extending over many square kilometers, to large and small bumps, and to a variety of columnar shapes.

A form identified as Anabaria juvensis and characterized by packed 1 to 2 cm. dia. columns many centimeters tall with convex upward laminae (dark plus light layer) about 0.2 mm thick were analyzed by Vanyo and Awramik[1]. A sinusoidal columnar growth pattern was interpreted to be a response of stromatolite forming microbes to the changing inclination of the sun over the seasons, with microbe growth rate positively related to solar intensity. A best estimate of laminae per sinusoidal wavelength agrees with an estimate of days per year (435) at the same age (0.85 billion years) by Munk, based on theoretical extrapolations from present data. Maximum tilt of the average column after correction for index of refraction yields an obliquity of the ecliptic of 26.5°. Both estimates are based on one small sample and require further refinement. Model necessities that the sinusoidal plane be aligned with the paleo north-south direction and for growth at a near equatorial location have been confirmed with paleomagnetic analyses.



Vanyo and Awramik using additional specimens and with NSF support are developing a systematic methodology for extracting data evidencing earth-moon-sun dynamics at time of stromatolite formation. In particular stromatolites span the time from 1 to 2 billion years age, critical for several theories of lunar formation and/or an earth-moon near encounter. Such cataclysmic events would most certainly influence stromatolite formation.

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D-23

N85 13732

CONSTRAINTS ON THE ORIGIN OF VISCOELASTIC BODIES: W. E. VanArsdale, Department of Mechanical Engineering, University of Houston-University Park, Houston, TX 77004

A possible explanation for the time scale of lunar orbital evolution has eluded investigators until recently. Lambeck (1980, p. 288) asserts that "...only a variable energy sink can solve the time-scale problem and the only energy sink that can vary significantly with time is the ocean." He suggests that the oceans are a significant energy sink accounting for more than 85% of all dissipation (Lambeck, 1975). While the oceans undoubtly contribute to energy dissipation, it seems implausible that such a small amount (0.02%) of the Earth's mass could play such a dominant role in this process. An alternate hypothesis assumes that most of the dissipation is associated with solid-body tides. This mechanism is also capable of varying significantly over time for viscoelastic bodies.

In this analysis of orbital evolution, the bodies are modeled as incompressible, Kelvin-Voight solids. While this material is simplistic, it does provide an analytical characterization of solid-body dissipation and the resulting tidal moment. This moment is calculated assuming an elliptic orbit and then used in approximate equations of motion. A solution to these equations is obtained for slowly varying orbital parameters. These results suggest that the orbital parameters are currently changing at a comparitively large rate. This rate was smaller in the past if the Earth's viscosity η changed significantly with time (VanArsdale, 1984).

The orbital history of a two body system is traced back in time to develop constraints on the satellite's origin. These calculations were performed using parameters for the Earth-Moon system and neglecting the tidal moment exerted by the Earth on the Moon. This analysis predicts a decrease in the lunar orbit to a minimum separation distance of ten Earth radii in a period of time controlled by η. The Earth's obliquity drops to $\pi/2$ during this close approach. These constraints suggest the Moon appeared in a significantly inclined orbit at a distance greater than ten Earth radii. This distance is outside of the Roche limit and would appear to alleviate some difficulties associated with capture hypotheses discussed by Kaula and Harris (1975). However, the small eccentricity at close approach is not favored by this hypothesis. As suggested by Goldreich (1966), this constraint suggests an origin by accretion.

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N85 13733 D24

TIDAL DISSIPATION IN THE EARTH AND MOON FROM LUNAR LASER RANGING;

C. F. Yoder, J. G. Williams, J. O. Dickey, X X Newhall, Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA 91109

The evolution of the moon's orbit is mainly governed by tidal dissipation in the earth while the evolution of its spin is controlled by its own internal dissipation. The analysis of lunar laser ranging data from August 1969 through May 1982 yields the present values of both of these parameters. The lunar secular acceleration is determined to be $\dot{n} = -25.3 \pm 1.2$ arcseconds/century^2, which is equivalent to a secular change in the mean distance of +3.7 ± 0.2 cm/yr. If the moon has orbited the earth since its formation, this must be an anomalously high value presumably due to changes in dissipation in the oceans due to continental drift. The rotational dissipation of the moon is measured by $k_2T = 0.0047 \pm 0.002$ days. With a lunar $k_2 = 0.032 \pm 0.007$, this dissipation would imply $Q = 30$, but we prefer the explanation that the dissipation occurs at the interface between the mantle and a liquid core or shell.

D25 N85 13734

TWO LUNAR GLOBAL ASYMMETRIES; J. B. Hartung, Solar System Associates, 9108 Potomac Ridge Road, Great Falls, Virginia 22066

The Moon's center of mass is displaced from its center of figure about 2 km in a roughly earthward direction(1). Most maria are on the side of the Moon which faces the Earth(2).

It has been argued that because the center of mass is so displaced and the crust of the Moon has a lower density than underlying material, the lunar crust must be thinner on the Moon's earth-facing side(1). The observed distribution of lunar maria is said to support this conclusion because it may be expected that mare basalt magma would reach the surface through a thinner crust more easily. A problem for this model is to explain how the lunar crust thickness asymmetry developed in the first place.

We suggest an alternative view and assume the Moon was initially spherically symmetric, or nearly so. The emplacement of mare basalts represents a transfer of mass which produces most of the observed center-of-mass displacement toward the Earth. As a worst case, if all of the center-of-mass displacement is due to basalt emplacement, then a mass equal to all of the mare basalts on the Moon(3) would have had to have been transferred a distance equal to the diameter of the Moon. Such a requirement might be satisfied, given the uncertainties involved, if mare basalt magmas were in "communication" over distances of thousands of km. The remaining question in this case is what causes the asymmetric distribution of lunar maria.

Because the Moon is in a spin-orbit-coupled relationship with the Earth, the effect of the Earth's gravity on the Moon is asymmetric(4). The earth-facing side of the Moon is a gravitationally favored location for the extrusion of mare basalt magma in the same way that the topographically lower floor of a large impact basin is a gavitationally favored location. This asymmetric effect increases inversely with the fourth power of the Earth-Moon distance. If the Moon were one-tenth its present distance from the Earth, the front-back asymmetric effect of the Earth's gravity would be equivalent to an elevation difference on the Moon of about 3 km(4).

A scenario for history of the Earth-Moon system consistent with the above discussion includes: formation of the Moon by accretion processes in a heliocentric orbit near that of the Earth; a gravitational encounter with the Earth about 4 billion years ago resulting in capture of the Moon into a geocentric orbit and heating of the Moon through dissipation of energy related to tides raised during close approaches to the Earth(5) to produce mare basalt magma; and evolution of the Moon's orbit to its present position, slowly at first to accomodate more than 500 million years during which magmas were extruded.

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D26

N85 13735

THE MOON'S ORBIT HISTORY AND INFERENCES ON ITS ORIGIN.

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A frequency-dependent model of tidal friction is used in the determination of the evolution of the Earth-Moon system. The analysis considers the lunar orbit eccentricity and inclination, the solar tide on the Earth, Earth oblateness, and higher-order terms in the tidal potential. A solution of the equations governing the precession of the Earth's rotational angular momentum and the lunar ascending node is found. This allows the analytical averaging of the variational equations over the period of relative precession which, though large, is necessarily small in comparison to the time step of the numerical integrator which yields the system evolution over geologic time.

The resulting history is consistent with a capture origin for the Moon[1]. It appears to rule out, in agreement with a previous result[2], origin of the Moon by fission. Results are shown for a range of assumed values for the lunar tidal dissipation (that is, for various k_2Q of the Moon) although they remain qualitatively the same. Tidal dissipation within the Moon, during what would be the immediate-post-capture period, is shown to be capable of significantly heating the Moon. This result is consistent with large-scale melting of the lunar surface dated at about 4.45×10^9 yr[3].

The immediate-post-capture orbit has a periapsis within the Earth's Roche limit. Capture into resonance with the Earth's gravitational field as this orbit tidally evolves has been suggested as a mechanism to prevent so close, and perhaps destructive, an approach[4]. We show that the probability of such capture is negligibly small, $P_c \approx .002$, and offer alternative hypotheses for the survival of the Roche limit passage.

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D27

N85 13736

34

A REAPPRAISAL OF DARWIN'S FISSION HYPOTHESIS AND A POSSIBLE LIMIT TO THE PRIMORDIAL ANGULAR MOMENTUM OF THE EARTH;

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A century ago G.H. Darwin proposed that the primordial earth may have rotated fast enough that the solar tidal period was nearly resonant with the fundamental free oscillation period of a fluid earth. A large and unstable tidal oscillation would then have split off to become the moon. Jeffreys developed an argument that dissipation during resonance would be sufficient to prevent such an unstable oscillation (1), however, and the hypothesis was laid to rest.

