BIBLIOGRAPHY

Edited by

E. B. CARLING

University of Manchester, England

Z. KOPAL

University of Manchester, England

and

F. B. WARANIUS

Lunar and Planetary Institute, Houston, Texas, U.S.A.

(January–March 1989)

1. THE MOON (Including aspects of the Earth–Moon System)

Dasch, E. J., Ryder, G. and Byquist, L. E. (NRC/NASA Johnson Space Center, Houston, TX 77058): 'Chronology and Complexity of Early Lunar Crust', *Tectonophysics* **161** (1989), 157–164.

The least equivocal age and petrographic data on lunar rock samples suggest that: (1) the lunar anorthostic crust was formed by about 120 Ma after the primary accretion of the Moon at 4.56 Ga; it may have been completed earlier. It was formed in a large magma system probably at least several hundred kilometers in depth, with rare earths not appreciably fractionated from chondritic-relative abundances; (2) at least some members of the diverse Mg-suites of rocks (norites, troctolites, dunites) crystallized very soon after lunar accretion – within a very few 100 s of Ma after 4.56 Ga – and cannot presently be distinguished chronologically from anorthositic crust formation. However, their parental magmas had clearly evolved from chondritic incompatible trace-element patterns; (3) a trace-element-rich material (KREEP) was formed by about 4.3 Ga ago (as residues from the previous episodes) with a remarkably constant rare-earth pattern. This residue was subsequently reworked in melting and impact processes such that most samples which contain it have ages around 3.9–4.0 Ga, whether impact or volcanic in immediate origin; (4) the onset of ferrous mare basalt volcanism began much earlier (about 4.33 Ga ago). The sources for this mare volcanism are complementary in characterisdtics to KREEP and were also in place by 4.4 or 4.3 Ga ago at a depth of several hundred kilometers. These characteristics of lunar materials demonstrate that lunar crustal formation happened quickly, in a complex fashion, and affected depths in the mantle to at least several hundreds of kilometers.

Dickinson, T., Taylor, G. J. and Keil, K. (Department of Geology and Institute of Meteoritics, University of New Mexico, Albuquerque, NM 87131): 'Germanium Abundance in Lunar Basalts: Evidence of Mantle Metasomatism?', in *Proceedings of the 19th Lunar and Planetary Science Conference (1989)*, pp. 189–198.

To fill in gaps in the present Ge database, mare basalts were analyzed for Ge and other elements by RNAA and INAA. Mare basalts from Apollo 11, 12, 15, and 17 landing sites are rather uniform in Ge abundance, but Apollo 14 aluminous mare basalts and KREEP are enriched in Ge by factors of up to 300 compared to typical mare basalts. Those Ge enrichments are not associated with other siderophile element enrichments and thus are not due to differences in the amount of metal segregated during core formation. Based on crystal-chemical and interelement variations, it does not appear that

Earth, Moon, and Planets **52**: 171–212, 1991.

the observed Ge enrichments are due to silicate liquid immiscibility. Elemental ratios in Apollo 14 aluminous mare basalts, green and orange glass, average basalts and KREEP suggest that incorporation of late-accreting material into the source regions or interaction of the magmas with primitive undifferentiated material is not a likely cause for the observed Ge enrichments. We speculate that the most plausible explanation for these Ge enrichments is complexing and concentration of Ge by F, Cl, or S in volatile phases. In this manner, KREEP basalt source regions may have been metasomatized, and Apollo 14 aluminous mare basalt magmas may have become enriched in Ge by interacting with these metasomatized areas. The presence of volatile- and Ge-rich regions in the Moon suggest that the Moon was never totally molten.

Eicher, D. J., 'A Picture-Perfect Lunar Eclipse', *Astronomy* **17**(2) (1989), 78–79.

Photographing a lunar eclipse.

Espenak, F. (Goddard Space Flight Center, Greenbelt, Maryland 20771): 'Fifty Year Canon of Lunar Eclipses: 1986–2035' NASA-RP-1216 (1989), pp. 228.

A complete catalog is presented, listing the general circumstances of every lunar eclipse from 1901 through 2100. To complement this catalog, a set of figures illustrate the basic Moon-shadow geometry and global visibility for every lunar eclipse over the 200 year interval. Focusing in on the next fifty years, 114 detailed diagrams show the Moon's path through Earth's shadow during every eclipse, including contact times at each phase. The accompanying cylindrical projection maps of Earth show regions of hemispheric visibility for all phases.

The appendices discuss eclipse geometry, eclipse frequency and recurrence, enlargement of Earth's shadow, crater timings, eclipse brightness and time determination. Finally, a simple FORTRAN program is provided which can be used to predict the occurrence and general characteristics of lunar eclipses.

This work is a companion volume to NASA Reference Publication 1178: *Fifty Year Canon of Solar Eclipses: 1986–2035.*

Hawke, B. R., Coombs, C. R., Gaddis, L. R., Lucey, P. G. and Owensby, P. D. (Planetary Geosciences Division, Hawaii Institute of Geophysics, University of Hawaii, Honolulu, HI 96822): 'Remote Sensing and Geologic Studies of Localized Dark Mantle Deposits on the Moon', in *Proceedings of the 19th Lunar and Planetary Science Conference (1989)*, pp. 255–268.

Localized lunar dark mantle deposits (LDMD) are small, smooth low-albedo units of pyroclastic origin commonly found associated with endogenic source craters. These deposits occur across the nearside of the Moon. They are predominantly concentrated around the perimeters of the major lunar maria and in the floors of large Imbrian and pre-Imbrian-aged impact craters. These deposits are characteristically small in size (typically $<250–550\ km^2$, although coalesced deposits often cover $1000–2000\ km^2$), are aligned along crater floor fractures, and are generally associated with source vents that are noncircular in shape. An eruption mechanism analogous to terrestrial vulcanian explosive eruptions is thought to be responsible for the emplacement of LDMD, in contrast to the strombolian or continuous eruption styles of the regional dark mantle deposits. In a vulcanian eruption, the accumulation of gas in a capped magma body leads to explosive decompression and the subsequent emplacement of a pyroclastic deposit around an endogenic source crater. Analysis of near-infrared spectra, multispectral images, and radar data obtained for 25 LDMD has led to the identification of three compositional groups of LDMD. Group 1 deposits are composed predominantly of highlands-rich wall rock but also contain a substantial juvenile component. Group 2 deposits are composed largely of mare plug rock material, while Group 3 deposits are rich in a mixture of olivine and pyroxene. Variations in eruption conditions are interpreted to be largely responsible for the varying minerology of these three types of deposits.

