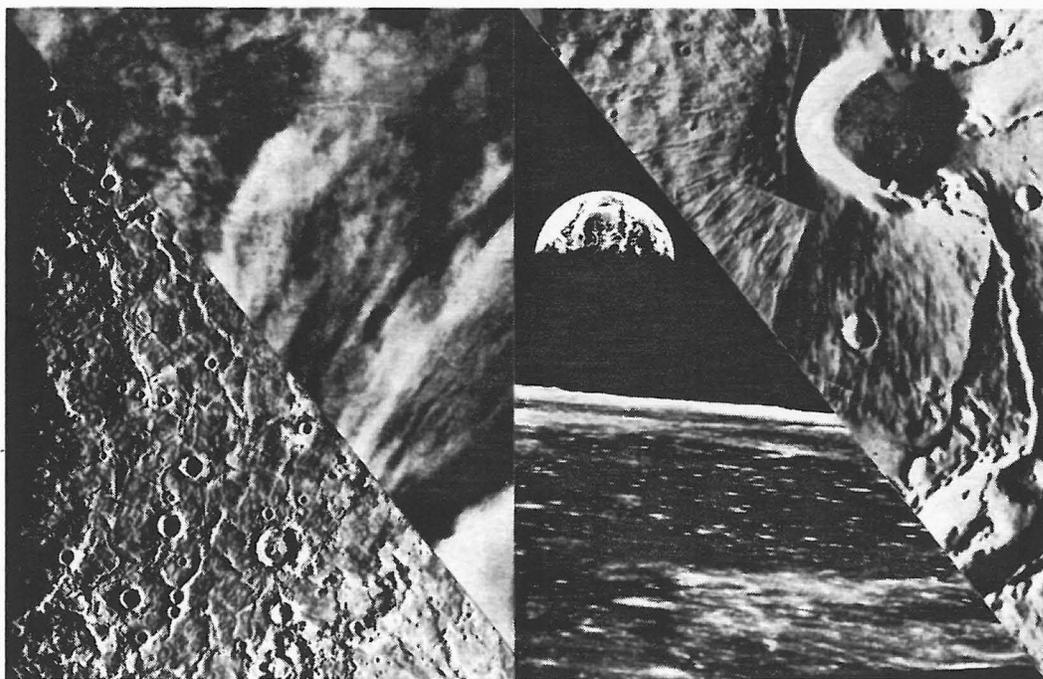
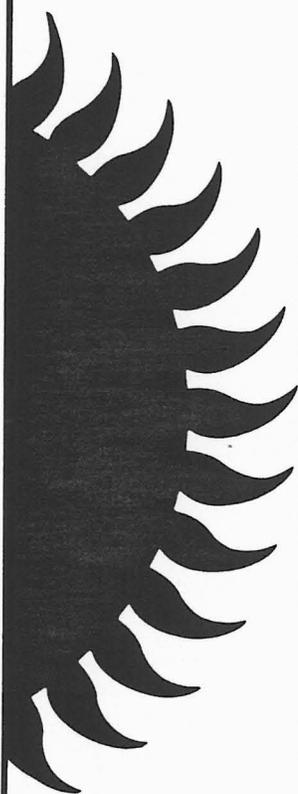


TERRESTRIAL PLANETS: COMPARATIVE PLANETOLOGY

June 5-7, 1985



Hosted by

California Institute of Technology, Ramo Auditorium

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American Geophysical Union

Division for Planetary Science (American Astronomical Society)

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Division of Geological and Planetary Sciences (California Institute of Technology)

Abstracts Presented to

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NOBLE GASES IN METEORITES AND TERRESTRIAL PLANETS. J.F. Wacker (Enrico Fermi Inst., Univ. of Chicago, Chicago, IL 60637)

Terrestrial planets and chondrites have noble gas patterns that are sufficiently alike, especially Ne/Ar, that they may have acquired their noble gases by similar processes. Meteorites presumably obtained their noble gases during formation in the solar nebula. Adsorption onto C — the major gas carrier in chondrites — is the likely mechanism for trapping noble gases; recent laboratory simulations (Wacker *et al.*, 1985; Zadnik *et al.*, 1985) support this hypothesis. Thus at least in principle, the range of elemental fractionations in chondrites, which is not large, can be explained by variations in T, P and gas carriers. The story is more complex for planets. An attractive possibility is that the planets acquired their noble gases in a late-accreting veneer of chondritic material (Anders & Owen, 1977). In chondrites, noble gases correlate with C,N,H, and volatile metals; by Occam's Razor, we would expect a similar coupling in planets. Indeed, the Earth's crust and mantle contain chondritic-like trace volatiles and Pt-group metals, respectively, and the Earth's oceans resemble C-chondrites in their enrichment of D (8X vs 8-10X of the galactic D/H ratio, Geiss and Reeves, 1981)). However, though the noble gas abundances and elemental patterns overlap in chondrites and planets, there are distinct differences, e.g. Kr/Xe is less fractionated in planets and Xe is isotopically fractionated, at least in the Earth.

Other models have been proposed to explain some of the specific noble gas patterns in planets. These include: 1.) Noble gases may have been directly trapped by pre-planetary material instead of arriving in a veneer (Pollack & Black, 1979). 2.) For Venus, irradiation of pre-planetary material, followed by diffusive loss of Ne, could explain the high concentration of ³⁶Ar (Wetherill, 1980; McElroy & Prather, 1981). 3.) The Earth and Venus may have initially had similar abundances of noble gases but the Earth lost its share during the Moon-forming event (Cameron, 1983). 4.) Noble gases could have been captured by planetesimals, possibly leading to gravitational fractionation, particularly of Xe isotopes (Ozima & Nakagawa, 1980). 5.) Noble gases may have been dissolved in the hot outer portion of the Earth during contact with a primordial atmosphere (Mizuno, *et al.*, 1980). Each of these models has its advantages, but a general criticism is that all require different processes for chondrites and planets, or even for each planet.

RELATIONSHIPS BETWEEN CHONDRITIC METEORITES AND PLANETS.

John T. Wasson (University of California, Los Angeles, CA 90024)

Chondrites formed in the solar nebula prior to the formation of planets; they probably constituted the bulk of preplanetary solids in the inner solar system. In the highly reduced enstatite chondrites 10% of Si is metallic; in the highly oxidized CM and CI chondrites 20-30% of Fe is in the +3 state. The high density of Mercury implies that nebular Fe was reduced, whereas the low density of Mars indicates that a large fraction was oxidized. Most rare gases in the terrestrial planets seem to have accreted trapped in grains; Venusian interelement ratios resemble those in enstatite chondrites; Earth and Mars ratios are more like those in ordinary or carbonaceous chondrites. The enstatite-chondrite O-isotopic composition falls directly on the terrestrial-fractionation line, indicating formation in the hot, well-mixed, inner portion of the nebula; eucrites, related achondrites and SNC meteorites (from Mars?) also fall near the line. Grain-gas isotopic equilibration did not occur where the CV, CO and CM chondrites formed. These observations imply that enstatite chondrites formed near the Sun (near Venus?), the carbonaceous chondrites formed far from the Sun, the ordinary chondrites at an intermediate location. Compositional data on Mercury, comets, an asteroidal fragment, and the moons of Mars are badly needed.

TERRESTRIAL Xe ISOTOPIC CONSTRAINTS ON THE EARLY HISTORY OF THE EARTH
M. Ozima (Geophys. Inst. Univ. of Tokyo, Tokyo 113), F.A. Podosek (Dept. Earth Planet. Sci., Washington Univ., St. Louis), G. Igarashi (Geophys. Inst., Univ. of Tokyo, Tokyo 113)

We examine all the available data on Xe isotopic compositions in terrestrial materials and discuss their constraints on the early history of the earth.

Radiogenic $^{129}\text{Xe}_r$ reported in New Mexico CO_2 well gas and in some mantle-derived materials such as mantle xenoliths, MORBs and diamonds has been generally regarded to reflect very early mantle degassing, i.e., within a few half-lives of ^{129}I ($T_{1/2} = 17$ Ma) after the formation of the earth. These samples also show excess in ^{136}Xe relative to air Xe. However, except for the CO_2 well Xe in which the excess in ^{136}Xe is clearly attributable to ^{244}Pu -fission, it is not possible to resolve whether the excess ^{136}Xe is due to ^{244}Pu -fission or to ^{238}U -fission. The fact that the CO_2 well Xe has a smaller ^{244}Pu -fissiogenic $^{136}\text{Xe}_f$ relative to $^{129}\text{Xe}_r$ than air Xe shows that the source for the CO_2 well Xe is not related to the source from which air Xe was degassed. That is, the existence of $^{129}\text{Xe}_r$ does not necessarily indicate very early mantle degassing as often argued. The source region for the CO_2 well Xe must have been isolated from the mantle-atmosphere system for almost the whole history of the earth. The difference in $^{136}\text{Xe}_f/^{129}\text{Xe}_r$ between the CO_2 well gas Xe and air Xe, which reflects the difference in $^{244}\text{Pu}/^{129}\text{I}$, may be interpreted to mean that the inner region of the earth, from which the CO_2 well Xe was derived, accreted a few tens of millions of years earlier than the outer region from which the atmosphere was degassed.