If the earth and moon are recombined so as to conserve angular momentum, and the resulting object is modeled as a Maclaurin spheroid with a density equal to the earth's present density ρ, then its spin frequency ω will be $0.303\sqrt{\pi G\rho}$ (period = 5.36 hr.). Solar tidal forcing will be at twice this frequency. Lord Kelvin showed that the fundamental ($\ell=2$) free oscillation for a fluid sphere occurs at $(16/15)^{1/2}\sqrt{\pi G\rho}$. This oscillation is composed of $2\ell+1 = 5$ modes that are degenerate when $\omega = 0$ only. The sectoral ("football") modes ($m=\pm 2$), relevant to tidal resonance, are split such that the frequency of the "backward" propagating tide ($m=-2$) is significantly decreased (as seen in the inertial frame). This frequency, based on the calculations of Chandrasekhar (2), is $0.654\sqrt{\pi G\rho}$ (period = 2.48 hr.) for the rapidly rotating proto-earth, or only 8% greater than the tidal frequency (period = 2.68 hr.). Considering that solar tides have extracted angular momentum from the earth-moon system over 4.5 b.y. (a few percent of the present total [3]), the correspondence of the primordial tidal and resonant frequencies is nearly exact. (The effect of central condensation of the proto-earth is to increase both frequencies by a similar, though for the resonance not precisely known, amount [10-20%]). This result, unknown to Darwin or Jeffreys, is curious, to say the least.

To evaluate the effects of resonance, consider the problem as a driven, damped oscillator, governed by

$$\ddot{x} + \gamma(A)\,\dot{x} + \omega_o^{\,2}(\omega)x = F\cos(\omega[t]t) \quad ,$$

where γ, ω, ω_o, and F have their usual meanings, and A is the amplitude of the tidal displacement $\dot{x}$. Classical results apply, notably that, for large Q ($=\omega_o/\gamma$) and equilibrium conditions, $A_{\omega=\omega_o} = QA_{\omega<<\omega_o}$. If $A_{today} \sim 1$ m, and A_{res} needs to exceed 10^6 m for resonant fission, then Q must exceed 10^6. This seems dubious even for an accretionary earth with very low viscosity (10^3 - 10^{10} P) due to supersolidus temperatures (4). Q may be estimated from $GM/2\omega_o R\nu$, where M and R are the earth's mass and radius, and ν is the kinematic viscosity derived from mixing length theory (5,6). For very large A, ν might approach $R^2\omega$, so the resonance is likely to be too damped for fission. This argument is more general than Jeffreys' (1), who considered friction between the oscillating mantle and a rigid core. An even more robust argument follows from the fact that Q must be so great for fission that equilibrium is not maintained; the fluid proto-earth passes so quickly through resonance that maximum amplitude is not reached (Δt for resonance $\alpha\ Q^{-2}$; the system $\tau\ \alpha\ Q^{-1}$).

If resonant fission is not possible, what is the significance of the commensurate periods above? Numerical coincidence? We suggest not; perhaps solar resonant tides acted as a brake on the spin of the primordial partially molten earth. Certain proposed origins for the moon (binary accretion, capture) do not necessarily involve addition of substantial amounts of angular momentum to the earth-moon system. The primordial earth-moon system may have had nearly the same angular momentum as it has today.

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N85 13737 D28

NUMERICAL SIMULATIONS OF FISSION; R.H. Durisen, Indiana Univ., R.A. Gingold, Mt. Stromlo and Siding Spring Obs., and E.H. Scott, National Space Science Data Ctr.

Up until recently, the fission theory of lunar origin had to rely on classic results for the equilibrium and stability of self-gravitating, incompressible fluids (1). Because this work was mostly analytic, conditions for the onset of dynamic instability could be determined but not the outcome. Over the past seven years, several research groups have applied modern hydrodynamic simulation techniques to the fission problem. The most comprehensive study to date (2) indicates that, for fluids with the compressibility of stars, dynamic fission instabilities lead to spiral-arm ejection of mass and angular momentum in the form of a ring or disk of debris, not as a single body. Some quantitative aspects of these results seem favorable to lunar origin by fission (3). We have expanded on this work by considering fission instabilities in fluid objects with a smaller degree of compressibility, more closely approximating terrestrial material. Although the qualitative features are similar, there are significant quantitative differences for the stiffer equation of state. We will discuss the implications of our new results for the fission hypothesis of lunar origin. We also hope to present evolutions illustrating possible approaches to instability.

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D29

N85 13738

36

THE DYNAMIC FISSION INSTABILITY AND THE ORIGIN OF THE MOON;

Alan Paul Boss and Hiroshi Mizuno, DTM, Carnegie Institution of Washington

One theory for the formation of the Moon involves the dynamic fission of a rapidly-rotating protoplanet, which might then result in the formation of the Earth and the Moon. The fission hypothesis was originally based on analytic, linearized models of the growth of asymmetry in homogenous (incompressible) bodies. Recently the fully nonlinear evolution of the dynamic instability in inviscid, compressible bodies has been calculated using numerical techniques. The dynamic instability was found to degenerate into the ejection of a ring of matter with a substantial fraction of the mass, leaving behind a central body with most of the mass, which is still an attractive means for forming the Moon (1). All theories of fission require a similar catastrophic, dynamic phase in order to obtain two bodies from the initial single body, even those theories which involve a prior phase of secular evolution (2). We have used both the linearized analytical approach and the more recent numerical approach to show that dynamic fission probably does not occur in rocky protoplanets.

The numerical calculations are performed with a fully three dimensional hydrodynamical code, which allows the nonlinear, time evolution of the instability to be followed. The protoplanet is represented by a fluid with a Murnaghan equation of state ($p = (K_o/\gamma)((\rho/\rho_o)^\gamma - 1)$) in the solid regions ($\rho > 3$ g cm^{-3} $= \rho_o$) and zero pressure otherwise. The numerical method ensures global conservation of both the total mass and the total angular momentum of the system. The protoplanet is constrained to rotate essentially as a rigid body. The kinetic energy in the solid regions (i.e., motion other than rigid body rotation) is dissipated throughout the evolution in order to simulate the effects of viscous dissipation in rocky bodies. The basic numerical method is the same as that which originally helped discover the outcome of the dynamic instability in compressible, inviscid bodies. The above alterations to the numerical methods have been successfully tested on a series of test problems involving the equilibrium of a body subjected to tidal forces (the Roche problem and lower dimension analogues). Sequences of uniformly-rotating equilibria (≈ Maclaurin spheroids) have been constructed and are used as the initial models for the fission calculations. The results can be scaled to protoplanets of arbitrary size, with the same K_o and γ.

We have studied the dynamic instability in a numerical model consisting of a $\gamma = 5$ protoplanet with a mass of 6.2×10^{27} g, rotating well above the limit for dynamic instability (rotational energy/|gravitational energy| = $\beta = 0.30 > \beta_{cr} = 0.274$). An initially imposed asymmetry consisting of a 10% binary perturbation in the density was found to disappear on the rotational period time scale. No dynamic instability occurred.

This result has been verified analytically by including our velocity dissipation terms in the linearized analysis of the stability of a Maclaurin spheroid (using the tensor virial equation approach): the dynamic instability disappears when our simulated viscous dissipation terms are included (the secular instability remains). We intend to extend this analysis to ellipsoidal equilibria.

These results apply to bodies with large viscosities (kinematic viscosity $\nu > 10^{12}$ cm^2 s^{-1}). Any rocky body, even with considerable partial melt or a molten core, should be stable to dynamic fission; any rotational instability that occurs can only result in equatorial mass loss.

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N85 13739 D30

TIDAL DISRUPTION AND THE ORIGIN OF THE MOON; Hiroshi Mizuno and Alan Paul Boss, DTM, Carnegie Institution of Washington

The dynamic problem of the tidal disruption of a rocky planetesimal has been solved by a direct integration of the fully three dimensional, nonlinear equations of motion. Tidal disruption has long been thought to be a crucial process in the accumulation of the terrestrial planets. Previous work has been limited to static, equilibrium models in circular orbit about a primary, and the result that stable equilibria do not exist inside a critical radius (≈ Roche limit) has been hypothesized to mean that any object that passes within the Roche limit is disrupted. We have disproven this hypothesis.

Our time-dependent solution is performed numerically, treating the planetesimal as a fluid with a Murnaghan equation of state ($p = (K_o/\gamma)((\rho/\rho_o)^{\gamma} - 1)$) in the solid regions ($\rho > 3$ g cm$^{-3} = \rho_o$) and zero pressure otherwise. The kinetic energy in the solid regions is dissipated throughout the evolution in order to simulate the effects of viscous dissipation in rocky bodies (tensile strength is negligible). The boundary between the solid regions and the "atmosphere" is accurately followed. The numerical methods have been extensively tested on a series of one, two (Jeans), and three (Roche) dimensional test problems involving the equilibrium of a body subjected to tidal forces; the test results predict critical radii for disruption of the equilibrium which agree very well with the analytic solutions. Sequences of uniformly-rotating equilibria (≈ Maclaurin spheroids) have been constructed for use as initial models for the calculations. The results may be scaled to planetesimals of arbitrary size, providing that the same equation of state applies (same K_o and γ).