Hawke, B. R., Coombs, C. R. and Lucey, P. G. (Planetary Geosciencs Division, Hawaii Institute of Geophysics, University of Hawaii, Honolulu, HI 96822): 'A Remote-Sensing and Geologic Investigation of the Crüger Region of the Moon' in *Proceedings of the 19th Lunar and Planetary Science Conference (1989)*, pp. 127–135.

Crüger is an unusual mare-filled crater located in the lunar highlands southwest of Oceanus Procellarum and south of Grimaldi basin. The origin of Crüger crater, as well as the other geologic units in the region, has long been the subject of considerable controversy. Therefore a variety of Earth-based and spacecraft photography, as well as spectral reflectance and radar data, were utilized to investigate the origin, composition, and mode of emplacement of the geologic units in and around Crüger crater. The composition of the mare unit within Crüger crater was found to be similar to that of other intermediate TiO_2 basalt deposits on the lunar nearside. Three previously unmapped localized dark mantle deposits of pyroclastic origin were identified in the region. Spectra obtained for the localized pyroclastic deposit on the south flank of Crüger indicate that this mafic unit is dominated by an olivine-pyroxene mixture This localized dark mantle deposit was emplaced by explosive eruptions during an early phase of the eruptive sequence that flooded the floor of Crüger; the source vent or vents were subsequently buried by mare lava. All of the pyroclastic units in the Crüger region were emplaced by vulcanian-style eruptions. The highlands in the Crüger region are dominated by nonritic anorthosite. This composition is very similar to that determined for the highlands units on the Orientale basin interior. However, one area rich in gabbroic anorthosite was identified. An endogenic origin for Crüger crater can be ruled out. Crüger is not a lunar caldera. Rather, it is a normal pre-Orientale impact crater that was modified by Orientale ejecta and later flooded by mare basalt. However, few, if any, of the other members of the lunar smooth-rimmed crater class formed in an identical manner.

Hood, L. L. and Williams, C. R. (Lunar and Planetary Laboratory, University of Arizona, Tucson, AC 85721): 'The Lunar Swirls: Distribution and Possible Origins', in *Proceedings of the 19th Lunar and Planetary Science Conference (1989)*, pp. 99–113.

Many of the strongest lunar magnetic anomalies correlate in location with swirl-like high-and low-albedo markings of the Reiner Gamma class. Models involving both meteoroid and cometary impact processes have previously been proposed to explain their origins. It has also been proposed that the high-albedo markings represent areas of the surface that have been magnetically shielded from the solar wind ion bombardment and have therefore not reached optical maturity. These models are investigated further here, using both correlative data analysis and theoretical modeling methods. Maps of the distribution of swirls on the lunar farside constructed from available orbital photography reveal relative concentrations in zones antipodal to Imbrian-aged basins where electron reflection maxima have previously been mapped. Correlative analyses show that electron reflection maxima are statistically correlated with both swirl locations and with the occurrence of probable seismically modified terrain produced at the times of the associated basin impacts. These results suggest that the relatively strong magnetization of basin antipode zones in some manner favored the formation of swirls in the same regions, i.e., the generation of swirls is not entirely exogenic. As a further test of the solar wind deflection model for swirl origins, trajectories of simulated solar wind ions deflected by the Lorentz force in the presence of model crustal magnetic fields are calculated numerically. For surface fields comparable in amplitude and horizontal scale with those measured at the Apollo landing sites ($B \leq 327$ nT), deflections are small and the net surface flux differs little from the incident solar wind flux. For surface fields with amplitudes and scales expected for the strongest observed orbital anomalies ($B > 1000$ nT), deflections are stronger and regions as large as 30 km in extent are partially shielded from the ion bombardment under nominal conditions. The shielded regions have curvilinear shapes and may be crossed by lanes with higher than average fluxes in a manner that depends on the details of the assumed surface field configuration. It is concluded that the solar wind deflection model provides a possible explanation for the unusual morphologies of these albedo markings and their preferred occurrence in basin antipode zones. Meteoroid impacts occurring in zones of strong preexisting crustal fields may also have contributed to the formation of the lunar swirls.

Hughes, S. S., Delano, J. W. and Schmitt, R. A. (Departments of Chemistry and Geology and Radiation Center, Oregon State University, Corvallis, OR 97331): 'Petrogenetic Modeling of 73220 High-Ti Orange Volcanic Glasses and the Apollo 11 and 17 High-Ti Mare Basalts', in *Proceedings of the 19th Lunar and Planetary Science Conference (1989)*, pp. 175–188.

Sixteen individual spherules of orange volcanic glass were extracted from the 74220,689 soil and analyzed by INAA in order to determine trace element signatures in a primary high-Ti mare magma. In agreement with major element characterization of the 74220 orange glass by previous EPMA studies, the current data exhibit a striking uniformity in composition at the scale of 5–15 μg spherules. This composition is nearly identical to that of 74220 bulk soil, indicating a general absence of constituents other than volcanic glass in the soil, except for slightly higher La, Yb, Lu, and Th in the bulk soil reflecting a small amount (<1%) of KREEP. Trace element patterns in 74220 orange glass and average Apollo 11 and 17 high-Ti mare basalts are shown to be possible derivations from hybridized source regions. These sources were likely developed in the primordial lunar magma ocean by the commingling of early cumulate olivine with late cumulate minerals (pyroxene, plagioclase, ilmenite, apatite) and trapped residual liquid. Petrogenetic models based on a least-squares analysis of required magmatic sources vs. potential hybrid sources suggest that accessory apatite, which has very high trace element partition coefficients, plays a major role in the high-Ti trace element signatures. Apollo 11 intermediate- and high-K basalt compositions cannot be explained completely by the least-squares modeling procedure, although appropriate models are obtained for Apollo 11 low- and low-intermediate-K compositions. Intermediate- and high-K trace element patterns can be adequately modeled as magmas initially having a low-K signature, but which were contaminated by ~10% of a KREEPy component and experienced variable amounts of olivine fractionation. In addition to these modeled complexities, a slight difference in the major element composition of average Apollo 11 intermediate-K basalt relative to other high-Ti basalts was likely caused by minor contamination by either anorthosite or another plagioclase-rich component. Compared to our previous models of Apollo 12 and 15 low-Ti mare magmas, which require depths greater than ~400 km to maintain both olivine and low-Ca pyroxene in the residuum, the models presented here suggest shallower olivine-dominated sources. While these models do not demonstrate an unequivocal mechanism of mare petrogenesis, they provide constraints on the possibility of source hybridization. We suggest that the evolving lunar mantle included processes of cumulate-mass transport and/or segregation of the primoridal lunar magma ocean into separate differentiating zones, which allowed commingling of early and later components. A review of volatile elements in the 74220 soil shows that the primordial lunar composition probably included a substantial carbonaceous chondritic component.