NOBLE GAS PATTERNS IN THE ATMOSPHERES OF MARS AND EARTH: A COMPARISON VIA THE SNC METEORITES. R. O. Pepin and R. H. Becker, School of Physics and Astronomy, University of Minnesota, Minneapolis, Minnesota 55455.

Noble gas and nitrogen compositions in the glassy phase of the EETA 79001 shergottite correspond closely with Viking measurements. This direct evidence for the origin of the SNC meteorites on Mars, and for trapping of an unfractionated sample of martian atmospheric gases in the 79001 glass, provides a reasonable basis for comparing the martian and terrestrial atmospheres with more precision than that afforded by the Viking data set. Results are that, with one exception, elemental and isotopic compositions of nonradiogenic martian noble gases are similar to those in the earth's atmosphere; relatively small isotopic discrepancies in Kr and perhaps Xe may be attributable to different degrees of mass fractionation of a common parent reservoir. The anomaly is in Ar composition, where martian $^{36}\text{Ar}/^{38}\text{Ar} \approx 4$ is strikingly lower than the values near 5.3 that characterize both the earth and major meteoritic gas carriers. Although a primordial martian ratio of 5.3 could in principle be altered by some planet-specific process (e.g., cosmic-ray spallation of surface materials) operating over geologic time, we have not found one that works.

SNC meteorites contain small, variable amounts of nonatmospheric indigenous gases, presumably from basalt source regions in the martian mantle. The indigenous $^{15}\text{N}/^{14}\text{N}$ ratio is comparable to or less than the terrestrial ratio; it is far below that in the martian atmosphere, suggesting that atmospheric gases enriched in ^{15}N have not been in contact with this mantle reservoir. Indigenous noble gas isotope ratios involving radiogenic products ($^4\text{Ar}/^{36}\text{Ar}$, $^{129}\text{Xe}/^{132}\text{Xe}$) are smaller than their corresponding atmospheric values. As pointed out recently by Ott and Begemann, this relationship indicates that the SNC source regions were not the parent reservoirs from which the martian atmosphere outgassed.

OXIDATION STATES OF IRON IN THE TERRESTRIAL PLANETS: EVIDENCE AND IMPLICATIONS FOR ACCRETION MODELS. R.L.Huguenin and S.L. Harris (University of Massachusetts, Amherst, MA 01003)

Analyses of Mars spectra reveal that primary minerals may be more iron-rich than average basalts on Earth, and the oxidation state of iron in the pyroxines suggests equally high or higher oxygen fugacities on Mars than Earth. Analysis of Mercury spectra reveal that silicate iron contents are substantially lower than those on Mars. Mercury, however, probably has a substantial iron core. This is consistent with a lower oxidation state of iron on Mercury than on Mars. These findings are consistent with predictions of models of equilibrium condensation and homogeneous accretion. Those models predict that Mercury would have negligible Fe^{2+} in silicates ($\text{Fe}/\text{Fe}+\text{Mg} \lesssim .001$), while on Mars Fe^{2+} contents in silicates would be significant ($\text{Fe}/\text{Fe}+\text{Mg} \approx 0.5$). For Mercury iron should be virtually all metallic, while for Mars the iron would be all oxidized as FeS and silicate. Surface measurements of $\text{Fe}/\text{Fe}+\text{Mg}$ on Venus, Earth, and Mars further support the predicted relative increase in $\text{Fe}/\text{Fe}+\text{Mg}$ ratio (increased oxidation state) with distance from the Sun. The implied high oxygen fugacities on Mars (Fe^{3+} in silicates) provide additional consistency with the model predictions. High oxygen fugacities suggest that significant H_2O occurred with the magma, and the models predict high interior H_2O contents due to accretion of tremolite-and-talc-family minerals. Talc would be the dominant source of H_2O , followed by less abundant tremolite, organic material, and H dissolved in metallic iron. An implication is that Mars should be significantly more H_2O -rich than Earth, since Earth would not have accreted talc, only the less abundant tremolite, organics, and dissolved H. At the same time Mars would have accreted negligible metallic iron to react with H_2O .

NEBULAR VOLATILE FRACTIONATIONS ASSOCIATED WITH CHONDRULE FORMATION. Alfred Kracher (Dept. of Earth Sciences, Iowa State Univ., Ames, IA 50011)

Chondrules are ubiquitous constituents of primitive solar system matter, indicating that chondrule formation was an important and widespread process in the early history of the solar system. If chondrules formed from fine grained, CI-like precursors, some volatile fractionation must have accompanied chondrule formation. This is most likely related to a separation of chondrules from gas (and dust fine enough to be coupled to gas) shortly after formation, a process required by most models of chondrule formation. If chondrules are continuously formed in and removed from a region of the solar nebula, the chemical environment in this region will change. 1. Sulfur and oxygen: Vaporization of solid increases both O and S in the gas relative to H. Depending on the O/S ratio, which may vary widely as a function of precursor composition and temperature, two cases can be distinguished: (a) Sulfur requires reaction with solid to condense, and thus may become much more enriched than O. In this case, S(gas) will react not only with metallic Fe, but also with FeO , and eventually with other elements, like Ca and Mg, to form "exotic" sulfides. These reactions should be studied in detail for their possible role in the formation of enstatite chondrites. (b) If a significant amount of silicate is vaporized together with sulfides and does not recondense, changes in H/O outweigh S enrichment. Under these conditions the only significant effect on bulk chemistry is that chondrules do not get reduced during formation, but otherwise there seems to be little chemical fractionation. In combination, these two effects may be able to account for much of the chemical variation among various types of chondrites. 2. Minor and trace elements: If dust is present in the chondrule forming region, excess volatiles, like Na, may condense on it. Opaque, fine grained matrix in unequilibrated chondrites, which is thought to derive from dust, has indeed been found to have a volatile element abundance complementary to chondrules. Oxygen isotope systematics suggest that different types of chondrites formed in different parts of the solar nebula. This means that the fractionations discussed here probably varied systematically on a large scale within the nebula rather than being local perturbations of a more or less chemically homogenous system.

THE DISTRIBUTION OF COMPOSITIONAL CLASSES IN THE ASTEROID BELT: A COSMOCHEMICAL FINGERPRINT? J. Gradie (Planetary Geosciences Division, HIG, University of Hawaii, Honolulu, HI 96822)

Studies of the physical properties of the asteroids show a nonrandom distribution of types across the belt (Gradie and Tedesco, *Science* 216, 1405-1407, 1982) for asteroid classes E, S, M, F, C, P, and D. The general trend is for asteroids in the inner belt to have higher albedos and stronger mafic silicate absorption features than those asteroids located further out in the belt. One interpretation of this trend is that the asteroids, which occupy the region between the silicate-rich terrestrial planets and the volatile-rich outer planets, have preserved in their heliocentric compositional distribution a cosmochemical fingerprint of the thermodynamic conditions present in the solar nebula at the time of their formation. This hypothesis predicts that the differences in the spectral properties among the low-albedo classes (C, P, F, P, and D) are due to temperature controlled processes which formed carbonaceous opaques. If this is true then the exact composition of the opaque components could, in principle, be used to determine the thermodynamic conditions between the orbits of Mars and Jupiter during the formation of the asteroids.

LATE-STAGE PLANETESIMALS: HOW BIG? R. Greenberg, D.R. Davis, C.R. Chapman, and S.J. Weidenschilling (Planetary Science Institute, Tucson, AZ 85719)

Numerical simulation of the early stages of planet growth (Greenberg *et al.*, 1978) show that a few bodies nearly 1000 km in diameter may have formed within $\sim 10^5$ yr after solid material grew into km-scale planetesimals by gravitational instability (Safronov, 1969; Goldreich & Ward, 1972). Even after such large bodies formed, the bulk of the mass of the future terrestrial planet zone resided in small bodies. Subsequent evolution is difficult to model because it requires simultaneous consideration of continuum (multitudinous small bodies) and discrete (a few large bodies) evolution. Some relevant issues include definition of accretional feeding zones, evaluation of the range of gravitational influence, viscous transport and diffusion, orbital commensurabilities, role of gas, etc. The first large bodies may have been (a) the embryos of the final planets, which grew by accreting tiny planetesimals, or (b) merely the first of many 1000+ km bodies, which grew independently and later collided to form the planets. Other scenarios, perhaps between the extremes of (a) and (b), are possible. Models of late-stage accretion that assume all bodies to be initially nearly Moon-sized (e.g., Wetherill, 1985) provide insight into relevant collisional and dynamical processes; but until the processes that might have led up to such assumed "initial" conditions are understood, any application of such models to planet growth (e.g., the giant-impact Moon-origin model) is speculative. Alternative possibilities, such as scenario (a) above, would have more orderly accretion of small planetesimals throughout planet growth and indeed up to the present. A size distribution that evolved in accord with scenario (a) could also help resolve some long-standing problems: It would explain growth of Uranus and Neptune in reasonable time, with comets as a by-product (Greenberg *et al.*, 1984), and would allow Vesta to survive the collisional evolution of the asteroid belt intact (Davis *et al.*, 1985). On the other hand, scenario (a) fails to provide the moderately large planetesimals probably needed to explain terrestrial planets' obliquities. Our chief point is that the correct size distribution during the later stages of planet growth remains unknown.