The calculations show that a rocky body (radius = 1000 km, $\gamma = 1$) which passes by the Earth on a parabolic orbit with a perigee within the Roche limit ($\approx 3\ R_{Earth}$) is <u>not</u> tidally disrupted, even for grazing incidence ($\approx 1.2\ R_{Earth}$). At most, a few percent of the mass is lost from the surface of the planetesimal. Objects on hyperbolic orbits would experience even less tidal disruption. There are two coupled reasons for why this result differs from previous hypotheses: (1) in a dynamic encounter, there is insufficient time to disrupt the planetesimal (compared to the infinite time available in the Roche problem), and (2) the velocities in the solid region must remain small because of viscous dissipation, and hence it takes many orbital periods to completely disrupt a rocky planetesimal (in which case the disruption consists of gradual mass loss from the surface, not a catastrophic failure).

Our results do not apply to bodies with very low viscosity: if the kinematic viscosity $\nu > 10^{12}$ cm^2 s^{-1}, then our results apply. Nakazawa and Hayashi's study (private communication) of tidal disruption indicates that inviscid bodies can tidally disrupt, which is consistent with our results (as we decrease the amount of dissipation, more mass is lost). Thus only completely molten bodies are inviscid enough to undergo tidal disruption; any rocky body, even with considerable partial melt, or with a molten core, should be able to resist disruption.

In the accumulation theory of the formation of the terrestrial planets (including the Moon), one of the important factors for determining the relative velocity in the swarm of planetesimals (and hence the growth time) is the mass spectrum. We have shown that tidal disruption can be ruled out as a mechanism for reducing planetesimal masses. Furthermore, mechanisms for forming the Moon which rely upon tidal disruption (e.g., tidal disruption by Earth in order to capture a circumplanetary ring of matter which can later accumulate into the Moon), are unlikely to be correct.

D3/

N85 13740

A NUMERICAL INVESTIGATION OF PLANETESIMAL COLLISION TRAJECTORIES WITH A MOON ACCUMULATING IN EARTH ORBIT; L. P. COX J. S. Lewis Associates, Inc.; Tucson, Arizona and Concord, Mass.

In the scenario of lunar origin in which the moon is assumed to have accreted most of its mass while in orbit about the Earth, a knowledge of the relative impact rates of heliocentric planetesimals on the accreting Earth and moon is essential for any attempt to establish dynamical constraints on lunar origin. All previous models of lunar accumulation in Earth orbit have treated gravitational encounters, including collisions, between planetesimals and the accreting moon as two-body interactions. However, this idealized two-body treatment of encounters has been found to break down when the ratio of the unperturbed relative encounter velocity of the two bodies to their mutual surface escape velocity, V/V_e, is less than $\sim$0.3(1,2).

Consequently, numerical integrations of the regularized equations of motion for four bodies (Sun, Earth, moon, planetesimal) are in progress. A planetesimal impact trajectory is calculated by assuming that the planetesimal has hit the surface of the moon at an assumed location, traveling in an assumed direction, and with an assumed impact speed. Next, the equations of motion are numerically integrated backward in time in order to determine where the planetesimal has come from as given by its osculating orbital elements at large enough separations from the Earth and moon that the elements are sufficiently close to their heliocentric values. In this way those volumes in heliocentric orbital element space which contribute trajectories that directly impact the moon, analogous to the "bands" of trajectories impacting a planetoid Earth found by Giuli(3) and Dole(4), can be mapped out.

In numerical integrations of the three-body equations of motion, many impacts were observed at low velocities, $V/V_e < 0.1$, to result from encounter trajectories having unperturbed separation distances far beyond the two-body gravitational radius(1,2). The present investigation should quantify the extent to which the moon benefits in the late stages of its accretion from this "anomalous gravitational focusing" of low-velocity heliocentric planetesimals by the Earth, assumed at this stage to be closely approaching its present mass.

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N85 13741

D32

STOCHASTIC ≠ AD HOC; William K. Hartmann, Planetary Science Institute, Tucson, Arizona 85719.

Many lunar origin theorists have felt constrained by Occam's razor to avoid postulating a role for stochastic events, such as large impacts. This attitude is a misreading of Occam's razor, which asks that we not posit ad hoc events. Some classes of influential events in solar system history are class-predictable but not event-predictable: we believe the class of events occurred, but we cannot predict times and magnitudes of individual events. The events are thus stochastic, but not ad hoc.

An example is the probable K-T boundary asteroid impact: Asteroid statistics long ago implied such events every few 10^7-10^8 yr, but we could not convincingly tie specific geologic effects to specific impacts. As a result, large impacts tended to be ignored; we should have given more thought to geologic and climatic consequences of these class-predictable events.

Analogously, we should be careful about adopted constraints on lunar origin and not ignore class-predictable stochastic events. As long ago as 1958, O. Yu. Schmidt[1] emphasized the statistical effects of innumerable small planetesimals, explaining the tendencies toward regularity: prograde rotations, small obliquities, i's and e's, etc. Superimposed were the effects of large-scale stochastic events, emphasized by Safronov[2] as early as 1966. The magnitude and timing of the largest impact in each planet's history may have been crucial to that planet's development.[3] Theoretical and observational results support the importance of large-scale stochastic events (impacts or encounters?) in explaining differences among planets: (1) Safronov[2] attributed obliquities to impacts of masses up to a few percent of planetary mass (5% for Uranus; 0.1% for Earth); (2) D.R. Davis and I[3] obtained similar results for e's and i's. Items (1) and (2) imply planetesimals as large as $D \geq 1000$ km striking planets during the planet-forming period; (3) Lunar and planetary basins dating back an estimated 4.0 Gy. give direct evidence of impactors as large as $D \simeq 150$ km;[3] (4) Several satellites show impact scars nearly big enough to disrupt them, 34-40% of the diameters for Phobos, Mimas, and Tethys. Voyager analysts concluded that Mimas and other moons had been completely disrupted and reassembled -- accretion involved catastrophe; (5) Some asteroids have been fragmented, but others have survived with primitive surfaces; (6) Differences in ring systems and satellite systems also suggest stochastic processes.

Impacts and close encounters with large objects during planet formation are class-predictable. These stochastic events, such as large impacts that triggered ejection of Earth-mantle material into a circum-Earth cloud, should not be rejected as ad hoc. A way to deal with such events scientifically is to investigate their consequences; if it can be shown that they might produce the moon, they become viable concepts in theories of lunar origin.

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MY MODEL OF LUNAR ORIGIN I

Monday, October 15, 1984
3:30 - 5:15 p.m.

D33

N85 13742

A TESTABLE GRAVITATIONAL CAPTURE MODEL FOR THE ORIGIN OF THE EARTH'S MOON;

Robert J. Malcuit, Dept. of Geology, Ronald R. Winters, Michael E. Mickelson, Dept. of Physics and Astronomy, Denison University, Granville, Ohio 43023

A great-circle pattern of large circular maria can be interpreted as the signature of a tidal disruption event associated with a gravitational capture origin for the Earth-Moon system. The features that delineate this lunar surface rock pattern are Maria Orientale, Imbrium, Serenitatis, Crisium, Smythii, and the mare-filled crater Tsiolkovsky. Our proposed gravitational capture scenario is divided into five eras.

ORBITAL ERA I. Jupiter-Perturbed Heliocentric Orbital Era (~4.6 to ~4.3 b.y.). The model begins with formation of the planets from nebular condensates about 4.6 b.y. ago. The Earth accumulates in the vicinity of its present orbit but Luna (= pre-capture Moon) forms as a small planetary unit on the inner edge of the Asteroid Zone at about 1.7 - 2.0 A.U. Gravitational perturbations by Jupiter cause an increase in eccentricity of Luna's orbit so that it becomes Mars-crossing and eventually Earth-crossing. During this orbital era, the lunar magma ocean would lose heat and eventually become mainly crystalline by 4.3 b.y.

ORBITAL ERA II. Earth-Crossing Heliocentric Orbital Era (~4.3 to ~3.9 b.y.). This orbital era commences when Luna's orbit becomes Earth-crossing. At this point, occasional energy-dissipating gravitational encounters of the non-capture type can occur between Luna and Earth. A large quantity of orbital energy (~4 X 10^{38} ergs) must be dissipated within the bodies of Luna and Earth during this orbital era. Although much of this energy can be absorbed by the Earth's upper mantle over this time interval, periodic tidal activity would be effective in reheating Luna's magma ocean zone.

ORBITAL ERA III. Luna's Capture (~3.9 b.y.). As Luna undergoes periodic gravitational encounters with Earth while in a near Earth-like orbit, the lunar body becomes warmer, more deformable, and thus more capturable. However, gravitational capture of a lunar-sized body during a close encounter would entail dissipation of about 2 X 10^{35} ergs if Luna had a v_∞ of about 0.2 km/sec. Even if we assume the Earth to be about twice as deformable as it is today, the lunar body must have Love numbers around h=0.5 and k=0.25 to facilitate capture in one pass. Since energy dissipation is related to r^{-6} (r= distance of separation between the two bodies), only encounters within 1.4 R_e could be expected to result in Luna's capture. Encounters within 1.4 R_e are well within the Weightlessness Limit for the Earth-Moon system and such a close encounter of a sufficiently "warm" Luna could result in tidal disruption during the time of the encounter.