Hyde, T. W. and Alexander, W. M. (Space Science Laboratory, Department of Physics, Baylor University, Waco, TX 76798): 'Transport Dynamics Calculated under the Full Mie Scattering Theory for Micron and Submicron Lunar Ejecta in Selenocentric, Cislunar, and Geocentric Space', in *Proceedings of the 19th Lunar and Planetary Science Conference (1989)*, pp. 607–614.

In 1967, Lunar Explorer 35 was launched from the Earth and placed into a stable orbit around the Moon. The data from the dust particle experiment on this spacecraft was essentially continuous over a 5-yr period from the time of insertion in lunar orbit. Analysis of this data has been interpreted to show that micron-sized lunar ejecta leave the Moon and traverse through selenocentric and cislunar space and obtain either interplanetary/heliocentric orbits or intercept the Earth's magnetosphere and move into geocentric orbits. Extensive studies of the orbital trajectories of lunar particles in this size range have now been conducted that include a calculation of the solar radiation force using the full Mie scattering theory. A significant flux of particles with radii less than 0.1μ are found to intercept the Earth's magnetopause surface. This flux is shown to be strongly dependent upon both the particle's density and its index of refraction.

James, O. B., Lindstrom, M. M. and Flohr, M. K. (959 National Center, U.S. Geological Survey, Reston, VA 22092): 'Ferroan Anorthosite from Lunar Breccia 64435: Implications for the Origin and History of Lunar Ferroan Anorthosites', in *Proceedings of the 19th Lunar and Planetary Science Conference (1989)*, pp. 219–243.

A composite clast of ferroan-anorthosite-suite rocks from lunar breccia 64435 contains three lithologies. The first is a monomict, course-grained troctolitic anorthosite with abundant mafic minerals (>11%) and relict igneous texture. Major minerals are plagioclase (An_{97}), olivine (Fo_{71}), and inverted pigeonite (orthopyroxene is Wo_2En_{74}); augite is a minor mineral. The mafic are the most magnesian thus far found in a ferroan anorthosite. The second lithology is a monomict coarse-grained anorthosite with little relict texture. Plagioclase (An_{975}) makes up about 98% of the rock; mafic minerals are orthopyroxene (Wo_2En_{57}) and augite. The third lithology is a fine-grained troctolitic anorthosite with granulitic-breccia texture and a mineralogy nearly identical to that of the coarse-grained troctolitic anorthosite. The composite clast probably formed as follows. The parent rocks all crystallized from the same magma body. They were sheared and granulated in the floor or walls of a growing impact crater cavity, and the shear juxtaposed rocks that formed some distance apart. Extensive subsolidus recrystallization followed. The coarse-grained lithologies are relatively ungranulated relics, and the fine-grained lithology is a much more granulated and slightly more mixed rock derived from troctolite anorthosites nearly identical to the coarse-grained troctolitic anorthosite. The coarse-grained troctolitic anorthosite formed as an igneous cumulate of plagioclase, olivine, and pigeonite and is a member of a mafic, magnesian subgroup within the ferroan-anorthosite suite. There are at least three other subgroups within the suite. One, represented by the 64435 coarse-grained anorthosite and most other Apollo 16 anorthosites, is anorthositic and ferroan. Two others are represented by small numbers of samples: an anorthositic, sodic subgroup and a mafic, ferroan subgroup. It is not clear how these subgroups are related to each other. Detailed studies of splits of the coarse-grained troctolitic anorthosite by INAA, SEM and electron microprobe demonstrate that two of the splits contain 1–2% parent liquid, which has a nearly flat chondrite-normalized REE pattern and a pronounced negative Eu anomaly. The course-grained anorthosite, although much more ferroan, appears to have crystallized from a much less REE-rich parent liquid. Consideration of various hypotheses for ferroan-anorthosite genesis, in light of the new data, indicates that no truly adequate petrogenetic scheme has yet been devised for the lunar ferroan-anorthosite suite.

Jones, J. H. and Delano, J. W. (Lunar and Planetary Laboratory, University of Arizona, Tucson, AZ 85721): 'A Three-Component Model for the Bulk Composition of the Moon', *Geochimica et Cosmochimica Acta* **53** (1989), 513–557.

Using detailed analysis of lunar pristine glasses as a basis (Delano, 1986), we present a suite of models of lunar bulk composition which are based on the following assumptions: (i) that the early Moon differentiated into two primary reservoirs – (1) an FeO-rich magma ocean, and (2) an olivine-rich residuum of $\sim Fo_{90}$; and (ii) that this magma ocean then differentiated into an olivine-dominated cumulate ($\sim \geqslant Fo_{80}$) and a primitive liquid composition (PPG). Thus, in these models the bulk composition of the Moon is given by a mixture of three components – an early olivine residuum, a later olivine ± orthopyroxene cumulate and PPG liquid – with the constraint that the Moon possess a CI-chondritic Mg/Al ratio.

Our model lunar compositions are grossly similar to the lunar composition of Ringwood *et al.* (1987), and, when projected from FeO, they appear very similar to the composition of the Earth's upper mantle. Again, when projected from FeO, our model magma ocean compositions are very similar to the *bulk* lunar composition derived by Taylor (1982). Remelting of cumulates from the magma ocean can produce the mare basalts and the pristine glasses. Remelting of the early residuum may be the source of the highly magnesian olivines found in the lunar highlands. Our ability to relate such diverse chemistries as the Earth's mantle and Taylor's Moon is relatively model-independent.

The model compositions discussed above are generated by assuming that the cumulate formed by equilibrium crystallization. To better determine if there is a significant difference between the FeO contents of the Earth and the Moon, we have also calculated bulk lunar compositions whose cumulate component is formed by fractional crystallization – a more realistic approximation. We find that, if the Mg/Si ratios of the Earth and Moon are similar and if the early residue is dominated by olivine,

then the bulk silicate Moon is 25 to 50% enriched in FeO over the Earth's upper mantle – 10 to 13 wt% FeO for the Moon as compared to 8 wt% for the Earth. Again, the ultimate basis for this estimate of lunar FeO is the set of lunar pristine glasses.

A characteristic of all our models is that refractory lithophile elements such as Ca and Al are calculated to be ~2 to 3 times CI in the bulk silicate Moon. These abundances are largely determined by our requirement that the Moon possess a chondritic Mg/Al ratio. To emphasize this point, we discuss the implications of the choices of various Mg/Al and Mg/Si ratios in the calculation of bulk planetary compositions.

Kerr, R. A., 'Making the Moon, Remaking Earth', *Science* **243** (1989), 1433–1435.