WHAT DETERMINES THE LOCATION OF SATELLITES AND PLANETS?

G. Arrhenius (University of California, San Diego, La Jolla, CA 92093)

The discrete structural pattern in the distribution of the satellites and planets around their primaries has since its discovery been thought to hold the key to the origin and evolution of the solar system. Different attempts to rationalize this distribution are reviewed with emphasis on theories with foundation in verifiable physical processes. Foremost among these is the band structure theory, which relates the emplacement of interstellar dust and gas source material around the magnetized primarily to the critical velocity for ionization of the four major interstellar gas components. The uncertainties, that are inevitable in all reconstructions, are in this theory compensated by the support from precise manifestations of the 2/3 effect in the Saturnian ring system and in the asteroid belt, and by the reproduction of related phenomena in laboratory and space experiments.

INTERRELATIONSHIPS AMONG THE TERRESTRIAL PLANETS.

A.S.P.Rao (Dept. of Geology, Osmania University, Hyderabad-500007 India).

The spatial distribution of mass in the Solar system provides invaluable clues pertaining to the condensation history of the solar nebula, to the sequence of condensation of minerals and metal alloys in different P-T Regimes in the nebula and to the time sequence in the nucleation of planetary iron cores. Massive planets (Earth & Venus) were due to the twin processes of early nucleation of iron into massive cores and late termination of accretion processes which resulted in the accretion of volatile rich materials also. On the other hand, less massive planets (Mercury & Mars) were due to late start in nucleation of iron into cores leading to early termination of accretion processes which resulted in non-accretion or poor accretion of volatile rich materials. This paper maintains that the accretionary features (High-lands, basins/craters) are present on all the planets and the thermally controlled tectonic styles (Rifts, fracture zones, volcanic plains, Canyons, trenches, domes etc.) are essentially of same origin but are of different magnitude and the interactions of degassed volatiles (atmosphere together with hydrosphere) with the lithosphere are dictating and diversifying the tectonic style on the Earth.

IMPACT PROCESSES AND THEIR IMPLICATIONS FOR PLANETARY FORMATION AND EARLY EVOLUTION. H. J. Melosh (Lunar and Planetary Lab, U. of Arizona, Tucson, Az. 85721)

Small impact craters dominate the geomorphology of small planetary bodies. Even Mars has extensive impact-dominated landscapes. The regoliths of the Moon and asteroids are created and maintained by impacts. It is now widely recognized that large impacts (craters 100-1000 km in diameter) are one of the major tectonic elements in the lithospheres of bodies like the Moon, Mercury, Mars and Callisto. The multiring basins these large impacts produce sometimes extend over an entire hemisphere. Such basins may have also affected tectonics during the earth's Hadean era.

Although it has long been appreciated that low velocity collisions played a major role in the accretion of planetesimals into planets, recent work indicates a far more profound role for impacts. Studies of the interaction of planetary atmospheres with large impacts, begun in an effort to define the climatological effects of the K-T impactor, suggest that impacts may remove a significant fraction of a planet's atmosphere. Such removal now offers hope of explaining the puzzling systematics of the heavy noble gases in the atmospheres of the earth, Venus, and Mars. More spectacularly, investigations of the effects of very large impacts, bodies of Moon to Mars-size that may have struck the protoearth, suggest that conditions in these impacts are nearly ideal for the occasional creation of large, devolatilized satellites, such as the earth's Moon. Such giant impacts are also likely responsible for the present spin states of the terrestrial planets.

QUESTIONS ABOUT MERCURY'S ROLE IN COMPARATIVE PLANETARY GEOPHYSICS. C.R. Chapman, S.J. Weidenschilling, D.R. Davis, R. Greenberg (Planetary Science Institute, 2030 E. Speedway, Tucson, AZ 85719) and M.A. Leake (Valdosta State College, Valdosta, GA 31698)

Previous discussion of Mercury's geophysical evolution has been in the context of a cratering chronology tied to that of the Moon and other terrestrial planets. Problems have arisen in formulating a mutually consistent picture of Mercury's evolution. It appears that one or more of the following widely adopted assumptions must be wrong about Mercury: (1) that its original composition at least approximately resulted from equilibrium condensation; (2) that its magnetic field arises from a still-active dynamo; (3) that its thermal evolution should have yielded early core formation followed by cooling and a global contraction approaching 20 km in the planet's radius; (4) that Mercury's surface is basaltic and the intercrater plains are of volcanic origin. We suggest that Mercury's role in comparative planetology be re-evaluated in the context of an alternative timescale based on the possibility that Mercury has been subjected to a continuing source of cratering projectiles over recent aeons, which have not impacted the other terrestrial planets. Although such "vulcanoids" have not yet been discovered, the evolution of Mercury's orbit due to secular perturbations could well have led to a prolonged period of sweeping out any intra-Mercurian planetesimals that were originally present. Under this hypothesis, Mercury's surface could be younger than previously believed, and we can more readily understand why Mercury's core is still molten.

VOLATILE LOSS FOLLOWING VERY LARGE IMPACTS. D.J. Stevenson,
(California Institute of Technology, 170-25, Pasadena, CA 91125)

Large impacts on growing planets can be fundamentally different in outcome than small impacts because they can lead to a planet-enveloping cloud of silicate vapor with a radiative cooling time long compared to dynamic time scales. Under these circumstances, there can be preferential volatile loss by hydrodynamic outflow immediately above the silicate cloud deck. This loss is in addition to the prompt, non-preferential loss immediately following the impact event. For example, if protoEarth is hit by a Mars-sized body at 14 km/s then the result is a brown dwarf star-like body ($T \sim 2000$ K, radius ~ 8500 km) for $\sim 10^2$ yr after impact. During this time, evaporative (Jeans loss) can be $\lambda 10^{-4}$ of the planetary mass, provided the impact has substantial angular momentum and a magma disk forms. The loss is preferentially from the extremities of the disk and can be easily 10^2 bar-equivalents of CO_2 or H_2O . This implies devolatilization of Moon-forming material in an impact origin and may have important implications for the CO_2 reservoirs of Venus, Earth, and Mars.

ORIGIN OF THE ATMOSPHERE AND HYDROSPHERE OF THE
TERRESTRIAL PLANETS. Takafumi Matsui and Yutaka Abe (University
of Tokyo, Bunkyo-ku, Tokyo 113, Japan)

It has been widely accepted that the terrestrial planets were formed by accretion of planetesimals. Frequent high-velocity impacts of planetesimals into a growing planet cause the formation of a proto-atmosphere and/or proto-ocean generated by impact degassing. Since an intense gravitational energy was liberated during accretion of planetesimals, existence of a proto-atmosphere affects the energy balance at the surface layers of a growing planet. We study an early thermal evolution of a planet growing by planetesimal impacts by taking into account simultaneously an evolution of an impact induced atmosphere. It is shown that the surface of a growing planet is heated due to the blanketing effect of the atmosphere and exceeds the melting temperature, which means that the surface of a growing planet was entirely covered by a "magma ocean". The amount of water in a proto-atmosphere is influenced by the formation of a "magma ocean". The result suggests that not the water content in planetesimals but the solubility of water in silicate melt controls the water content in a proto-atmosphere. It is interesting to note that irrespective of difference in initial water content of planetesimals the final water content in the atmosphere becomes almost constant and is about 10^{21} kg which is almost identical with the present amount of the ocean. It is also shown that the water in a proto-atmosphere can be liquid for the earth and thus becomes to be ocean but not for Venus.

AN IMPACT-INDUCED TERRESTRIAL ATMOSPHERE AND
IRON-WATER REACTIONS DURING ACCRETION OF THE EARTH
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Center, 2850 Bremerhaven, FRG) and T.J. Ahrens (Seismological
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Shock wave data and theoretical calculations have been used to derive models of an impact-generated terrestrial atmosphere during accretion of the Earth (Lange & Ahrens, *Icarus* 51, 1982a, 96; Lange & Ahrens, *PLPSC* 13, *JGR* 87 Suppl., 1982b, A451). In the models it was shown that impacts of infalling planetesimals not only provided the entire budget of terrestrial water but also led to a continuous depletion of near-surface layers of water-bearing minerals of their structural water. This resulted in a final atmospheric water reservoir comparable to the present day total water budget of the Earth.