ORBITAL ERA IV. Early Post-Capture Geocentric Orbital Era (~3.9 to ~3.6 b.y.). After the lunar body is inserted into a geocentric orbit within the stability limit of the Earth-Moon system, a geocentric orbital evolution would occur which results in circularization of an initially highly elliptical orbit. Computer simulation of this early geocentric orbital evolution suggests that circularization of the orbit occurs rapidly, i.e., within a few 10^5 years after capture. About 5 X 10^{35} more ergs must be absorbed by the Earth and Moon during this orbital era.

ORBITAL ERA V. Subsequent Geocentric Orbital Evolution (~3.6 b.y. to Present). Following orbital circularization at about 35 to 40 R_e (prograde), the lunar orbit gradually expands to its present dimensions by way of "normal" tidal friction processes.

D34

N85 13743

DIRECTIONAL PROPERTIES OF "CIRCULAR" MARIA: INTERPRETATION IN THE CONTEXT OF A TESTABLE GRAVITATIONAL CAPTURE MODEL FOR LUNAR ORIGIN;

Robert J. Malcuit, Dept. of Geology, Ronald R. Winters, Michael E. Mickelson, Dept. of Physics and Astronomy, Denison University, Granville, Ohio 43023

Photogeologic study of "circular" maria and mare-filled craters reveals that several of these features are either elliptical and/or asymmetrical. The ellipticity/asymmetry is interpreted as a directional property which may have genetic significance. The features with the most apparent directional properties are Maria Orientale, Crisium, Humorum, Moscoviense, and the mare-filled crater Tsiolkovsky. Other features with weaker vectorial signatures are Maria Imbrium, Serenitatis, and Smythii. The asymmetric pattern associated with Mare Orientale is somewhat different from that of the other maria. There are extensional features to the southwest of Orientale and compressional features to the northeast. Thus movement appears to have been from southwest to northeast. All other maria, except Moscoviense, indicate movement in easterly directions and these vectors are within 30° of the trend of a great-circle pattern of large circular maria described by [1]. The vector for Mare Moscoviense is in a north-easterly direction and is oriented nearly perpendicular to the great-circle trend. The directional properties of these features are consistent with at least three models of mare basin formation: (1) that the mare basins were excavated by a swarm of fragments from a tidally disrupted planetary body impacting from a westerly direction [2]; (2) that the mare basins were excavated by lunar satellites whose orbits decayed sufficiently to cause the satellites to impact onto the lunar surface from a westerly direction [3]; and (3) that the basins were formed by the impact of large spheroids of lunar basalt onto the lunar surface from a westerly direction [1]. According to [1], such basaltic spheroids may be necked off a lava column during the tidal disruption phase of a very close gravitational encounter between Earth and Moon early in Solar System history. In this tidal disruption model, each major basaltic spheroid impact zone should be characterized by a basaltic lava "lake" surrounded by anorthositic crust "flooded" by the overflow of basalt resulting from the collapse of the basaltic spheroid onto the lunar surface. A raised rim could then result from the rebound of the area in response to excess loading during impact.

General tests for the model are the following: (1) there should be no anorthositic crust under the postulated tidal disruption zones of Mare Orientale and a restricted region of Oceanus Procellarum; (2) there should be a normal thickness of crust under the postulated fall-back zones; and (3) the crust under the mare basalt in the mare basins in the fall-back zones should not be greatly disturbed by the impact of the magmatic spheroids. Specific tests for the Mare Crisium region (a typical impact zone in this model) are: (1) the morphology of the anorthositic crust under the mare basalt should be spoon-shaped (asymmetrical) with the deep part on the western end; (2) the shape of the mascon associated with the basin should mimic the shape of the mare basalt fill; (3) the bulk of the rim-mantling material should be composed of a black-matrix breccia consisting of anorthositic crustal fragments within a matrix of lunar basalt; and (4) a negative gravity anomaly should be associated with the raised rim. Other "circular" maria in the fall-back zones should have similar characteristics.

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D35

N85 13744

THE 'PROBLEM' OF IRON PARTITION BETWEEN EARTH AND MOON DURING SIMULTANEOUS FORMATION AS A DOUBLE PLANET SYSTEM: W. A. Cassidy, Department of Geology and Planetary Science, University of Pittsburgh.

Given certain conditions, there should be no problem in forming the moon as a sister planet of the earth, from the same reservoir of material, within the same time frame. The model described here requires fractional vapor/liquid condensation, planet accumulation during condensation, a late start for accumulation of the moon, and volatile accretion to the surfaces of each planet only near the end of the accumulation process. While most workers resist the suggestion that liquid phases could be stable in the primitive solar nebula, transient conditions as distant from the sun as 1.6 A.U. produced during nebular flares or a T Tauri phase of the early sun could be characterized by pressures and temperatures within the stability fields of iron and silicate liquids and vapors (1). That glassy chondrules formed, possibly as far from the sun as 3 A.U., is not inconsistent with the suggestion. At 1 A.U., therefore, cooling vapor may have condensed to liquids, and may have fractionated in the process. In the model, initial accumulation of small objects is helped if the agglomerating particles are somewhat sticky, as liquids might be, but still there would be a critical size range within which rotating bodies are unstable. Assuming that growth proceeds through this range, agglomeration continues. If the reservoir of vapor is being preferentially depleted in iron by fractional condensation, an iron-rich planetary core forms. As the temperature decreases, condensing material becomes progressively richer in silicates and poorer in iron, forming the silicate-rich mantle of an already differentiated earth (cf. 2,3). Continuing to develop the model, a second center of agglomeration successfully forms near the growing earth after most of the iron in the reservoir around 1 A.U. has been used up. The bulk composition of the moon then is similar to the outer mantle of the accumulating earth, since from some instant in time they drew on the same iron-depleted reservoir. As each body increased in cross-sectional area and mass it became a more efficient collector of additional material, but the earth had started sooner and became more efficient more rapidly. Volatiles accumulated late and were incorporated into surface materials of both planets, but disproportionately more were gathered by the earth because by that time it was competing much more successfully for the remaining available material. (1) Cameron, A.G.W. (1984) Lunar and Planetary Science XV, p. 118-119. (2) Cassidy, W. A. (1964) Ann. N.Y. Acad. of Sciences 119, p. 17-40. (3) Turekian, K. K. and Clark, S. P., Jr. (1969) Earth and Planetary Sci. Lett. 6, p. 346-348.

D36

ORIGIN OF THE MOON;

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The earth's mantle and the moon possess similar (∿x2) abundances of the siderophile elements (Co,Ni,Fe,W,P,S,Se and Te. (1) The abundances of these elements in the earth's mantle have been determined by the interaction of several complex processes unique to the earth, which relate to core formation and the distribution of siderophile elements between metal and silicates. These processes could not have operated similarly within the moon, in which the maximum size of a core is smaller than 10 percent of the proportional size of the earth's core and which would have formed under drastically different P,T,fo_2 conditions to the earth's core. The similarities in siderophile abundances strongly suggest that the moon was derived from the earth's mantle after the earth's core had formed (1). This conclusion is not weakened by the existence of some important geochemical differences between the moon and the earth's mantle, which can readily be explained by selective loss of volatile elements (1) and segregation of a small amount (<0.5%) of metal within the moon (eg,2).

The energy required to remove material from the earth's mantle and place it into geocentric orbit can be supplied most readily by impact processes during accretion of the earth (3,4,5,6). Theoretical studies of tektites, together with experimental impact mechanics investigations (6) show that impacts from accreting planetesimals can accelerate material from the mantle to velocities exceeding 10km/sec and can also evaporate large amounts of target material. Currently, most of this material would be recaptured by the earth or it would escape. However, at a late stage of its accretion, after segregation of the core, the earth probably possessed a strong magnetic field and a rotation period of 4-5 hours (3). Impacts of late-accreting, high-velocity planetesimals (possibly cometary bodies from the outer planet region) would evaporate many times their masses of mantle material (6). These gases would be accompanied by a massive spray of shock-melted silicate droplets. Evaporated gases would be transiently ionized and thereby coupled hydromagnetically to the earth's rotation. It is suggested that the gases produced from such near-equatorial impacts were rapidly spun out into equatorial geocentric orbit. Viscous coupling between the gases and shock-melted liquid spray also caused the latter to achieve similar orbits. The evaporated material was selectively recondensed, and, accompanied by the shock melted, devolatilised silicate droplets, accreted to form a sediment-ring of earth-orbiting planetesimals. The volatile components condensed further away at lower temperatures as sub-micron smoke particles and were blown away by an enhanced early solar wind. This sediment-ring also captured a significant proportion of earth-bound planetesimals as advocated by (7), thereby increasing the total iron content of the sediment-ring to a level exceeding that in the earth's mantle. The moon was formed by accretion from planetesimals comprising the sediment ring.

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D37

N85 13746

ON THE ORIGIN OF THE MOON BY ROTATIONAL FISSION; A.B. Binder, Senior NRC Fellow, Johnson Space Center, Houston, TX 77058.

There is an increasing body of evidence which suggests that the moon originated by fission. The observations, etc. which support this concept are as follows.

1) Essentially all stars are members of close or contact binary systems (1). These observations suggest that such systems formed by fission of the proto-star at the end of its formation. Also, like the earth-moon system, the Pluto-Charon system has a large secondary to primary mass ratio and orbital characteristics which are expected for a fission pair. These empirical observations suggest that the formation of binary stars and planets by fission is a prevalent process in the formation of astronomical bodies.