It now seems likely that the impact of a Mars-size object somehow formed the Moon; the effects of such a giant impact must still be reconciled with the present state of Earth.

Kitt, M. T., 'Eight Lunar Wonders', *Astronomy* **17** (1989), 66–71.

Investigate eight geological oddities on the Moon and ponder the mysteries of their formation.

Laul, J. C., Gosselin, D. C., Galbreath, K. C., Simon, S. B. and Papike, J. J. (Chemical Sciences Department, Battelle Pacific Northwest Laboratories, Richland, WA 99352): 'Chemistry and Petrology of Apollo 17 Highland Coarse Fines: Plutonic and Melt Rocks', in *Proceedings of the 19th Lunar and Planetary Science Conference (1989)*, pp. 85–97.

A suite of 21 fragments from the Apollo 17 coarse-fines consists of ferroan anorthosites, anorthositic gabbros, granulitic and regolith breccias, and impact melts. These samples belong to known petrographic and chemical groups. Three ferroan anorthosites were found, including one which appears to be the lowest in REE (La = 0.60×) and probably the purest of the Apollo 17 anorthosites identified thus far. The ferroan suite is a more important component at the Apollo 17 site than previously recognized. The Apollo 17 melt rocks are similar to other samples with LKFM and low-K KREEP compositions and show less diversity in trace elements (REE) than the Apollo 15 melt rocks. Nickel/iridium ratios of 25,000 to 40,000 are common in the Apollo 17 melt rocks and are probably characteristic of the projectile that formed the Serenitatis basin. The projectile may have been an enstatite chondrite. Nickel/iridium ratios of 40,000 to 70,000 are assigned to the Imbrium basin, but the Apollo 15 melt rocks may record several impact events. Apollo 17 melt rocks consist of aphanitic and pokilitic types that show some compositional variability with identical Ni/Ir, suggesting that either two distinct melt sheets formed by similar projectiles, or compositional heterogeneity within one melt sheet is possible.

Lindstrom, M. M., Marvin, U. B. and Mitlefehldt, D. W. (NASA Johnson Space Center, Houston, TX 77058): 'Apollo 15 Mg- and Fe-Norites: A Redefinition of the Mg-Suite Differentiation Trend', in *Proceedings of the 19th Lunar and Planetary Science Conference (1989)*, pp. 245–254.

The Apollo 15 highland rocks from the Apennine Front include clasts of mafic plutonic rocks from deep in the lunar crust that were brought to the surface by the Imbrium and Serenitatis impacts. The Apollo 15 norites exhibit wide variations in mineral and bulk compositions and include Fe-norites that plot between the three major pristine rock fields on a diagram of Mg′ in mafic minerals vs. An in plagioclase. On the basis of assemblages and compositions of minerals, and of ratios of elemental abundances, we conclude that these Apollo 15 Fe-norites are differentiated members of the Mg-norite suite. The Apollo 15 and 17 norites and troctolites form a closely related suite of rocks, whose variations in mineral compositions represent the main differentiation trend of the Mg-suite. This trend in mineral compositions has a steeper slope than the previous Mg-suite field. The parent magmas for these Mg-suite stocks formed by partial melting deep in the lunar mantle. Differentiation by fractional crystallization may also have included assimilation of crustal components as the magmas rose from the mantle and crystallizd as plutons in the lower crust.

Lu, F., Taylor, L. A. and Jin, Y. (Department of Geological Sciences, University of Tennessee, Knoxville, TN 37996): 'Basalts and Gabbros from Mare Crisium: Evidence for Extreme Fractional Crystallization', in *Proceedings of the 19th Lunar and Planetary Science Conference (1989)*, pp. 199–207.

Petrographic and electron microprobe techniques were used to examine igneous fragments in Luna 24 samples 24088 and 24105. It is the complex chemistry of the pyroxenes that distinguishes the different rock types. Basaltic pyroxenes exhibit an Fe-enrichment trend; the evolutionary trends are more complex in the gabbros (≈coarse-grained basalts), with enrichments in both Fe and Ti and a depletion in Cr. These chemical evolutionary trends are displayed by a progressive variation in rock types from Mg-rich olivine-gabbro to olivine-gabbro, and to ferrogabbro and ferrotroctolite. The low TiO_2 content of the primary melt, possibly represented by the least-evolved Mg-rich olivine-gabbro, retarded the formation of early ilmenite and spinel, such that "Fenner Trend" Fe enrichment occurred. The ferrotroctolite is probably the end product of chemical evolution by extreme fractional crystallization, controlled primarily by olivine and pyroxene crystallization.

Malcuit, R. J., Mehringer, D. M. and Winters, R. R. (Department of Geology and Geography, Denison University, Granville, OH 43023): 'Numerical Simulation of Gravitational Capture of a Lunar-like Body by Earth', in *Proceedings of the 19th Lunar and Planetary Science Conference (1989)*, pp. 581–591.

A three-body numerical integration code with a subroutine simulating radial tidal energy dissipation has been devised to assess the possibility of gravitational capture of a lunar-like body from a heliocentric orbit into a geocentric orbit. The radius and mass of the present Earth and Moon and the present mass of the Sun are used throughout the calculations. The major variables for the two interacting bodies are the perigee distance (r_p) of close encounters, the displacement Love number (h) for each body, the specific dissipation factor (Q) for each body, the Earth anomaly (the position of Earth relative to the sun at the beginning of the calculation), and the planetoid anomaly (the position of the lunar-like planetoid relative to Earth at the beginning of the calculation). Each computer run is commenced with a close, energy-dissipating encounter and all successful capture runs are terminated after a maximum of 20 orbits. Four basic types of scenarios have been documented: noncapture encounters, noncapture geocentric orbital scenarios, stable capture scenarios, and collision scenarios. The approximate maximum apogee distance for an orbit that is stable relative to solar perturbations is about $200R_e$ (Earth radii). The total orbital energy of a lunar-like body in such an orbit is about -2.0×10^{35} ergs. Thus, if the relative velocity at infinity (V_∞) is near 0, the minimum quantity of energy to be dissipated for stable capture is about 2.0×10^{35} ergs. Some conclusions from our limited set of calculations are: (1) Capture into a stable geocentric orbit by way of one close energy-dissipating encounter can occur only under very restricted conditions; (2) most successful capture scenarios involve two or three close energy-dissipating encounters within a few years of time; and (3) to dissipate sufficient energy for capture, the h of the lunar-like body must be high (over 0.5) and the tidal effective Q must be near one for at least the first close encounter of a geocentric orbital scenario.