One problem to consider is the interaction of metallic iron with free water at the surface of the accreting Earth. We carried out model calculations simulating these processes during accretion (Lange & Ahrens, *EPSL* 71, 1984, 111). We assume that these processes are the prime source of the terrestrial FeO component of silicates and oxides. We demonstrate that the iron-water reaction would result in the absence of atmospheric/hydrospheric water, if homogeneous accretion is assumed. In order to obtain the necessary amount of terrestrial water, slightly heterogeneous accretion with initially 36 wt.% iron planetesimals, as compared with a homogeneous value of 34 wt.% is required.

CLIMATIC CONSEQUENCES OF VERY HIGH CO₂ LEVELS IN EARTH'S EARLY
ATMOSPHERE. J.F. Kasting (MS 245-3, NASA Ames Research Center, Moffett Field,
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Earth has approximately 60 bars of carbon dioxide tied up in carbonate rocks, or roughly 2/3 the amount of CO₂ that Venus has in its atmosphere. Two different lines of evidence, one based on thermodynamics and the other on geochemical cycles, indicate that a substantial fraction of this CO₂ (10-20 bars) may have resided in the atmosphere during the first few hundred million years of the Earth's history. A natural question which arises concerning this hypothesis is whether this would have resulted in a runaway greenhouse, that is, an atmosphere which was too hot to allow the existence of liquid water at the surface. One-dimensional radiative/convective model calculations presented here show that the surface temperature of a hypothetical primitive atmosphere containing 20 bars of CO₂ would have been less than 100 °C; thus, no runaway greenhouse should have occurred. The climatic stability of the early atmosphere is a consequence of three factors: reduced solar luminosity at that time, an increase in planetary albedo caused by Rayleigh scattering by CO₂, and the stabilizing effects of moist convection. The latter two factors are sufficient to prevent a CO₂-induced runaway greenhouse on the present Earth as well, for CO₂ levels up to 100 bars. Further studies are being undertaken to determine whether a runaway greenhouse could have occurred during the latter stages of the accretion process and, if so, whether it would have collapsed once the influx of material slowed down.

THE POLAR CAPS AND THE CLIMATIC EVOLUTION OF MARS. David A. Paige
(California Institute of Technology, Pasadena, CA 91125)

Both Mars and Earth experience quasi-periodic variations in the distribution of incident solar radiation due to secular perturbations in their orbital and axial elements. On Mars, the potential climatic effects of these perturbations are large because the mass of the Martian atmosphere may be determined by the vapor pressures of semi-permanent CO₂ frost deposits at the poles. A recent analysis of Viking Orbiter observations of the Martian polar caps suggests that the sensitivity of the Martian climate system to variations in the polar insolation may be considerably reduced by the tendency for polar frost deposits to become brighter with increasing rates of incident solar radiation. It is suggested that this phenomenon can be explained by the tendency for dust particles to sink into CO₂ frost at rates that depend on the magnitude of the incident solar flux.

BIOLOGICAL MODULATION OF PLANETARY ATMOSPHERES: THE EARLY EARTH SCENARIO. M. Schidlowski (Max-Planck-Institut für Chemie D-6500 Mainz, W. Germany).

The establishment and subsequent evolution of life on Earth was bound to have a profound impact on the chemical regime at the planet's surface and its atmosphere. This impact ultimately results from an accumulation of negative entropy in living systems which, in turn, stems from the very nature of life processes as entropy-deferring chemical reactions. Thereby, a thermodynamic gradient was imposed on near-surface environments that served as the driving force for a number of important geochemical transformations. The most glaring example is the redox imbalance between the modern atmosphere and the material of the Earth's crust. Current photochemical models predict extremely low partial pressures of oxygen in the Earth's prebiological atmosphere since photodissociation of water vapor is diffusion-limited and determined by the temperature of the tropopause cold trap that prevents a major leakage of H₂O to the upper atmosphere (because of this diffusion limitation, increased UV luminosity during the Sun's T-Tauri phase is unlikely to have dramatically enhanced photodissociation rates on the ancient Earth). Accordingly, there is widespread consensus that any large-scale oxygenation of the primitive atmosphere was contingent on the advent of biological (autotrophic) carbon fixation. Several independent lines of evidence suggest that photoautotrophy had been extant as both a biochemical process and as a geochemical agent since at least 3.8 Ga ago. Combining the stoichiometry of the photosynthesis reaction with a carbon isotope mass balance and current concepts for the evolution of the stationary sedimentary mass as a function of time, it is possible to quantify, within certain limits, the accumulation of oxygen and its photosynthetic oxidation equivalents through Earth history.

VOLATILES ON SATELLITES OF THE OUTER SOLAR SYSTEM. J. I. Lunine (Univ. of Arizona, Tucson 85721)

Under appropriate conditions, molecules of cosmochemically abundant elements can act as volatiles (i.e., undergo phase changes) and hence play a dominant role in the climatic and surficial evolution of solid bodies. Examples on terrestrial planets are H₂O on Earth and H₂O and CO₂ on Mars. We explore analogous processes in the outer solar system focussing on CH₄, its associated hydrocarbons, and N₂ on Titan and Triton, the large moons of Saturn and Neptune. A kilometer-deep C₂H₆-CH₄ ocean has been proposed for the surface of Titan to reconcile data on the lower atmosphere with understanding of the photochemical conversion of methane to heavier hydrocarbons (Lunine, Stevenson and Yung, *Science* 222, 1229, 1983). If such an ocean exists, then it has dissolved in it an amount of N₂ (the dominant atmospheric constituent) equal to the present atmospheric abundance. Since N₂ contributes with CH₄ a substantial greenhouse effect (Courtin, *Icarus* 51, 466, 1982), the atmospheric physical and chemical characteristics are strongly coupled to those of the ocean, which change with time as methane is photolyzed in the stratosphere. The surface of Titan could have been substantially cooler in the past, enough perhaps to have frozen out a CH₄-N₂ layer. Because the solubility of N₂ in H₂O is negligible under terrestrial conditions, this process has no direct analog on earth; however, some relationship exists to the "runaway greenhouse" model for primordial Venus (Pollack, *Icarus* 37, 479, 1979) and the possible climatic implications of the buffering of Earth's atmospheric CO₂ by the oceans (Walker, *Evolution of the Atmosphere*, 1977). Two important diagnostics, measurable in Titan's atmosphere, of the conditions under which icy satellites formed are the abundances of noble gases and the CH₃D/CH₄ ratio. Both of these indicators have been altered during the evolution of Titan's surface-atmosphere system, the former by interaction with the ocean and the latter by progressive photolysis of methane into heavier hydrocarbons (Lunine and Stevenson, *Ap. J. Suppl.* 58, 1985; Pinto, et. al., *Nature*, submitted, 1985). The physical state and composition of volatiles on the surface of Triton is controversial (Cruikshank, Brown, and Clark, *Icarus* 58 293, 1984; Lunine and Stevenson, *Nature* submitted, 1985), but plausibly could include CH₄, N₂ and perhaps CO. If condensed CH₄ and N₂ (or equivalently CO) are widespread, their transformation to and from the vapor phase dominates the surface energy balance with sunlight. The extreme seasonal modulation of subsolar latitude on Triton is thus primarily expressed by volatile transport rather than large temperature changes, with possibly drastic observational consequences (Trafton, *Icarus* 58, 312, 1984). The presence of two volatile species differing greatly in their vapor pressures (CH₄ vs. N₂/CO), particularly if the condensed phases are solid, makes Triton a crude analog of Mars. However, Triton might be more appropriately regarded as a "deep-freeze" version of Titan.

PLANETARY SURFACE PROCESSES: A REVIEW. R. Greeley (Department of Geology and Center for Meteorite Studies, Arizona State University, Tempe, AZ 85287)

Earth's surface has been shaped by a variety of processes, including volcanism, tectonism, impact cratering, and gradation. Solar System exploration and geological mapping have shown that these processes operate on all the terrestrial planets, but that the intensity of specific processes varies with planet and time. Gradation is a complex process that begins with weathering and erosion, continues with transport of weathered debris, and ends with deposition. Gradation works through the agents of gravity (e.g. landslides, all planets), wind (Earth, Mars, Venus), and water (Earth, Mars, Venus [?]) and can shed light on planetary surface evolution. Because much of gradation involves interactions between the atmosphere and the lithosphere, surface features resulting from gradation often provide clues to climate history. Rates of surface erosion vary with planet and must be taken into account in assessing ages of surface units based on impact crater frequency distributions. The products of gradation may substantially influence remote sensing "signatures" for determination of composition and must be taken into account in interpreting such data.

Gradation is a planetary "leveling" process that erodes topographically high areas and fills topographically low areas. Thus, it tends to balance relief produced by cratering, tectonism, and volcanism.