2) Recent advances in the dynamical study of fission show that the "... results are consistent with some of the requirements of the fission hypothesis for the origin of the moon." (2) and indicated that stellar bodies also undergo fission. Also these studies confirm that fission leads to a secondary body having a mass of 10 to 20% of that of its primary.

3) As shown earlier (3), the newly formed proto-moon, whose temperature was 2000 to 3000 °C and which therefore had an extensive, volatile enriched atmosphere of vaporized silicates, would have lost a large fraction of its original mass via mass transfer through the L_1 point. While most of this mass would have been recaptured by the earth, some of it would have escaped the earth-moon system, thereby removing angular momentum from it. In addition, the proto-moon itself was rotationally unstably and this would have lead to the loss of mass from the proto-moon and the system. Calculation show that if only 0.7 to 1.5 lunar masses of material, i.e, only 5 to 10% of the original mass of the proto-moon, escaped the earth-moon system, the current angular momentum deficiency of the system can be accounted for (3).

4) The processes described above would result in a moon of terrestrial mantle material which was depeted in both metallic iron and volatiles. The moon would have been totally molten and would have differentiation in to a dunitic lower mantle, a peridotite upper mantle, and a feldspathic crust (4). As small core should have been formed mainly from Fe produced by the reduction of FeO as the moon lost its volatiles. The formation of a small lunar core would account for the observed lunar depleation pattern for the siderophile elements (4,5).

The above characteristics are consistent with our current understanding of the moon's bulk composition, internal structure, seismic, and tectonic characteristics.

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D38

GEOCHEMICAL EVIDENCE FOR THE FORMATION OF THE MOON BY IMPACT INDUCED FISSION OF THE PROTO-EARTH.

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The Earth's mantle exhibits a number of geochemical peculiarities which make our planet to an almost unique object in the solar system. This becomes evident if one compares terrestrial basalts (TB) with those from the eucrite parent body (EPB), and the shergotty parent body (SPB), which to all probability is Mars. EPB and SPB basalts differ in their oxygen isotope systematics and in their higher contents of Mn from TB. Under "normal" planetary conditions (ol+opx+cpx, being the major Fe- and Mn-bearing phases), the liquid-solid partition coefficients of FeO and MnO are only slightly above 1. Hence, comparing basalts from different planetary objects the depletion of Mn for Earth and Moon is immediately evident.

Aside its lower abundance of volatiles and highly siderophiles, the Moon comes compositionally in all details very close to the Earth's mantle except the lower FeO content of the latter which can be explained by a gradual transfer of some FeO into the core during geological times (1). Compared to their metal/silicate partition coefficients ($D_{m/s}$), all siderophile elements are highly overabundant in the Earth's mantle assuming equilibration with a pure metal phase. Lunar basalts contain much less Ir, Au, etc. ($D_{m/s} \approx 10^5$) than TB, while these differences diminish for Ni ($D_{m/s} \approx 10^3$) to about a factor 3 (2), and to less than a factor of 2 for W, Co and P ($D_{m/s} \approx 10^2$). In terms of a huge lunar magma ocean formation or addition and segregation of small amounts of metallic iron (≈ 0.5 %), could account for the depletion of siderophiles according to their $D_{m/s}$.

Recently, impact induced fission became a most plausible physical process for the formation of the Moon (3,4). According to Wetherill (5), the largest objects impacting on the Earth during its accretion was in the order of several lunar masses. Wänke et al. (6) have presented evidence for the presence of unfractionated primary matter in the lunar highland breccias, which in composition should be almost identical to that of the bulk Moon. This observation also argues for an impact induced fission scenario. In such an impact process large fractions of vaporized target material will be placed in orbit around the Earth and after recondensation - loss of volatiles - forms the Moon in a fast time scale. It is plausible that in addition to a massive Proto-Moon several smaller satellites formed which were swept up by the Proto-Moon on a larger time scale (7) (basin forming objects). These smaller satellites would of course have a composition identical to that of the Proto-Moon.

It is also plausible that impact induced fission occurred at the moment at which accretion of the Earth was not yet totally completed. In terms of an inhomogeneous accretion of the Earth (8), most of the oxidized and volatiles containing component is added towards the end of accretion. Hence at time of fission the mantle would have had somewhat lower concentrations of (oxidized) siderophiles and volatiles as today. Formation of the Moon from material of the Earth's mantle has been advocated since long by Ringwood (9,10).

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MY MODEL OF LUNAR ORIGIN II

Tuesday, October 16, 1984
9:00 a.m. - 12:00 noon

AN INTEGRATED DYNAMICAL AND GEOCHEMICAL APPROACH TO LUNAR ORIGIN MODELLING;

R. Greenberg*, C.R. Chapman*, D.R. Davis*, M.J. Drake**, W.K. Hartmann*, F.L. Herbert**, J. Jones**, and S.J. Weidenschilling*, constituting the Tucson Lunar Origin Consortium, *Planetary Science Institute, Tucson, Arizona, **Lunar & Planetary Laboratory, Tucson, Arizona.

None of the three major categories of models of lunar origin readily explains the Moon's properties: The fission model suffers from dynamical uncertainties and from compositional inconsistencies with the mantle of the Earth;[1] the model of growth in circum-terrestrial orbit suffers from the gross bulk compositional differences between the Earth and Moon, e.g., the latter's lack of metallic iron; the capture hypothesis requires some unknown capture mechanism to slow a full-sized Moon into a bound orbit, and also fails to address the problem of low iron content.

Our consortium considers each of those models to represent an end member of a more general scenario: As the Earth grew by planetesimal bombardment, a circum-terrestrial cloud of particles was created from a combination of impact-ejected mantle material and planetesimals captured directly into orbit around the Earth. Such a swarm continued to capture planetesimals and to receive ejecta until the bombarding population thinned, the Earth stopped growing, and the Moon accreted in orbit. If Earth-mantle material dominates the swarm, the model resembles the fission hypothesis; if small planetesimals dominate, the model represents the "growth in Earth orbit" end-member; if the swarm were dominated by a single large planetesimal, we would essentially have a capture model. A model intermediate between these extremes appears most promising.

In this context, we see two ways to explain compositional properties. First is the stochastic route: A few big late planetesimals of diverse composition are captured in orbit and/or hit Earth. Such rare events control the final composition of the Earth and Moon. This approach may be reasonable because some late planetesimals were probably big, and they had large orbital eccentricities and thus may sample a range of compositional zones. However, a stochastic explanation is difficult to analyze or test. Some might call it <u>ad hoc</u>, yet such events are quite plausible.

We consider a second route which may provide a systematic explanation of composition: The circum-terrestrial swarm acts as a filter, preferentially capturing small weak silicate bodies, while passing large iron planetesimals (cores of broken parents). The dynamics of this filtering process are described in a subsequent paper.[2] There are a number of issues related to this hypothesis that are also considered in subsequent papers: What other geochemical properties need to be explained?[3] How was the swarm produced in the first place?[4,5] And finally, how was the swarm maintained in orbit? Or more specifically, can captured material contribute enough angular momentum? The answer to the latter seems to be <u>no</u>,[6] a seeming stumbling block to any model involving a circum-terrestrial swarm. Unless some systematic source of angular momentum can be identified, we may be forced to rely on stochastic dynamical processes[4,5] for an explanation.

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D40

N85 13749

LUNAR ORIGIN: ROLE OF GIANT IMPACTS*; William K. Hartmann, Planetary Science Institute, Tucson, Arizona 85719.

The impact flux required to accrete Earth's mass during accretion time T = 0.03 to 150 m.y. ranges from some 10^7 to 10^{12} x the present flux.[1] In 1975, Hartmann and Davis[2] suggested that impacts of a large planetesimal(s?) during this period ejected "iron-deficient crust and upper mantle material, forming a cloud of refractory, volatile-poor dust that could form the moon."

The high primordial flux implies 1 impact/week of bodies ranging about 2-50 km across and about 10^{13} to 10^{17} kg. A small fraction of the resulting ejecta reaches near-Earth space, with sub-orbital stay-times of the order of a week. (In fast-accretion models, the "weekly impactors" have dimensions larger than the present atmospheric thickness; they are especially efficient in ejecting debris into near-Earth space.) Therefore, the "weekly impactors" maintain a time-varying circum-Earth swarm or disk; its density needs further evaluation. The swarm may have interacted with incoming material, or accreted onto a small proto-moonlet already (captured?) in orbit.

Less frequent 100+ km impactors ejected transient surges of mass into the circum-Earth swarm. The largest impactors probably approached or exceeded lunar size. One or more giant impacts may have added enough heated, volatile-depleted upper-mantle material (from a magma ocean?) to contribute much of the moon's mass. Lunar formation in such a swarm is supported by Thompson and Stevenson, possibly within 100 yr.[3] If Earth spun rapidly, as in fission models, the largest impact may have introduced enough angular momentum and energy to trigger the ejection/fission event. Impact-induced fission thus overcomes certain problems of classical fission models.