Marvin, U. B., Carey, J. W. and Lindstrom, M. M. (Harvard-Smithsonian Center for Astrophysics, Cambridge, MA 02138): 'Cordierite-Spinel Troctolite, a New Magnesium-Rich Lithology from the Lunar Highlands', *Science* **243** (1989), 925–928.

A clast of spinel troctolite containing 8 percent cordierite ($Mg_2Al_4Si_5O_{18}$) has been identified among the constituents of Apollo 15 regolith breccia 15295. The cordierite and associated anorthite, forsteritic olivine, and pleonaste spinel represent a new, Mg-rich lunar highlands lithology that formed by metamorphism of an igneous spinel cumulate. The cordierite-forsterite pair in the assemblage is stable at a maximum pressure of 2.5 kilobars, equivalent to a depth of 50 kilometers, or 10 kilometers above the lunar crust-mantle boundary. The occurrence of the clast indicates that spinel cumulates are a more important constituent of the lower lunar crust than has been recognized. The rarity of cordierite-spinel troctolite among lunar rock samples suggests that it is excavated only by large impact events, such as the one that formed the adjacent Imbrium Basin.

Masursky, H. and Strobell, M. (U. S. Geological Survey, Flagstaff, Arizona): 'Memorials on the Moon', *Sky and Telescope* 77 (1989), 265.

Seven lunar craters now bear the names of the astronauts who lost their lives aboard the Challenger.

McCormick, K. A., Taylor, G. J., Keil, K., Spudis, P. D., Grieve, R. A. F. and Ryder, G. (Institute of Meteoritics and Department of Geology, University of New Mexico, Albuquerque, NM 87131): 'Sources of Clasts in Terrestrial Impact Melts: Clues to the Origin of the LKFM', in *Proceedings of the 19th Lunar and Planetary Science Conference (1989)*, pp. 691–696.

Low-K Fra Mauro (LKFM) "basalt," which is found exclusively as an impact melt rock, cannot be modeled geochemically from its clast population or from any combination of known pristine lunar rock types, there is a missing component enriched in both KREEP and transition metals (e.g., Ti and Sc). To clarify clast/melt relationships, we studied impact melt rocks from Mistastin Lake crater, Labrador, Canada, where there are only three target rocks: anorthosite, quartz monzonite, and granodiorite. Feldspar compositions in these rocks define distinct fields on the An-Ab-Or ternary diagram, allowing us to identify the source of each feldspar class. Clasts in the Mistastin impact melts do not reflect the abundance of target rocks melted during the impact: The abundance of anorthosite in the clast population varies from 34% to 100%, compared to a relatively constant value of 65% calculatd to be in the melt matrix. Therefore the clasts appear to be derived predominantly from material relatively far removed from the zone of impact melting. Melt-matrix composition is dictated strictly by the composition of the target materials within a small radius around and below the point of impact. This suggests that the LKFM composition was derived from a lower crustal source.

McFarlane, E. A. (Department of Planetary Sciences, Lunar and Planetary Laboratory, University of Arizona, Tucson, AZ 86721): 'Formation of the Moon in a Giant Impact: Composition of the Impactor', in *Proceedings of the 19th Lunar and Planetary Science Conference (1989)*, pp. 593–605.

This paper examines the compositional plausibility of an impactor that may have triggered the formation of the Earth's Moon according to the giant impact hypothesis. The relative contributions of impactor material and Earth mantle + crust to the ejecta (which accumulate to form the Moon) are varied and the compositions of the outer portions of associated impactors are calculated for each ratio using mass balance constraints. Specifically, the equation $I_j = (M_j - \alpha E_j)/(1 - \alpha)$ is used to generate impactor compositions for the entire range of fractional Earth mantle + crust contributions, where α represents the fraction of the Moon derived from the Earth, and E_j, I_j, and M_j are the concentrations of an element j in the outer portion of the Earth, the outer portion of the impactor, and the bulk Moon respectively. The composition of the outer portion of the impactor is determined in increments of 0.1 from $\alpha = 0$ to $\alpha = 0.9$. A differentiated impactor is simulated by systematically adding a 10%, 20%, 30%, and 40% by mass Fe core. Calculated bulk impactor compositions are evaluated for their plausibility by comparison with known meteorite types. Fits are best when a core is assumed to exist within the impactor, implying the impactor was differentiated. No more than approximately 80% of the Moon's material can be derived from the Earth since physically meaningless negative concentrations of some elements (Mg, Si) are required in the impactor at higher Earth contributions, seeming to rule out impact-induced pure fission as a viable hypothesis for the formation of the Earth's Moon. Best "matches" with meteorites tend to occur for values of $\alpha < 0.5$, implying the Earth contributed <50% to the Moon's composition. Finally, the impactor must be enriched in refractory elements compared to the Moon for estimates of lunar bulk composition employed here.

McGee, J. J. (U. S. Geological Survey, 959 National Center, Reston, VA 22092): 'Granulitic Breccia Clasts and Feldspathic Melt Breccia Clasts from North Ray Crater Breccia 67975: Precursors and Petrogenesis', in *Proceedings of the 19th Lunar and Planetary Science Conference (1989)*, pp. 73–84.

A suite of crystalline lithic clasts ("granulites") from feldspathic fragmental breccia 67975 were originally divided into light green, light gray, and dark gray groups based upon bulk sample characteristics (Lindstrom, 1984). Magnesian, feroan, and intermediate rocks are present in the clast suite: the light green clasts are relatively magnesian, the dark gray clasts are ferroan, and the light gray clasts are a mixture of ferroan and slightly magnesian lithologies. The results of the present petrologic study indicate that the light gray and dark gray groups are granulitic breccias and feldspathic microporphyritic melt breccias, respectively. The granulitic breccias from the light gray group have varied bulk and mineral compositions. Some of them may be metamorphosed feldspathic microporphyritic melt breccias or monomict, ferroan-anorthosite suite rocks that have recrystallized at high temperatures. Several of the granulitic breccias are polymict rocks with both ferroan and magnesian precursors. These breccias have all been metamorphosed at approximately the same temperatures, but textural and mineral compositional data suggest that the duration of heating was relatively short and may have varied among the samples. Some of the ferroan clasts contain hornfels that is mineralogically similar to its coexisting granulitic breccia. Complete homogeneization of the mineralogy of the granulitic breccias may have been prevented by their incorporation into the 67975 fragmental breccia; metamorphism of the clasts may have been interrupted by this breccia-forming event. The dark gray feldspathic microporphyritic melt breccias are polymict ferroan rocks apparently produced by impact melting and subsequent rapid crystallization of clast-laden melts. A relic gabbroic anorthosite lithic clast within one of the feldspathic microporphyritic melt breccias has mineral compositions similar to those of its host breccia. This gabbroic anorthosite may represent a slightly mafic, ferroan precursor of the feldspathic microporhyritic melt breccias, and may also be a precursor of the ferroan granulitic breccias. It is a sample of relatively mafic, ferroan-anorthosite-suite rock and is direct evidence of the existence of such a precursor for the feldspathic microporphyritic melt breccias.