PERMAFROST FEATURES ON EARTH AND MARS: SIMILARITIES -
DIFFERENCES. H. - P. Jöns (FRG, Geol. Inst.,
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On Earth, typical permafrost features are polygonal structures (ice wedges, sand wedges), pingos and soli-/ gelifluxion features. In areas around the poles and in mountain ranges the precipitation (snow) accumulates to inland ice or ice streams (glacier). On Mars the same features have been identified: Polygonal features cover the larger part of the Northern Lowlands indicating probably an ice wedge-/sand wedge system or desiccation cracks. These features probably indicate the extend of large mud accumulations which seem to be related to large outflow events of the chaotic terrains. The "shore line" of this mud accumulations is indicated by a special set of relief types (arcuate ground undulations, large gelifluxion-like features). In some areas large pingo-like hills have been identified. The melting of a thick layer of permafrost and/or ground ice in the area of updomings resulted in the origin of a special type of large-scale permafrost-related features which have not yet been identified on Earth: Chaotic terrains consist of large depressions which are embayed by steep escarpments. They are related to the Northern Lowlands by large outflow channels. In the vicinity of the largest martian volcano, Olympus Mons, the melting of underlying permafrost and/or ground ice led to the downslope sliding of large parts of the primary shield which formed the aureole around Olympus Mons. Glacier-like features have been identified along the escarpment which separates the Southern Uplands from the Northern Lowlands.

INTERPRETATION OF PHOTOMETRIC MEASUREMENTS OF AIRLESS
BODIES.

B. J. Buratti* and R. M. Nelson, JPL/Caltech. *NAS/NRC Research Associate

A wealth of new photometric observations derived from spacecraft images and IUE when combined with ground-based measurements provides an excellent basis for understanding the scattering properties of the surfaces of airless bodies. These properties are controlled primarily by the following physical parameters: the single scattering albedo, the single particle phase function, the porosity of the upper regolith, and large scale roughness. Comparison of the observations with scattering models reveals both similarities and differences among the airless bodies in the solar system. For example, the textural characteristics of the regoliths of icy satellites appear to be generally similar to those of the Moon and Mercury; differences in the scattering functions can be attributed to albedo alone. A notable exception is Europa, which has a much more compact regolith. Io has an especially porous regolith, with void space of about 90%.

Although the solar phase curves of the Moon and Mercury are similar, Mercury's phase curve drops off less rapidly at solar phase angles greater than 100 degrees. This suggests that the Moon is rougher at scales larger than a few mm.

INTERRELATIONS FOR THE ELEMENTS OF THE SCATTERING MATRIX.

J.W. Hovenier (Free University, Amsterdam), H.C. van de Hulst (Leiden Observatory, Leiden) and C.V.M. van der Mee (Texas Tech University, Lubbock).

Analysis of the light scattered by molecules and particulate matter in planetary atmospheres can provide a great deal of information, especially when polarization is taken into account. A key role is then played by the 4x4 scattering matrix that transforms the Stokes parameters of the incident beam into those of the scattered beam. Elementary methods are described to obtain interrelations (equalities and inequalities) for the 16 elements of the scattering matrix, when light is scattered by a particle of arbitrary size, shape and composition or by a collection of such particles. Related work of others is mentioned and a selection of our results is presented by means of diagrams. A brief discussion is given of the implications of our results for the interpretation of polarimetric data of planets with an atmosphere.

On the Importance of Viscous Dissipation in Io. M.N. Ross and G. Schubert (University of California, Los Angeles, CA, 90024)

A model of Io is presented that consists of an elastic inner core, a low strength asthenosphere, and a thin elastic outer shell. The middle layer is assumed to possess negligible shear strength and to be characterized by a Newtonian viscosity. The fluid in the viscous layer is forced to circulate mainly by the tidal distortion in the outer shell, modeled here as a variation in the distortion amplitude. As a result, heat is generated in the fluid by viscous dissipation. There are three important unconstrained parameters in the model: the fluid viscosity, the thickness of the fluid layer, and the degree to which the distortion of the outer shell is affected by the fluid viscosity. For a wide range of these model parameters viscous heating can generate just as much or even more heat than does 'elastic' dissipation in the outer shell. The asthenospheric flow is a strong function of fluid layer thickness; for a thin (≤ 100 km thick) outer shell viscous heating in a 10 km thick fluid layer is 1000 times that for a 100 km thick layer. Viscous heating is also a strong function of angular distance from the Jupiter-Io line; the volumetric heating rate reaches a maximum 54 degrees from the sub- and anti-Jovian points. The model suggests that much of Io's heat flow may be generated below the outer shell and could provide a source of energy for any silicate volcanism on the satellite.

MODELS OF PLANETARY STRUCTURE AND EVOLUTION: THE CASE OF IO.

T. Spohn (Forschergruppe "Erde-Mond-System", Geologisch-Paläontologisches Institut, Westfälische Wilhelms-Universität, Corrensstraße 24, D-4400 Münster)

The interior structure of Jupiter's satellite Io is probably layered with a liquid core surrounded by a rigid mantle, a partially molten asthenosphere and a thin rigid lithosphere. The core radius could roughly equal half the planetary radius if the core is mostly FeS and if the mantle's compressibility is close to that of Earth's upper mantle rocks. The lithosphere thickness is controlled by the balance of the heat flux q_e across the lithosphere with the tidal heating rate H within the lithosphere and the heat flux q_i from the interior into the lithosphere. The maximum thickness determined by a balance of q_e with H is probably much smaller than the lithosphere thickness that maximizes H . Thus, if Io's interior was once melted and if it's resonant orbital state is ancient it will freeze from the inside out. The time scale of internal and latent heat removal in a molten Io is 10^8 a. Io's strong volcanic activity suggests the persistence of a partially molten asthenosphere to the present time.

MAGNETOTAILS OF THE TERRESTRIAL PLANETS: A COMPARATIVE STUDY

J.A. Slavin, E.J. Smith, B.E. Goldstein (Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA 91109), and S. P. Christon (Physics Department, California Institute of Technology, Pasadena, CA).

Spacecraft observations have established that all of the terrestrial planets interact strongly with the solar wind and possess well developed magnetic tails. At Mercury, Earth, and possibly Mars the tail forms as a result of the solar wind dragging back field lines intrinsic to the planet. Venus differs dramatically from the other planets in that its magnetotail is composed of interplanetary field lines draped about the ionopause. Accordingly, the observations made at the terrestrial planets provide an opportunity to compare not only induced (Venus) magnetic tail properties with those of intrinsic field tails, but also the variation among intrinsic field tails in the limits of no ionosphere (Mercury), weak intrinsic magnetic field (Mars), and strong magnetic field and ionosphere (Earth). This study conducts a comparative investigation of terrestrial planet magnetotail structure and dynamics. Mariner 10, Venera 9 & 10, Pioneer Venus Orbiter, ISEE-3, and Mars 2,3, & 5 measurements are used to characterize each magnetotail with respect to magnetic field topology, particle populations, and substorm activity. The results are discussed in terms of the physical properties of these planets and their interactions with the solar wind.

VENUS, EARTH AND MARS: PRESENT BOUNDS ON SIMILARITIES AND DIFFERENCES IN BULK COMPOSITION. K.A. Goettel (Dept. of Geological Sciences, Brown University, Providence, RI 02912)

The bulk compositions of the terrestrial planets are constrained in part by rigorous bounds derivable (to varying extents for each of the planets) from geophysical data and from chemical data obtained in situ or by remote sensing. In large part, however, the bulk compositions are constrained only by the inferred plausibility of assumptions made about the processes responsible for producing planets; such inferred "constraints" are subject to varying interpretations depending on the predilections of the interpreter. Present data are consistent with Venus, Earth and Mars all having solar (i.e., C1 chondritic) ratios of the major, non-volatile elements. The mantle of Mars has a higher FeO content than the Earth's present upper mantle. The FeO content of the Venus mantle is poorly constrained. Abundances of minor elements (including volatiles) are virtually unconstrained by geophysical data and only weakly constrained by existing chemical data. Inferences drawn from SNC meteorites suggest that Mars may be enriched in most volatiles relative to the Earth; the volatile content of Venus is poorly constrained. Abundances of volatile species probably vary in a very complex manner with the initial abundance of each volatile in a planet determined by the product of volatility during condensation in the nebula and volatility during accretion. Initial volatile contents could also be modified by later addition of volatile-rich material and/or by loss of some atmospheric constituents. Therefore, simple models in which volatiles are added in a single component probably do not accurately predict bulk volatile inventories of the planets. Quantitative bounds on the major element compositions of Venus, Earth and Mars and qualitative trends expected for volatile abundances will be discussed.

MINERALOGY AND CHEMISTRY OF THE EARTH. Don. L. Anderson
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The Earth is the prototype if not typical terrestrial planet. Ideas about the origin, evolution, structure and chemistry of the planets can be tested most thoroughly on the Earth. Similarly, the study of the other planets has generated new ideas which may be applicable to the Earth but which are not a part of terrestrial folklore. For example the concepts of magma oceans, large polar wander, global stress fields, buoyant lithosphere, deep cumulate reservoirs, multiple tectonic styles and crust generation may also apply to the Earth, present or past.