The suggestion by Hartmann and Davis[2] and later by Cameron and Ward[4,5] that lunar origin involved giant impacts remains attractive. Large planetesimals are consistent with current accretion models, and may have been widely scattered in the early solar system: their existence is a reasonable, if not necessary, assumption in moon-origin models. Furthermore, isotopic data require the moon's formation primarily from local material resembling Earth's upper mantle, not material from elsewhere in the solar system. Giant impacts are stochastic, class-predictable events that would provide the required type of ejected Earth-mantle material without requiring large moons to form near other planets (a problem with less stochastic processes). Such material may have mixed with incoming meteorites during lunar formation, affecting lunar chemistry. Further work on this hypothesis should include dynamical studies of whether: (1) some ejected material in each large impact would remain in orbit, causing growth of the swarm; (2) a small moonlet captured or accreted in the swarm could serve as a nucleus to catalyze lunar accretion; (3) spontaneous accretion could yield a moon without a catalyst-moonlet; (4) tidal action could help the primordial moon move outward instead of spiraling in due to drag; (5) Earth's rotation rate or an oblique impact is critical in launching the swarm; and (6) the swarm helps differentiate incoming material, preferentially capturing low-density silicate dust.

*Research conducted in conjunction with the Tucson Lunar Origin Consortium.

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N85 13750

D41

MODELS OF ANGULAR MOMENTUM INPUT TO A CIRCUMTERRESTRIAL SWARM FROM ENCOUNTERS WITH HELIOCENTRIC PLANETESIMALS⁺; Floyd Herbert, Lunar and Planetary Laboratory, University of Arizona, Tucson AZ 85721, and Donald R. Davis, Planetary Science Institute, Tucson AZ 85719.

Models of lunar origin in which the Moon accretes in orbit about the Earth from material approaching the Earth from heliocentric orbits must overcome a fundamental problem: the approach orbits of such material would be, in the simplest approximation, equally likely to be prograde or retrograde about the Earth, with the result that accretion of such material adds mass but not angular momentum to circumterrestrial satellites. Satellite orbits would then decay due to the resulting drag, ultimately impacting onto the Earth.

In the present work we investigate one possibility for adding both material and angular momentum to Earth orbit: imbalance in the delivered angular momentum between pro- and retrograde Earth-passing orbits which arises from the three-body dynamics of planetesimals approaching the Earth from heliocentric space. The existence of this imbalance for planetesimals directly striking the Earth and its tendency to be of prograde sense was first demonstrated by Giuli(1) in numerical computations and later in analytic work by Harris(2).

In order to study angular momentum delivery to circumterrestrial satellites we have numerically computed near-Earth velocities as a function of distance from the Earth for a large array of orbits systematically spanning heliocentric phase space. The resulting distribution $f(\underline{v},r,a,e)$ of Earth-passing velocities $\underline{v}$ at each distance r resulting from orbits at each heliocentric a and e together with one of the various plausible assumed heliocentric planetesimal number densities $n(a,e)$ determines the mean velocity near the Earth of all planetesimals from all parts of the feeding zone by $\underline{\langle v \rangle} = \int \underline{v}\, f(\underline{v},r,a,e)\, n(a,e)\, d^2\underline{v}\, da\, de / \int f(\underline{v},r,a,e)\, n(a,e)\, d^2\underline{v}\, da\, de$.

The results of this experiment for most assumed planetesimal distributions produced mean tangential Earth flyby velocities that were positive (prograde) both near the Earth's surface and at distances up to 40 R_E. A constant $n(a,e)$ yielded mean flyby tangential velocities of only a few percent of local circular Earth orbit speed $v_c(r)$, whereas a quasi-thermal distribution around heliocentric eccentricity of 0.03 gave flyby tangential velocities varying from a few to 10% of v_c (at 40 R_E). Raising the mean thermal eccentricity to 0.05 and assuming that planetesimals crossing the Earth's orbit without terrestrial perturbations are reduced in frequency by a factor of 10 produced a mean flyby tangential velocity 20% of v_c at 1 R_E and 30% of v_c at 40 R_E (but about zero at 2.5 R_E). The significance of heliocentric feeding zone weighting is shown in Figs. 1 and 2, which are histograms of the sign of the zonal statistic $\langle \underline{v}(a,e) \rangle$ at 4 R_E, computed by evaluating the above expression over small a and e bins with $n(a,e)$ constant. Fig. 2 values are relative to $v_c(r)$, while Fig. 1 refers to a non-rotating frame. These diagrams indicate the heliocentric phase space source regions for significant angular momentum input to the near-Earth region. Therefore, while other weightings of the heliocentric population might increase angular momentum input, Fig. 2 suggests that there is no simple weighting that would spin up the circumterrestrial swarm.

These preliminary experiments show that heliocentric planetesimals passing through the Earth environment possess significant angular momentum. However it also appears that these same planetesimals impacting a circularized circumterrestrial planetesimal swarm would likely remove angular momentum (though possibly increasing mean kinetic energy), presumably promoting both swarm infall upon the Earth and escape to heliocentric space. Only a distribution of highly eccentric satellite orbits with mean tangential velocities of a few tens of percent of local circular velocity would be immune against angular momentum loss to passing heliocentric planetesimals.

⁺Research conducted in conjunction with the Tucson Lunar Origin Consortium

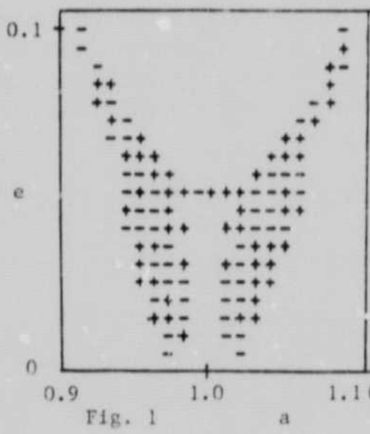

Fig. 1

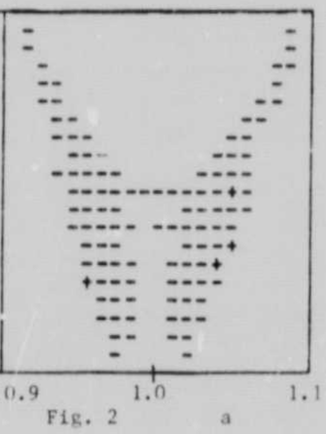

Fig. 2

ACKNOWLEDGEMENTS: The authors thank C.P. Sonett for making computer time available. This work was funded in part by NASA under grant number NASW-3516.

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FIGURE CAPTIONS:

Fig. 1 A 2-D histogram of the sign of the mean tangential velocity of heliocentric planetesimals passing through the Earth neighborhood at a distance of 4 R_E, expressed as a function of a and e for the heliocentric source orbits. Symbols only appear at positions corresponding to orbits capable of reaching the 40 R_E circumterrestrial disc.

Fig. 2 A 2-D histogram the same as Fig. 1 except that the zero of velocity is taken to be (prograde) circular orbit velocity at 4 R_E.

D42

CAPTURE OF PLANETESIMALS INTO A CIRCUMTERRESTRIAL SWARM*; Stuart J. Weidenschilling, Planetary Science Institute, Tucson, Arizona 85719

The lunar origin model considered by the Tucson Consortium[1,2] involves processing of proto-lunar material through a circumterrestrial swarm of particles. Once such a swarm has formed, it can gain mass by capturing infalling planetesimals[3] and ejecta from giant impacts on the Earth,[4] although the angular momentum supply from these sources remains a problem. Here we examine the first stage of formation of a geocentric swarm by capture of planetesimals from initially heliocentric orbits.

The only plausible capture mechanism that is not dependent on very low approach velocities is the mutual collision of planetesimals passing within Earth's sphere of influence. The dissipation of energy in inelastic collisions or accretion events changes the value of the Jacobi parameter, allowing capture into bound geocentric orbits. Ruskol[5] noted that this process is most effective for small bodies with larger area/mass, possibly allowing compositional sorting (e.g., if mean Fe content varies with size).[1,5] She assumed that planetesimals captured in this way would bring net prograde angular momentum sufficient to ensure stable orbits about the proto-Earth.

We have tested this capture scenario directly by many-body numerical integration of planetesimal orbits in near-Earth space. Initial orbits are chosen randomly from a uniform distribution in a outside the sphere of influence. The program can integrate up to 200 trajectories simultaneously. For a reasonable chance of collision with this limited number, only the planar case is considered, with approaches within 4×10^9 cm scored as collisions. All collisions result in coagulation. A particle's status, free or bound, is determined by the value of the Jacobi parameter. Collisions within the sphere of influence are scored as free-free, free-bound, or bound-bound. The number of events is severely limited by computer time, but allows some useful conclusions.

With no initial random velocities ($e = 0$), 78 free-free collisions yielded 27 captures (35%), 9 prograde and 18 retrograde. A uniform distribution of random velocities up to 0.05 times the heliocentric circular velocity yielded 68 free-free collisions with 14 captures (21%), evenly divided prograde-retrograde. In both cases, free-bound collisions tend to cause captured bodies to spiral inward until accreted by Earth. These results agree with those of Davis and Herbert[3] that the systematic contribution of angular momentum is insufficient to maintain an orbiting swarm under heavy bombardment. Thus, a circumterrestrial swarm can be formed rather easily, but is hard to sustain because the mean net angular momentum of a many-body swarm is small. The requisite angular momentum can be supplied by a single collision (or a few, at most) of large bodies within Earth's sphere of influence. A swarm formed in this way could have subsequently accreted up to several times its original mass without collapsing onto the planet, possibly allowing enough processing of proto-lunar material to produce iron-silicate fractionation.