McKay, D. S., Bogard, D. D., Morris, R. V., Korotev, R. L., Wentworth, S. J. and Johnson, P. (NASA Johnson Space Center, Houston, TX 77058): 'Apollo 15 Regolith Breccias: Window to a KREEP Regolith', in *Proceedings of the 19th Lunar and Planetary Science Conference (1989)*, pp. 19–41.

We made a multidisciplinary study of 28 regolith breccias returned from the Apollo 15 site. Measured densities of a subset of them range from 1.98 g/cm^3 to 2.94 g/cm^3, which slightly overlaps the most dense Apollo 15 core soil sample (1.35–2.15 g/cm^2). The maximum measured porosity in these regolith breccias is 37%. In the size range 20–500 μm, monomineralic fragments are the major component and pyroxene is generally more abundant than plagioclase. Feldspathic regolith breccias of the Apollo 16 type are absent, even among those collected from the highlands (Apennine Front). Plutonic highland lithic fragments are relatively rare (2% of the 20–500 μm fraction). However, KREEP basalt fragments are common (up to 18% of the 20–500 μm fraction), and in about a third of the analayzed breccias, the KREEP basalt fragments dominate the mare basalt fragments. Of the non-KREEP highland lithic fragments, subophitic melt rocks are the most common type, but even these do not exceed a few percent of fragments in this size fraction. Agglutinates are present in all of the porous and subporous regolith breccias, but their mean abundance (11.7% of the 20–500-μm size fraction) is low compared to surface and even core soils. We disaggregated four regolith breccias using ultrasonic and freeze-thaw techniques. Sieving and size analyses showed that the disaggregated size distribution is similar to that for soils. Electron microprobe analyses of glasses in the regolith breccias show that these breccias generally have higher abundances of KREEP glasses compared to surface soils from the same station. A small proportion of these KREEP glasses are highly enriched in K and Zr (up to 2800 μg/g Zr) and may represent a highly differentiated version of KREEP. All of the regolith breccias contain Apollo 15 volcanic green glass and mare basalts. While the range of the ferromagnetic resonance maturity index (I_s/FeO) for the regolith breccias overlaps the range for the soils, the mean for the regolith breccias (24 ± 16 units) is less than half that for the surface/trench soils (56 ± 22 units). The regolith breccias as a group therefore tend to be less mature than the surface/trench soils. A few regolith breccias (15015, 15205, 15426, and 15688) have extremely low maturities, comparable to some Apollo 16 regolith breccias. Elemental and isotopic ratios of rare gases in the regolith breccias are very similar to equivalent ratios in the surface soils. However, the regolith breccias appear to be somewhat depleted in lighter rare gases (He and Ne), compared to surface and core soils; this relative depletion may reflect mild heating that accompanied breccia formation. For some regolith breccias, $^{40}Ar/^{36}Ar$ ratios are somewhat higher (up to 4 or 5) than the 0.5 to 1.0 range typical for surface soils, suggesting that the regolith breccias were formed at an earlier time. Furthermore, this higher value appears to have a systematic relationship to the sampling site, which suggests that older regolith from depth was excavated by some of the large impacts in the area, or in the case of the Rille, was uncovered by downslope movement into the Rille. Chemical analaysis of regolith breccias by instrumental neutron activation (INAA) shows that their compositions are generally similar to those of nearby surfce soils and to other regolith breccias from the same sampling station. Abundances of siderophile elements correlate closely with the breccia maturities, suggesting that most of siderophile elements were acquired during micrometeorite reworking. Some of the regolith breccias have concentrations of incompatible trace elements significantly greater than those in any soils, and four (15028, 15205, 15467, and 15528) have concentrations nearly as high as those in KREEP basalts. Chemical data support an argument that similarities between soils and regolith breccias at a given station may result because the soils contain a high proportion of old breccias, which are being comminuted and reworked into the finer fractions. KREEP (basalts, glasses, and chemically identified components) is so abundant at the Apollo 15 site in soils, cores, and especially regolith breccias, that it cannot be exotic to the site and must be derived from a local source, probably a KREEP regolith that underlies the mare basalts. The KREEP regolith was previously derived from KREEP basalt flows, which now may be mostly converted into regolith.

Morris, R. V., Korotev, R. L. and Lauer, H. V., Jr. (NASA Johnson Space Center, Houston, TX 77058): 'Maturity and Geochemistry of the Van Serg Core (79001/2) with Implications for Micrometeorite Composition', in *Proceedings of the 19th Lunar and Planetary Science Conference (1989)*, pp. 269–284.

The soil maturity parameter I_s/FeO and the concentration of Fe metal and 18 major and trace elements were measured on samples from approximately every half centimeter along the 47 cm length of the 79001/2 double drive tube collected near Van Serg crater, Apollo 17. Samples from the top 8.5 cm of the core are very mature (I_s/FeO: mean = 96, maximum = 115) and enriched in Fe metal and siderophile elements compared to soil lower in the core. The maturity and siderophile element enrichment is too great to have developed by surface exposure after the soil was emplaced by the Van Serg impact (~1.6 m.y. ago), but instead results from a significant exposure at some time in the past. Except for enrichment in siderophile elements, the mature soil has essentially the same composition as the less mature soil underneath. Variations in chemical composition with depth are small and can be attributed to minor variation in the proportions of known local rock types. On the average, the core contains about one-third material of highlands origin and two-thirds material of mare origin (basalt and pyroclastic glass). The chemical signature of a primitive variant of mare basalt is observed at three depth zones and is most prevalent (>30% by mass) about 42 cm depth; the other two zones are enriched also in a chemical component of anorthositic gabbro. Enrichments of Ni and Co at both the top and bottom of the core result from a component with a chondritic Ni/Co ratio. The soils contain a component of metallic Fe, which correlates with surface exposure (concentrations up to 0.5% in the most mature samples) but is too coarse gained to result directly from reduction of Fe(II) by solar wind protons. This component presumably relates to micrometeorite impact, but does not derive primarily from metal-bearing micrometeorites. We cannot determine whether this metal component is the carrier of the excess Ni, Co, and Ir at the top of the core, although a similar enrichment in Ni, Co, and Ir at the bottom of the core is not accompanied by an enrichment in metal.