The combination of seismological, geochemical and high pressure research has changed our views of the Earth. It is no longer valid to think of the mantle as an essentially homogeneous undifferentiated shell of olivine with pockets of basalt providing melts to midocean ridges and oceanic islands. It appears to be a well differentiated, outgassed body with both radial and lateral chemical variations. The lower mantle is close to chondritic in its major element chemistry. The transition region is garnet and clinopyroxene-rich and may be a major basalt reservoir. This would explain the "thin crust paradox." Chemical stratification of the Earth probably occurred during accretion.

A SOLID-STATE FRAMEWORK FOR TERRESTRIAL UPPER MANTLES. L. Estey¹, B. Douglas, H. Spetzler² (CIRES/NOAA, Campus Box 449, University of Colorado, Boulder, CO 80309; also ¹Dept. of Physics, ²Dept. of Geological Sciences)

We propose a framework for understanding the upper-mantle structure of the terrestrial planets which is based on solid-state dislocation processes. First, we propose that the base of the lithosphere on any planet with a Mg-Fe silicate-rich upper-mantle is defined by the threshold temperatures of low-energy dislocation glide systems in olivine and the pyroxenes. This threshold temperature is ~ 1100 – 1200 K and is directly tied to the mobility of olivine $[100]\{0kl\}$ and pyroxene $[001](100)$ dislocations. Using this definition, all terrestrial planets of the Inner Solar System are expected to have mantle lithospheres. Second, the anomalous properties of the asthenosphere in the Earth (actively-maintained anisotropy, low velocity, high attenuation, low viscosity) are related to the rheological properties of an olivine-rich differentiate ~ 220 km thick. All of these properties can be the result of the abundant low-energy glide systems in olivine which are mobile at temperatures above ~ 1200 K. We propose that a true planetary asthenosphere must be both olivine-rich and at temperatures above ~ 1200 K. This model for the asthenosphere does not require partial melting and is therefore less sensitive to the constraints of volatile content (e.g. water) in the upper mantle. We estimate 1) the thickness of planetary lithospheres (from surface temperatures and temperature profiles) and 2) the maximum thickness of the olivine-rich differentiate on each planet (using the Earth as a base-line case of maximum mantle differentiation). We conclude: 1) The Median Plains on Venus should have an average lithospheric thickness not exceeding ~ 10 km. 2) Only Earth and Venus can presently have true asthenospheres. 3) Mars probably had a true, planet-wide asthenosphere not too long ago geologically. The cooling of the olivine-rich layer on Mars (and hence disappearance of the asthenosphere) may coincide with the cessation of global tectonic activity ~ 1 Gyr ago.

CRUSTAL DEVELOPMENT IN THE TERRESTRIAL PLANETS.

S.R. Taylor, R.S.E.S., Australian National University, Canberra, Australia.

The development of planetary crusts may be divided into primary, resulting from melting during accretion, and secondary crusts developed by partial melting from planetary mantles. The lunar highland crust is an example of the first type while the mare basalts form an example of the second. The Mercurian crust is probably primary with no compelling evidence of later basaltic extrusions. Reflectance spectral evidence for the existence of Fe^{2+} is equivocal (1,2). The Viking Lander XRF data on Mars indicate basaltic material at both sites 4,000 km apart. Surface aeolian processes would be expected to provide a homogeneous average of the crust, but no evidence of more siliceous material is present. This conclusion is weakly supported by the Russian gamma-ray data. No evidence for granite appears from the Russian Venera XRF data which indicates MORB-type and alkali basalt (4% K_2O) surface compositions. The highlands of Ishtar Terra and Aphrodite probably owe their elevation to tectonic processes rather than compositional effects. Venus may thus resemble the early Archean Earth. The terrestrial granitic continental crust is a product of episodic multiple partial melting events, probably a consequence of the presence of surface water (3,4).

(1) Vilas, F. (1985) LPS. XVI, 881 (2) McCord, T.B. and Clark, R.N. (1979) JGR, 84, 7664 (3) Campbell, I.H. and Taylor, S.R. (1984) GRL, 10, 1061 (4) Taylor, S.R. and McLennan, S.M. (1985) The Continental Crust: Its Composition and evolution. Blackwell (Oxford).

CONTRASTS IN EVOLUTION OF VENUS AND EARTH. W. M. Kaula (National Geodetic Survey, Rockville, MD 20852)

The differences of the two planets in dynamical characteristics and inert gas abundances require major differences of formation. There probably was an impact into the Earth much greater than any into Venus. The resulting heat pulse would have caused more rapid and thorough outgassing of the Earth, lending to an ocean retaining water. Water is the key to the differences in evolution between the planets. A most important consequence was less effective recycling of lithosphere on Venus, leading to a thick global crust which suppressed plate tectonics. Stratification is more pronounced in Venus, but there must remain sufficient heat sources at depth for convective support of the high plateaus.

ADIABATIC THERMAL MODELS FOR PLANETARY BODIES. T. Spohn
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In a number of recent experiments R. Boehler and co-workers have found the logarithmic derivative with respect to volume of the adiabatic temperature increase with pressure P to be an approximately constant quantity n . They find n to decrease slightly with temperature, to be virtually unaffected by increasing pressure and to take values between 4 and 8 for a wide variety of materials. We will show that these findings can be substantiated from thermodynamic arguments, finite strain theory, atomic potential theory and experimental data on the thermal expansion coefficient and the bulk modulus B . It will be shown that n is independent of pressure if it is exactly equal to $dB/dP + 1$. For these materials $d \log \gamma / d \log v = -1$, where γ is the thermodynamic Grüneisenparameter. It will increase with P during an isothermal transformation if $n > dB/dP + 1$ and decrease if $n < dB/dP + 1$. For most materials n is close to dB/dP and the changes will be slight if pressures do not become too extreme. During an adiabatic transformation n is virtually constant. Adiabatic thermal models for planetary bodies have been calculated and will be presented.

PRIMORDIAL MAGMASPHERES AND THEIR LASTING CONSEQUENCES

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The lunar magmasphere is a useful but potentially misleading analog for the earliest evolution of other planetary objects. A significant fraction of the lunar magmasphere became a crust rich in buoyant cumulus plagioclase. Another significant fraction became a series of ultramafic "cumulates" (the mare basalt sources) complementary to the anorthosite. These events predetermined all subsequent lunar evolution. Empirically, the Moon was big enough to produce a magmasphere. Assuming roughly similar rates of heat input, an asteroid-sized body is probably too small to have a magmasphere, whereas all bodies larger than the Moon probably had magmaspheres at least as large (in absolute terms) as that of the Moon. For bodies big enough to have magmaspheres, the long-term importance of the magmasphere is inversely related to the size of the planet. Beyond a depth limit of roughly 200 km, nearly independent of the size of the planet, the remainder of the magmasphere will probably at all times be a single convective, and therefore essentially non-differentiating layer. The fraction of the mantle contained in the outer 200 km is of course inversely related to planet size. Compared to the Moon the Earth's mantle comprises a volume 40 x greater and a pressure range 30 x greater. Steeper dP/dZ , favoring garnets and pyroxenes, also works to dampen differentiation in larger planets. One long-term consequence of the Earth's magmasphere was probably a depletion of H_2O in much of the mantle. Because water is a flux for mantle convection, anhydrous parts of the mantle probably had anomalously thick lithospheres and hot asthenospheres.

GEOLOGIC PROCESSES ON VENUS: AN UPDATE. H. Masursky (U.S. Geological Survey, Flagstaff, AZ 86001)

Studies of Venera 15 and 16 radar-image and altimetry data and reevaluation of Pioneer Venus and earlier Venera data have greatly expanded our perception of the variety and complexity of geologic processes on Venus. PV data have discriminated four highland regions (each different in geomorphic appearance), a large upland rolling plains region, and smaller areas of lowland plains. Two highland volcanic centers were identified that may be presently active, as suggested by their geomorphologic appearance combined with positive gravity anomalies, lightning-strike clusters, and a change in SO_2 content in the upper atmosphere. Geochemical data obtained by the Venera landers have indicated that one upland area and nearby rolling plains are composed of volcanic rocks, probably basalts or syenites. The recently obtained USSR images, which cover the northern third of the planet, appear to verify the subdivision of geologic terrain units determined from PV and Earth-based radar data.

New Venera radar images of the Ishtar Terra region show folded and/or faulted linear terrain and associated volcanic features that may have been deformed by both compressional and extensional forces. Rolling uplands bordering Ishtar Terra display multiple ringed features called "coronae" that are 300 to 1200 km in diameter; some have radiating features that may be extrusive igneous rocks. The coronae may be igneous centers similar to those thought to have formed in Archean rocks on Earth. Alternatively, they may be impact craters that initiated igneous activity, as at the Sudbury complex on Earth. Linear ridge-and-valley terrain may be composed of fold or fault mountains with associated volcanic features. Rectilinear crosshatched areas called "tesserae" may have been formed by block faulting due to tectonic extension. Lowland areas south and west of Ishtar Terra appear to contain multiple small volcanic centers. Lowland surfaces resemble the mare basaltic lava flows that fill basins on the Moon, Mars and Earth. Ubiquitous crater-like forms may be of either volcanic or impact origin; the origin of similar lunar features was determined by the character of their ejecta deposits. Higher resolution images must be obtained to settle this issue for the Venusian features.