*Research conducted in conjunction with the Tucson Lunar Origin Consortium.

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C-2

N85 13752 D43

THE LUNAR ANGULAR MOMENTUM PROBLEM*; Stuart J. Weidenschilling, Planetary Science Institute, Tucson, Arizona 85719.

Formation of the Moon by classical Darwin-type fission of a rapidly spinning proto-Earth requires ≈3 1/2 times the present angular momentum of the Earth-Moon system. Proponents of fission have proposed mechanisms for the escape of the excess after fission, but have generally assumed that the proto-Earth could acquire the requisite angular momentum during its accretion. Both numerical[1,2,3] and analytic[4] studies yield the result that the systematic angular momentum delivered by impacting planetesimals is small, and should produce a slowly rotating planet. Even the most favorable case of Davis and Herbert,[2] with *a* and *e* distributions maximizing prograde angular momentum of impacting orbits, yields barely the present angular momentum of the system. More plausible distributions yield much lower values. These results appear to rule out acquisition of enough angular momentum for fission by the accretion of small bodies directly impacting the planet.

More angular momentum could be supplied if Earth was surrounded by a prograde accretion disk. Orbital decay of disk particles due to viscous spreading or "accretion drag" due to impact of low angular momentum material onto the disk would add mass to Earth with specific angular momentum of circular orbital motion at its surface. For fission instability, Earth would have to acquire ≈3/4 of its total mass via a disk. The low mean angular momentum delivered by infalling planetesimals makes it hard to maintain such a disk, but viscous spreading might prevent it from collapsing onto the planet, while allowing most of the mass to flow inward. To maintain a steady-state disk, the mean specific angular momentum of material impacting the disk must equal that reaching the Earth at the surface orbital velocity. The most favorable case of Davis and Herbert requires a disk radius greater than $10R_\oplus$ for a steady state; the processing of so much mass through a region well outside the Roche limit would favor a co-accretion scenario rather than fission.

Even if the entire planetary mass were processed through an accretion disk, it might not reach rotational instability. At ≈80% of the critical angular momentum, the planet would evolve from an axially symmetric Maclaurin spheroid to a triaxial Jacobi ellipsoid. The non-axisymmetric gravitational field would transfer angular momentum back to the disk beyond the synchronous altitude (≈ $1.5\ R_\oplus$) via resonances and density waves. Thus, fission instability could not be reached by disk accretion, either. The requisite angular momentum could be delivered only by a large (stochastic) impact of a Mars-sized body, but this scenario does not resemble classical fission.

There is a lesser but similar problem with co-accretion models.[5] To avoid orbital collapse by accretion drag, the Moon must gain angular momentum from the rapidly rotating Earth via tides. Accumulation of the planet by direct impacts of planetesimals does not supply enough angular momentum. It would require processing ≈$0.2\ M_\oplus$ through an accretion disk, or else a giant impact, to spin up the proto-Earth before the lunar embryo formed. Thus, co-accretion requires an earlier event that might in itself have sufficed to form the Moon.

*Research conducted in conjunction with the Tucson Lunar Origin Consortium.

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D44 (4)

N85 13753

A CIRCUMTERRESTRIAL COMPOSITIONAL FILTER*; Clark R. Chapman and Richard Greenberg, Planetary Science Institute, Tucson, Arizona 85719.

A major question about the moon is its under-abundance of iron. We seek (as others have) to understand whether a metal-silicate fractionation of heliocentric bodies can be achieved through collisional interactions with a circumterrestrial swarm. Large, dense metallic cores of disrupted, differentiated planetesimals could pass through such a swarm relatively unimpeded, while silicate fragments would be filtered out and captured by the cloud, which might later accrete into a metal-depleted moon. We envision planetesimals left over during the very late stages of accretion of the Earth[1], with heliocentric orbits extending a few tenths of an AU beyond the Earth's orbit. They may have been heated and geochemically differentiated into silicate bodies with iron cores, just as has apparently happened to a major fraction of the asteroid population. Such bodies would diffuse toward Earth's orbit. We consider the rates of such diffusion and of the mutual collisional destruction within the population. We then consider the interaction of the differentiated planetesimals and their collisional products (both silicate mantle-fragments and iron cores) with a swarm of Earth-orbiting *lunesimals* (perhaps ejecta from the Earth) of km-scale, totaling 0.1 lunar mass, extending out 10 or 20 Earth radii. We find that such a small near-Earth population of lunesimals can filter out silicate-rich material, while passing iron cores, and form a moon composed partly of terrestrial material, but more substantially of the captured silicate-rich portions of the planetesimals. This silicate-separation process and accretion of lunesimals into the moon must go to completion in a time short compared with 10^7 yr, which is the timescale for the planetesimals to be swept up by, or scattered away by, the Earth.

Our quantitative conclusions are: (1) Silicate fragments will be trapped, while iron cores can pass through the circumterrestrial swarm dozens of times, taking at least 10^6 yr before being trapped. (2) Until the supply of planetesimals is depleted, it may prevent the circumterrestrial swarm from accreting: planetesimals larger than 100m in size could fragment rocky-strength lunesimals and would impact them on a timescale shorter than the timescale for accretion of lunesimals (1 year). (3) The iron cores are large and strong enough to withstand collisions with the lunesimal population. (4) If collision velocities among the planetesimals are <300 m/sec, as expected if they are governed chiefly by gravitational interactions with each other (rather than with larger planets), then the planetesimals and iron cores will survive long enough for the segregation process to go to completion. (5) The planetesimals apparently can diffuse toward the Earth's orbit on a timescale of 10^7 yr by their own collisional dissipation; they interact with the circumterrestrial swarm at velocities of several km/sec, as required for the segregation process. (6) During the course of 10^7 yr, the iron cores will be swept up by the Earth and Venus (or gravitationally scattered away), so little metal will remain for accretion by the moon once the moon forms; the stirring-up of the circumterrestrial swarm will slow as the cores are depleted, and the moon will accrete. (7) The whole scenario works only if there is a way to maintain the hypothesized circumterrestrial swarm, which otherwise would collisionally diffuse on a timescale of 10^3 yr (much of it collapsing on the Earth); the source of angular momentum to maintain the swarm remains a mystery.[2,3]

*Research conducted in conjunction with the Tucson Lunar Origin Consortium.

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D45

THE ORIGIN OF THE MOON.

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Bulk density alone shows that the Moon is depleted in metallic FeNi relative to the Earth or to chondritic meteorites having similar FeO/MgO ratios (e.g., H chondrites). This depletion implies that the Moon formed not from chondrites but from differentiated material. Origin of the Moon by fission from the Earth offers a simple explanation for its depletion in FeNi, but this mechanism seems unlikely because of associated dynamical difficulties. Furthermore, the currently accepted moment of inertia, 0.3905±0023, implies that the Moon possesses a core roughly 300 km in radius, inconsistent with formation from the mantle. Lunar volatile element depletions have been invoked in support of fission, but volatile contents of eucritic meteorites are similarly low and the eucrites did not form by Earth fission. Much of the high volatile content of the Earth may reflect efficient late capture of volatile-rich cometary material due to the Earth's possession of an atmosphere.

A more plausible origin of the Moon is that developed by Ruskol (1977), accretion from the circumterrestrial swarm. She suggests that the low FeNi content of the Moon can be understood if the mean size of interplanetary silicate particles was much smaller than that for metal particles, since this would have led to preferential capture of silicates into Earth orbit, but we question whether the mean particle size of the metallic particles would have been great enough to prevent their capture into the swarm.

Although igneously formed meteorites are much less common than chondrites, the statistics are biased because most meteorites come from parent bodies that are near or beyond the Asteroid Belt; it is plausible that most of the asteroidal-size bodies ≲1 AU from the Sun melted within 100 Ma of the birth of the solar system, and that most of the protoplanetary matter was in these bodies. The eucritic parent body experienced metal/silicate fractionation >4.4 Ga ago. We (Wasson and Warren, 1979) suggested that near 1 AU asteroid differentiation occurred before the bulk of the protolunar material had been captured into a circumterrestrial swarm. These differentiated bodies broke up as a result of mutual impacts. Fragmentation tended to reduce the more brittle silicate crusts and mantles to relatively small (perhaps ≲1 m) size, whereas because of their much greater strength many of the metallic cores may have survived intact. Collision of small silicate fragments with debris already in Earth orbit led to the orbital capture, but the debris cloud was essentially transparent to the metallic cores, and these objects continued in heliocentric orbit until removed by a close planetary encounter of the first or second kind.

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FORMATION OF THE PRELUNAR ACCRETION DISK;

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Bill Ward and I (1,2) were led to the suggestion of a collisional origin of the Moon through the following consideration. The angular momentum of the Earth-Moon system is less than sufficient to spin the Earth to rotational instability, we were nevertheless interested to determine the mass of the body which, striking a tangential blow to the protoearth, could impart the angular momentum of the Earth-Moon system to the protoearth. The required projectile turned out to be about the mass of Mars. That defined the basic scenario of our lunar formation process.