Neal, C. R. and Taylor, L. A. (Department of Geological Sciences, University of Tennessee, Knoxville, TN 37996): 'Metasomatic Products of the Lunar Magma Ocean: The Role of KREEP Dissemination', *Geochimica et Cosmochimica Acta* **53** (1989), 529–541.

The origin of the incompatible element-rich lunar component, KREEP, is in the Lunar Magma Ocean (LMO). The fractionated residual melt after crystallization of the LMO represents "urKREEP" (after Warren and Wasson, 1979). The percentage of this residual melt is low enough to be within the realm of silicate liquid immiscibility (SLI). This process has the ability to split the KREEP signature into K- and REEP-Fractions, which are manifest as lunar granite (K) and phosphate phases present in highland lithologies or as quartz ferrotroctolite in lunar soils (REEP). We envisage this as a localized, but significant process since only a small portion of urKREEP undergoes SLI. Norms of experimental and Apollo 15 basaltic immiscible glases suggest that the REEP-Fraction found in the lunar highlands has undergone post-SLI fractionation of at least fayalite. This significantly reduces the denstiy of the REEP-Fraction and coupled with its low viscosity (10–15 poise), it can percolate upward, metasomatizing the lunar crust. The higher viscosity of the granitic melt ($\cong$30000 poise) inhibits its mobility, and it forms "pods" in the lower crust (as required for VHK basalt petrogenesis).

With the identification of KREEPy components, the composition of urKREEP can be calculated. Using experimental evidence, the KREEP components may be recombined to give the pre-SLI composition, or liquid-liquid *Kd*'s can be used to calculate a pre-SLI composition from lunar granite. Both calculated urKREEP compositions are lower in MgO and AL_2O_3 and higher in FeO and P_2O_5 than reported low- and high-K KREEP compositions. The calculated REE abundances are higher and the REE profiles are slightly more LREE-enriched than the previously reported KREEP compositions. However, the REE profile calculated using liquid-liquid *Kd*'s in concave-upwards, compared to the LREE-enriched profile produced by recombining the KREEP components. Pre-SLI whitlockite/apatite fractionation occurred prior to immiscibility in order to generate the concave-upwards profile. The LREE-enriched profile represents the pre-SLI magma *prior* to phosphate fractionation. The presence of "superKREEPy" rock types can be accounted for by K- and REEP-Fraction assimilation, and the compositions of olivine vitrophyres can now be modeled using analyzed lunar rock types without the inference of a mythical "high-Mg" component.

Other, more widespread KREEPy rocks (e.g., Apollo 14 breccias, Apollo 15 KREEP basalts, LKFM basalts) are produced by incorporation of the more widespread pre-SLI urKREEP component. The splitting of KREEP into identifiable lithological components allows the petrogenesis and role of KREEP in lunar evolution to be better understood.

Neal, C. R. and Taylor, L. A. (Department of Geological Sciences, University of Tennessee, Knoxville, TN 37996): 'The Nature of Barium Partitioning between Immiscible Melts: A Comparison of Experimental and Natural Systems with Reference to Lunar Granite Petrogensis', in *Proceedings of the 19th Lunar and Planetary Science Conference (1989)*, pp. 209–218.

In order to evaluate lunar granite petrogenesis, we have undertaken a study of elemental partitioning between immiscible melts. Experimental liquid-liquid *Kd*'s have been combined with those determined by analysis of immiscible glasses in basalt mesostases. New probe data are presented of immiscible mesostasis glasses from basalt 15434,188. In general, the naturally and experimentally determined liquid-liquid *Kd*'s agree, except for Ba. All experimental data indicate that Ba is partitioned into the basic immiscible melt ($D_{b/a} > 1$), whereas probe analyses of immiscible glasses suggest Ba is partitioned into the granitic immiscible melt ($D_{b/a} < 1$). The partitioning of Ba is dependent upon the "alkali" (molar $K_2O + Na_2O + CaO + BaO$) and Al_2O_3 (moles) contents of the granitic melt. If the "alkali"/Al_2O_3 ratio is less than approximately 1, then Ba is preferentially partitioned into the granitic melt in order to charge balance tetrahedrally coordinated Al. If the "alkali"/Al_2O_3 ratio is >1, then tetrahedral Al is charge balanced by other alkalis, so Ba is partitioned into the basic melt. By calculating the "alkali"/alumina ratio of lunar granites, the $D_{b/a}$ for Ba can be estimated. The ratios of U/La and Th/La in granite are inconsistent with petrogenesis involving silicate liquid immiscibility (SLI). Although it is possible that these high ratios could be a result of the difference in magnitude betwen the respective liquid-liquid *Kd*'s, they could also be the result of whitlockite fractionation. Whether this is pre- or post-SLI is unclear. Modeling of an average lunar granite and granitic glass from 15434,188 by SLI produces a pre-SLI melt composition compatible with extreme Fenner Trend fractionation. This composition is not the 15405 QMD suggested as a parent to lunar granite by Shih *et al.* (1985). The occurrence of VHK basalts, formed by granite assimilation, argues for discrete granite bodies within the Moon. In order to allow separation of immiscible liquids, cooling rates must be relatively slow. Therefore we conclude that lunar granite of significant size can only occur in a plutonic or deep hypabyssal environment. This may account for the lack of returned granite samples, as meteorite impact may not have sufficiently sampled the depth at which abundant granite is present.

Neal, C. R., Taylor, L. A. and Patchen, A. D. (Department of Geological Sciences, University of Tennessee, Knoxville, TN 37996): 'High Alumina (HA) and Very High Potassium (VHK) Basalt Clasts from Apollo 14 Breccias, Part 1 – Mineralogy and Petrology: Evidence of Crystallization from Evolving Magmas', in *Proceedings of the 19th Lunar and Planetary Science Conference (1989)*, pp. 137–145.

The mineralogy and petrography of very high potassium (VHK) and high alumina (HA) basalts from the Apollo 14 site provide an insight into their magmatic evolution. Generally, their parageneses are similar, with olivine and chromite and early liquidus phases, followed by plagioclase and pyroxene, which crystallized together. Although late-stage ilmenite and FeNi metal occur in both VHK and HA samples, the VHKs also crystallize K-feldspar and Fa-rich olivine. Zoning of constituent minerals is similar for both basalt types, demonstrating that the parental magmas for both HA and VHK basalts became enriched in K, Na, Ca, Fe, and Ti and depleted in Mag and Al as crystallization proceeded. Enrichment of K in the VHK basalts is above that expected from normal fractional crystallization, witnessed by an interstitial K-rich residual melt (7–12 wt% K_2O), and requires an external input of K. This is consistent with the granite assimilation model proposed for VHK basalt on the basis of whole-rock chemistry. The mineralogy and petrography of HA basalt suggest petrogenesis by fractional crystallization alone; however, whole-rock chemistry necessitates the involvement of KREEP.