PLANNING FOR VRM: RADAR AND SONAR STUDIES OF VOLCANIC TERRAINS ON EARTH, VENUS AND MARS. Peter J. Mouginis-Mark, Lisa R. Gaddis, Pamela L. Blake, Patricia Fryer and Charles Ferrall (Hawaii Inst. Geophys., Univ. Hawaii, Honolulu, HI 96822).

Venera 15 and 16 radar images of Venus, together with Earth-based data from the Arecibo Observatory, indicate that volcanism has played an important role in the evolution of the venusian landscape. At the end of this decade, NASA's Venus Radar Mapper (VRM) spacecraft will return near-global information that will further constrain the planet's geologic history. Due to the diversity of volcano/tectonic features that have already been identified on Venus, and the intrinsic differences between radar images and conventional photography, additional expertise is being developed with which to interpret the VRM images of this unusual environment.

Several attempts to better understand the physical characteristics of volcanic terrains (as they will be measured by VRM) are described here. Pioneer Venus radar altimeter measurements of topographic variability and surface roughness are compared with Goldstone radar measurements of volcanic terrains on Mars. Synthetic aperture radar images obtained by the SIR-B Space Shuttle experiment over Kilauea Volcano, Hawaii, are employed to investigate the differences in radar returns from pahoehoe, aa and sheet lava flows. Four-polarization, multiple incidence angle, aircraft radar images of the Medicine Lake area of N. California are used to address the unusually high cross-polarization ratio of lobate flows around Beta Regio on Venus, as measured by the Arecibo radar. Finally, SeaMARC II side-scan sonar images and bathymetry for three submarine volcanoes in the Mariana Arc, and lobate flows off the south coast of the island of Maui (Hawaii), are used to investigate volcanism and sedimentation under a high-pressure environment believed to be similar to the one that exists on Venus due to the high ambient atmospheric pressure.

COMPRESSIONAL ENVIRONMENT IN THE LOCATION AND ORIENTATION OF PLANETARY DORSA AND TERRESTRIAL EARTHQUAKE FAULT STRUCTURES: Jouko Raitala (JPL, Pasadena, California (on leave from Department of Astronomy, University of Oulu, Oulu, Finland))

Under compressional circumstances structures generated along a shear zone form an echelon Riedel shear patterns (1,2,3,4). The main synthetic Riedel shears may consist of 'an echelon within an echelon' structures (5).

Lunar mare ridges are not pure compressional ridges but their locations and orientations are most likely controlled by shear zones as seen from their Riedel-shear-like arrangements (6). On the Moon the crustal shortening has mostly taken place within mare areas but some young terra ridges are also to be seen (7) indicating some crustal shortening also outside mare areas. This shortening has, however, not reached the same intensity as in the case of lobate scarp overthrusts on Mercury.

The Martian dorsa are situated on plateau areas around the Tharsis bulge and against the terra highland with an old, thick lithosphere. The compressional body forces generated by the gravitational sliding and volcanic push off have been transmitted from the Tharsis area through the lithosphere down to the areas where a rigid and thick highland lithosphere, unaffected by the mantle impingement, uplift and traction forces, was met. Within these areas, which are peripheral to the main Tharsis bulge and mantle plume, the lithosphere was shortened and compressed to guide the location and orientation of dorsa faults.

There may be some similarities in compressional intracontinental earthquake faults, lunar mare ridge arrangements (6,7,8) and Martian dorsa zones. The crustal shortening is essential in all the cases. This analogy must, however, not be considered as a definite identity but rather as a useful working hypothesis, which is postulated to attain some insight into the possible continuum of the tectonic processes within different terrestrial planets.

REFERENCES: 1) Cloos, H. 1928. Zentralbl. Min. Geol. Pal. 1928E: 609-624; 2) Riedel, W. 1929. Zentralbl. Min. Geol. Pal. 1929E:354-365; 3) Lajtai, E.Z. 1969. Geol. Soc. Am. Bull. 80:2253-2272; 4) Tchalenko, J.S. & Ambreys, N.N. 1970. Geol. Soc. Am. Bull. 81: 41-60; 5) Tchalenko, J.S. 1970. Geol. Soc. Am. Bull. 81: 1625-1640; 6) Raitala, J. 1982. Acta Univ. Ouluensis, Ser A 135; 7) Raitala, J. 1984. Earth, Moon, and Planets 31:63-74; 8) Plescia, J.E. & Golombek, M.P. 1984. Bull. Am. Astron. Soc. 16:681.

PLANETARY REORIENTATION BY SURFACE LOADS. R.J. Willemann (Dept. of Geophys., Texas A&M Univ., Coll. Sta., TX 77843)

Non-hydrostatic concentrations of mass at the surface of the planet have been suggested as mechanisms of permanent reorientation for all of the terrestrial planets and for the Moon. In order for such a load to control planetary orientation, three conditions must be satisfied. The surface load must be non-hydrostatically supported; the surface load must be large compared to internal departures from a hydrostatic mass distribution; and the load must be large compared to hydrostatic departures of the planetary figure from a sphere. The third condition comes from the consideration that if the load is non-hydrostatically supported, then the same processes which support the load will also support the hydrostatic figure.

In the case of Earth, the first condition is not satisfied because broad loads are not significantly supported by the earth's lithosphere. The earth's orientation is therefore controlled by dynamically supported non-hydrostatic mass distributions in the interior. In the case of Mars, the Moon, and Mercury, surface loads are significantly supported by membrane stresses in the lithosphere; i.e., the first condition is satisfied. The lack of current tectonic activity indicates that the dynamically supported mass anomalies in the interiors of these planets are more subdued than in the earth; the second condition is probably also satisfied. The third condition, however, is only marginally satisfied in the case of Tharsis on Mars, is certainly not satisfied in the case of the Moon, and is probably not satisfied in the case of Mercury. It is concluded that observed loads on the planetary surfaces have not significantly reoriented the terrestrial planets. However, dynamically supported internal mass anomalies may have reoriented these planets.

THE NON-HYDROSTATIC FIGURES OF THE TERRESTRIAL PLANETS. S.K. Runcorn (University of Newcastle upon Tyne, England, UK)

Solid state creep being exponentially dependent on temperature must dominate the mechanical behaviour of the mantles of terrestrial planets beneath their lithospheres. General arguments suggest that the lithospheres of the Moon and Mars are about 200 km thick; the Earth, Venus and Mercury much less. Short wavelength gravity anomalies are explained by the finite strength of the lithosphere: the lunar mascons being an example. The good correlation of the Venus and Mars gravity anomalies with topography up to spherical harmonics of degrees 10-15 is in striking contrast to the lack of correlation between the long wavelength components of the geoid and the continent-ocean distribution or even the plates. Attempts have been made to explain the former correlations by isostatic models but the depths of compensation seem implausible. Low degree harmonics of the gravity fields of the terrestrial planets as is certainly the case in the Earth must arise from the density variations driving solid state convection. In the case of Venus the less dense differentiated materials of the highlands seems to be positioned over the singular points of the convection pattern. Thus the correlated gravity field does not arise from the highlands but from the density difference in the convecting interior. In the Earth lack of correlation seems to arise from the fact that the plates have moved relative to the convection pattern in the last 100 M yr.

DYNAMIC COMPENSATION OF VENUS'S GEOID: A COMPARISON WITH EARTH
W.S. Kiefer, B.H. Hager, and M.A. Richards (Caltech, Pasadena, CA 91125)

Unlike Earth, on Venus long wavelength geoid anomalies correlate well with topography. Venus's admittance curve between harmonic degrees 3 and 18 is inconsistent with Airy isostasy but is consistent with dynamic support from convection being the dominant mechanism of compensation on Venus. We model dynamic compensation on Venus using simple flow models which assume a spherically symmetric Newtonian mantle viscosity profile. Preliminary models parameterize the viscosity variation with depth as a 2 layer model with a boundary at 720 km depth. A model in which viscosity in the lower mantle is a factor of 10 lower than in the upper mantle can explain Venus's observed admittance curve for degrees 3 through 18. Dynamic models which include a chemical boundary between the upper and lower mantle do not successfully explain the observed admittance curve, indicating that Venus does not have a chemically layered mantle. We have previously explained 90% of the variance in the Earth's geoid at degrees 2 through 9 using density contrasts from seismic tomography and subducted slabs. On Earth, the effective viscosity increases by a factor of 10 or more from the upper to the lower mantle. The decrease in viscosity with depth on Venus is surprising given the expected effects of increasing pressure on rheology. However, the effect of lateral viscosity variations due to hot plumes, when interpreted in terms of spherically symmetric models, is to give an apparent decrease in viscosity with depth. Heat transport in Venus's mantle may be dominated by hot plumes, whereas heat transport in the Earth's mantle is dominated by the sinking of cold slabs.