In such a collision we assume that both target and projectile, having formed fairly rapidly, are molten and have developed iron cores. A collision at the escape velocity of 11 km/sec (or slightly more) is sufficient to vaporize the rocky mantle of the projectile and a like amount of material in the mantle of the target. The result is a major explosion centered slightly below the surface of the protoearth. Material ejected from the site of this explosion would normally, under gravitational control of the protoearth, be on trajectories which would return it to collide with the protoearth. We were interested in the fact that, as long as the material was in the form of vapor, it would also be accelerated by pressure gradients. This would assure that a minor part of the material would be thrown into orbit about the Earth, forming a prelunar accretion disk.

The subsequent process of lunar formation consists of the viscous dissipation of this accretion disk, accelerated by the fact that the self-gravity of the disk would attempt to form local condensations in the disk, only to have them sheared apart inside the Roche lobe with accompanying dissipation (2). The material transported beyond the Roche lobe can accumulate to form the Moon; the efficiency of the process is so high that the disk is likely to be largely vaporized in the process (3). An accompanying process with observable consequences is the loss of the Earth's primordial atmosphere by flow along the surface of the accretion disk (4).

At the site of the impact the vaporization of the rock is largely a result of the compression of the material, and, with an expected efficient nucleation, recondensation of the vapor should occur before the exploding material has expanded very far. Assuming that the condensed material is still fairly finely divided (particles of the order of a centimeter), collisions would ordinarily be plentiful and the material could still act as a compressible fluid. However, relative internal motions are probably largely eliminated in the vapor phase, and the expansion is thus likely to take place with little further transverse acceleration (the "gas" is "cold"). This situation will form a prelunar disk of small dimensions and the yield of material at the Roche lobe is likely to be too small.

This situation would be improved if relative motions can be induced among the particles when they have been carried to larger distances from the protoearth following the explosion (so that they will act as a "hot gas"). Transverse accelerations under these conditions impart much more angular momentum and make a larger disk. Two processes are under study that can contribute to such accelerations. One is the residual vapor from the more volatile constituents of the original rocks that is unlikely to be able to recondense under the expected temperature conditions. The other is the effect of gravitational accelerations acting within the expanding material due to its own self-gravity. Some simple numerical illustrations of these processes will be presented.

The precise line of impact of the projectile onto the target is not known. However, there is a substantial probability that the iron core of the projectile will not be absorbed by the protoearth at the time of this impact, but will be collected on subsequent impact. If so, it is likely to be substantially fragmented and sheared following the collision, and significant mutual gravitational effects of these fragments near the top of their trajectories can be quite effective in stirring the condensed particles. These fragments carry a great deal of angular momentum, and transverse accelerations of the condensed particles at these large distances from the protoearth can lead to the formation of a much larger prelunar disk.

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N85 13756 D47

MECHANICAL MODELS OF CLOSE APPROACHES AND COLLISIONS OF LARGE PROTOPLANETS. W.M. Kaula & A.E. Beachey, Dept. of Earth & Space Sciences, University of California, Los Angeles 90024.

In models of lunar origin by great impact, attention is usually paid to the hydrodynamic expansion resulting from the great amount of thermal energy. However, the source of this energy is, after all, gravitational. Given that tidal disruption is inevitably significant in a close approach between large bodies (1,2,3,4), it is to be expected that significant departures from simple hyperbolic orbits would occur even before impact. These departures could arise from mechanical effects, and hence purely mechanical models are worth pursuing.

For close approaches between protoplanets the size of Mars or larger, we represent each planet as an accumulation of bodies, typically 125. The calculation is started beyond the Roche limit, but close enough that tidal stresses will be big enough that on a global scale the planet is essentially fluid. For economy, the model is bilaterally symmetric about the plane defined by the initial position and velocity vectors, and planet spins are assumed orthogonal to this plane. The initial configuration is the tidally distorted ellipsoid about the line between planets. The trajectory of each of the elemental bodies is calculated summing the gravitational attractions of all bodies in both planets. The principal difficulty is taking into account pressure effects between bodies which are in contact, as is the case before tidal disruption and after any subsequent collisions. This is done by requiring bodies within a prescribed distance of each other to have mutual accelerations leading to zero relative velocity, conserving linear momentum for any group of such bodies, but allowing the group to rotate. The integration time-step is controlled mainly by not allowing this simulation to cause an artificial pulsation.

The most interesting results are obtained for approach offsets which are a small multiple of the planet radius and approach velocities of a few kilometers / second. In the case of an interaction between Mars and Earth sized protoplanets, most of the material ends in collision, but a few percert end in elliptic orbits and a few percent escape. The planet is typically spun up to about one rotation / five hours.

Another model is to consider an offset collision, such as arises from a wide range of approach velocities and offsets. The fluid state of the planets upon impact leads to essentially three bodies: the overlapped portion, plus the two portions which are sheared off, as previously suggested (5,6). However, the state of the planets at this stage is already quite distorted, and it is not realisitic to treat them as spheres until the instant of impact.

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N85 13757

LUNAR ORIGIN FROM IMPACT ON THE EARTH: IS IT POSSIBLE? David J. Stevenson, Div. Geological and Planetary Sciences, Caltech, Pasadena, CA 91125.

All theories of lunar origin involve events or processes which seemingly have low efficiencies or low probabilities or both. The model I am pursuing is an impact-triggered "fission" lunar origin. Preliminary results indicate that the process is not necessarily inefficient nor unusually improbable. The model is, of course, not new (see refs 1-4, especially refs. 3,4) but this effort outlined here is the first attempt to replace hand-waving with physics. It is hoped to present some detailed modeling at the meeting; this abstract only outlines the issues that the models seek to address. Part of the work[5] relating to disk evolution has been presented previously; emphasis here is on the emplacement of earth-derived material into earth orbit immediately after a large impact. The "Second Burn." If impact ejecta (a mixture of target and projectile) leave the impact site ballistically and are subsequently acted upon only by the gravity field of a spherical Earth, then the ejecta either reimpacts the Earth or escapes on a hyperbolic trajectory. Hence the need for a "second burn." I have considered three possible resolutions: pressure gradient acceleration, non-central gravity and viscous spreading. (i) Pressure Gradient Acceleration: The expanding vapor-liquid-solid ejecta cloud may have highly non-Keplerian motion for distances at least as great as a few projectile radii away from impact.[6] Suppose that Keplerian motion occurs after material has reached a height h above the surface (measured in units for which earth's radius = 1) and has initial radial and tangential velocity components at this height of δ and $1 - \varepsilon$, respectively (measured in units for which escape velocity = 1). Assuming h, δ, ε all $\ll 1$, one finds that subsequent periapse occurs above the earth's surface for bound (negative total energy) trajectories provided $h/2 \lesssim \varepsilon \lesssim 2/3\ h^{1/2}$, $|\delta| \lesssim (h - 9/4\ \varepsilon^2)^{1/2}$. It follows that very large oblique impacts ($\gtrsim 10^3$ km bodies) are high desirable since they would lead to relatively large h with some of the material having low δ and potentially acceptable ε, leading to orbital injection. (ii) Non-central gravity can have a somewhat similar effect: near the impact site and time of impact, the actual gravitational field can have a markedly non-central character and a distance h ~ few projectile radii must be exceeded before central Keplerian motion occurs. Numerical results indicate comparable (but additive) effects to pressure-gradient acceleration. (iii) Consider a narrow, steady, 2-D viscous jet[7] emanating from the earth's surface. It is possible to approximate the equation of motion in the form $d\underline{V}/dt = \underline{g} + \alpha\nu(\underline{V}_K - \underline{V})/D^2$ where $\underline{V}$ is velocity at some position in the jet, $\underline{g}$ is the acceleration due to earth's gravity (assumed central), α is a numerical constant, ν is the viscosity in the jet (assumed turbulent; due to shear instabilities), $\underline{V}_K$ is velocity of the central streamline (i.e. equidistant from the inner and outer edges of the jet) which can be shown to be approximately Keplerian, and D(t) is the jet width. I find that material in the outer (i.e. further from Earth center) part of the jet gains both energy and angular momentum from viscous stresses and that orbital injection is possible (and, less commonly, escape) at the expense of dumping over half of the jet back on the Earth.

Spin-out of a Superrotating Atmosphere. Although "second burn" is possible, the amount of material emplaced in orbit tends to be small if the impact velocity ~escape velocity.[8] This difficulty is reduced if very large impacts occur since they cause an earth-encircling superrotating atmosphere (T ~ 10^4 K) of MgO-SiO-O plus liquid which can bleed out through the new equatorial plane to form a disk. A similar model has been proposed for the formation of the Uranian satellites.[9] The earth is then enveloped in a highly oblate and opaque silicate atmosphere which has a photospheric temperature of ~2000 K and a cooling time ~10^2 yr. In this time, the disk can evolve and emplace at the Roche limit sufficient material to form one or more proto-Moons.[5] It is concluded that orbital emplacement of material is possible and that the process is much more efficient for very large impacts than small (radius $\lesssim 10^2$ km) impacts. Major quantitative uncertainties remain.

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