ADMITTANCE FUNCTIONS FROM VENUS VERTICAL GRAVITY AND MODES OF TOPOGRAPHIC SUPPORT. David R. Williams and W.M. Kaula (Dept. of Earth and Space Sciences, University of California, Los Angeles, CA 90024)

Two-dimensional Fourier admittance functions have been estimated for various regions of Venus, using as input the Pioneer Venus topography data and the Venus vertical gravity model of Sjogren et al. (1983). Model admittance functions are computed for various cases, such as lithospheric loading from above, and support from below, for comparison. These models are functions of depth of compensation, flexural rigidity, and crust and mantle densities. The long wavelength ($\gtrsim 2000$ km) topography and gravity signals contain most of the spectral power in the Venus data, and the admittances at these wavelengths are compatible with deep compensation of surface topography. However, at wavelengths $\lesssim 2000$ km, the admittances are better fit by models with much shallower compensation, of the order of 30 to 40 km, and with loading (and unloading) from below the lithosphere, in contrast to most of the Earth. The flexural rigidity associated with these best-fitting models is consistent with a lithospheric thickness of 20 to 30 km. The following model is proposed for Venus. The deep compensation at long wavelengths is due to dynamic support. The high surface temperature of Venus is responsible for a thin lithosphere. At shorter wavelengths, the depth of compensation represents the base of the crust, which extends below the bottom of the lithosphere. This "mobile crust" is moved about underneath the lithosphere by convective forces and gravity, and so loads the lithosphere from below.

THE COORBITAL HYPOTHESIS

Gerard Andlauer, Guest Res., Mundelsheim, France

Voyager I and II have revealed the existence of 1980S1 and 1980S3 in the same orbit that add to the discovery of the Lagrange satellites 1980S6 for Dione and 1980S13 - 1980S25 for Thetys as a replica to the Trojan planets in the Jupiter orbit. These bodies may issue from the rupture of a primitive gaseous ring through a disturbance. The Lagrange figures keep stable while the rest of the objects drift in near paths and interact at each transit so as to form a gradual binary. The Moon - Earth system may have a such origin.

THE MAGNETIC FIELD OF PLANETS. Sh.Sh.Dolginov
(IZMIRAN.Troitsk.Moscow.region.142092.USSR)

The strength of the dipole fields H_{oi} of the various inspected planets are connected by a Simple scaling law, involving observable angular velocity ω , planetary radia R_p , velocity Ω and amplitude α of planetary precession, and radia R_c , densities ρ_c , conductivities σ_c of their liquid cores according to the contemporary models of planetary inner structure:

$$H_{oi} = H_E \frac{Q_i^3 R_{ci}^3 \omega_i \Omega_i \sin \alpha_i \rho_i \sigma_i}{Q_E^3 R_{cE}^3 \omega_E \Omega_E \sin \alpha_E \rho_E \sigma_E} ; Q = R_p / R_c \quad H_E = 30950$$

The Lunar paleofield of 1G, its decay to zero is also explained in the frames of precession-dynamo model, evolution of the Earth-Moon system and primeval satellites in it suggested by Runcorn.

WHAT WE HAVE LEARNED ABOUT THE MAGNETIC FIELD MARS.
Sh.Sh.Dolginov (IZMIRAN, Troitsk, Moscow.Region,142092, USSR)

Sufficient and unambiguous evidences of the intrinsic martian magnetic field are:

- a) The independence of the field polarity in martian magnetic tail from IMF polarity inversion, established with the help of Mars-5 data.
- b) The incongruity between the sign of the radial component of the field measured in martian tail (Mars-2) and that of the "draped" model with IMF data measured simultaneously (Mars-3) on February 23-24, 1972.

Mars's dipole magnetic moment is within the limits $(1,5 \pm 2,2) \cdot 10^{22} \text{ G cm}^3$. The dipole axis is deflected from that of rotation on the angle $\leq 15^\circ$. The North magnetic pole is located in the south hemisphere.

In the frame of the precession-dynamo model the magnetic fields of the planets Mars and Earth are similar. The martian magnetic field is the real obstacle for the solar wind near the planet.

MARS LANDING SITES. H. Masursky (U.S. Geological Survey, Flagstaff, AZ 86001)

An intensive effort has been underway for the past two years to study possible landing sites for a future Mars rover and returned-sample mission. The task has been to identify and study nine sites, each of which is near a variety of representative geologic units. The choice of sites is independent of future decisions as to whether the rovers will be manned or unmanned, except that unmanned rover traverses may be shorter and more restricted. We are studying north and south polar locations, the "Grand" canyon that exposes layered terrain, two stream channels, two volcanic centers, and two upland sites.

The Memnonia site in upland terrain, is thought to contain very old, intermediate-age, and young rocks of diverse rock chemistry. The Mangala Valles (channel) site would allow study and sampling of rock types similar to those at Memnonia; in addition, at least one stream channel in the area cuts into, and is overlain by, volcanic rocks. Samples returned from this site would enable radiometric dating of at least one fluvial episode and would establish absolute time relations between fluvial and volcanic activity in that region. Periods of tectonic activity could also be dated by extrapolation of known dates from the landing site rocks to nearby units.

Analyses of samples returned from the north polar site at the mouth of Chasma Boreale would determine the chemistry and stratigraphic relations of material contained in the polar ice in addition to the ratio of ice to rock inclusions. These results would augment our present imperfect knowledge of martian meteorology and climatology as they relate to past periods of volcanic and eolian events.

MAGNETIC FIELD GENERATION IN THE CORES OF TERRESTRIAL BODIES.

S.K.Runcorn (University of Newcastle upon Tyne, England, UK.)

Efforts to find some scaling law for the dipole moments of planets seem illusory for, although dynamo theory is still in a rudimentary state, once the critical magnetic Reynolds Number is exceeded it appears that the field strength is determined by the energy source, if it is permissible to treat the core as a "heat engine". For this reason the lunar magnetic field is of special significance as the palaeomagnetic evidence strongly suggests that the surface field was about 1 G 3.9 by diminishing exponentially to about .02 G 3.2 by ago and completely disappearing some time later. These data are based on palaeointensity determinations by the Thellier and ARM methods. The high field and subsequent decay is supported by Fuller and Cisowski's IRM method and some evidence exists of a rise prior to 3.9 by. Palaeomagnetic directions have been obtained from the Apollo 15 and 16 sub-satellite magnetometer surveys by Russell, Coleman and Hood. This has been interpreted on the hypothesis that the magnetising field was a dipole aligned along the axis of rotation. Evidence for three successive re-orientations of the Moon with respect to its axis of rotation between 4.2 and 3.8 by have been obtained and shown to be in accord with Euler's theory. The re-orientations are brought about by the formation of large multi-ring impact basins, which are found to have occurred in low latitude. From the latter observation it is inferred that the Moon had a primeval satellite system, the satellites being drawn in by tidal friction. Geological study of the basins indicate that the impacting bodies were orbiting near the equatorial plane at the time. The consistency of the palaeomagnetic data and lunar mechanics is strong evidence for a core dynamo but the heat source which drove convection in it remains an enigma.

GEOCHEMICAL CONFIRMATION OF THE LUNAR MAGMASPHERE HYPOTHESIS

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The lunar magmasphere (or magma ocean) hypothesis was originally conceived to account for the enrichment of cumulus plagioclase (Al and Ca) in the main (highlands) portion of the crust. The great age of the highlands, and the complementary pattern of Eu anomalies between the highlands and the younger mare basalts, helped convince most specialists that the magmasphere hypothesis is correct. Doubts persist, however, particularly among physicists concerned about heat sources. It was shown in 1976 that a plot of Na/Ca vs. Mg/Fe for "pristine" highlands cumulates manifests a profound bimodality: One group, the Mg-rich rocks, plots along a normal igneous trend of inverse correlation between Na/Ca and Mg/Fe; the other group, the ferroan anorthosites (FAN), features low Na/Ca and low Mg/Fe. Only the FAN group can be plausibly linked to plag. flotation over the magmasphere. For many years it was assumed that the Na/Ca vs. Mg/Fe bimodality resulted from Na volatilization as the FAN crystallized. The same bimodal trends are manifested if Eu/Al is plotted vs. Mg/Fe, however, so the volatilization model is not correct. A search for alternative mechanisms has yielded only one: The FAN were generated by plag. flotation over the magmasphere; shortly afterwards, the Mg-rich rocks formed in many separate, conventional intrusions. The two groups are geochemically distinct because the Mg-rich melts tended to reach plag. saturation earlier, mainly because they tended to assimilate FAN. In the complete absence of a plausible alternative genetic mechanism, the geochemical bimodality of lunar pristine rocks definitely confirms the magmasphere hypothesis.