Neal, C. R., Taylor, L. A., Schmitt, R. A., Hughes, S. S. Lindstrom, M. M. (Department of Geological Sciences, University of Tennessee, Knoxville, TN 37996): 'High Alumina (HA) and Very High Potassium (VHK) Basalt Clasts from Apollo 14 Breccias, Part 2 – Whole Rock Geochemistry: Further Evidence for Combined Assimilation and Fractional Crystallization within the Lunar Crust', in *Proceedings of the 19th Lunar and Planetary Science Conference (1989)*, pp. 147–161.

The understanding of basalt petrogenesis at the Apollo 14 site has increased markedly due to the study of "new" samples from breccia "pull-apart" efforts. Whole-rock compositions of 26 new high alumina (HA) and 7 very high potassium (VHK) basalts emphasize the importance of combined assimilation and fractional crystallization in a lunar regime. Previously formulated models for HA and VHK basalt petrogenesis are modified in order to accommodate these new data, although modeling parameters are essentially the same. The required range in HA basalt compositions is generated by the assimilation of KREEP by a "primitive" (high MG#, low SiO_2, low incompatible elements) parental magma. In order to generate all observed compositions, the inferred parental magma must undergo 70% fractional crystallization and 15.4% KREEP assimilation. The VHK basalts can be generated by three parental HA basalts (primitive, intermediate, and evolved) assimilating granite. In order to accommodate the compositional variability of granite, three granite assimilant compositions are used in the modeling. Results indicate the VHK basalt compositions are dominated by the parental magma, and only up to 8% granite assimilation is required. This modeling indicates that at least three VHK basalt flows must be present at the Apollo 14 site.

Newsom, H. E. and Taylor, S. R. (Inst. of Meteoritics, University of New Mexico, Albuquerque, NM 87131): 'Geochemical Implications of the Formation of the Moon by a Single Giant Impact', *Nature* **338**, 29–34.

The origin of the Moon by a single massive impact of a body slightly larger than Mars with the Earth can explain the angular momentum, orbital characteristics and unique nature of the Earth–Moon system. The density and chemical differences between the Earth and the Moon are accounted for by deriving the Moon from the mantle of the impactor. A cosmochemically plausible impactor can be formed in the region of the inner Solar System, lending support to the impact hypothesis.

Nyquist, L., Lindstrom, M., Bansal, B., Mittlefehldt, D., Shih, C-Y. and Wiesmann, H. (Planetary Science Branch NASA Johnson Space Center, Houston, TX 77058): 'Chemical and Isotropic Constraints on the Petrogenesis of the Large Mare Basalt Clast in Breccia 15459', in *Proceedings of the 19th Lunar and Planetary Science Conference (1989)*, pp. 163–174.

The large mare basalt clast in Apollo 15 breccia 15459 has a chemical composition similar to that of two rake samples that were also collected at station 7 on the Apennine Front. Because these picritic basalts are characterized by high MgO contents it has been suggested that they are related to the Apollo 15 olivine-normative basalts by olivine accumulation. We conclude that it is more likely that they represent one or more independent magma types because: (1) Complex, nonequilibrium pyroxene and plagioclase compositions and relatively abundant mesostasis indicate that the 15459 clast is not a slowly cooled crystal cumulate. Although some olivine accumulation may have occurred, the clast appears to be close to a melt composition. (2) Mixing model calculations show that the addition of about 40% olivine to an olivine-normative basalt parental magma would be required to explain the high MgO abundances of picritic basalts by accumulation of olivine in the magma. (3) Addition of 40% olivine to an olivine-normative basalt magma should decrease the REE abundances proportionally, which is not observed. (4) Exact compensation of the expected decrease in REE abundances by trapping of REE-rich residual liquid from the magma during crystallization of the basalt seems unlikely. (5) The initial Sr isotropic ratios measured for 15459 differ from those of the olivine-normative basalts for which appropriate isotopic data are available. The Rb–Sr internal isochron age (T) of the 15459 clast is 3.22 ± 0.04 Ga ($\lambda(^{87}Rb) = 0.0139\ Ga^{-1}$), and the initial $^{87}Sr/^{86}Sr$ ratio (I_{sr}) is 0.699502 ± 0.000017. The Rb–Sr age is in satisfctory agreement with, but slightly younger than, a previously determined ^{39}Ar–^{40}Ar age. Compared to most Apollo 15 basalts, the 15459 clast has a slightly younger age and a slightly higher I_{Sr}. In particular, although I_{Sr} for the 15439 clast is similar to those of olivine normative basalt 15555, the (T, I_{Sc}) parameters of the two basalts resolved; thus they are not comagmatic. However, the error limtis on the isotopic data permit the 15459 picritic basalt clast and 15555 olivine-normative basalt to have been derived from the same lunar mantle source region at different times.

Oberst, J. and Nakamura, Y. (Department of Geological Sciences and Institute for Geophysics, The University of Texas, Austin, TX 78713): 'Monte Carlo Simulations of the Diurnal Variation in Seismic Detection Rate of Sporadic Meteoroid Impacts on the Moon', in *Proceedings of the 19th Lunar and Planetary Science Conference (1989)*, pp. 615–625.

The rate of detection of meteoroid impacts on the Moon by the lunar seismic network shows a characteristic diurnal variation. Assuming that these meteoroids have a flux and a preimpact orbital distribution similar to that of fireballs observed by terrestrial camera networks, one can compute the expected diurnal variation for a given set of a parameters that describe the seismic wave generation and transmission on the Moon. An iterative process to match the theoretical variation with the observed one has led us to the following results: (1) The majority of the detected impact events occur within a closer range of the network than was believed earlier. This results in higher meteoroid flux estimates from lunar seismic data that agree with the terrestrially measured flux. (2) For meteoroid masses smaller than 1000 g, seismic amplitude is approximately proportional to the one-fifth power, provided that the terrestrial meteor data used for analysis are not biased. (3) Seismic efficiency of meteoroids smaller than 1000 g is significantly less than that of large meteoroids. (4) Using orbits of fireballs that represent meteorities, we predict that the share of meteorites among the detected impacts is approximately 15% assuming that seismic efficiency of the high-density meteorites is the same as that of average meteoroids. A greatly increased seismic efficiency for these high-density objects is not likely.

Pieters, C. M. and Taylor, G. J. (Department of Geological Sciences, Brown University, Providence, RI 02912): 'Millimeter Petrology and Kilometer Mineralogical Exploration of the Moon', in *Proceedings of the 19th Lunar and Planetary Science Conference (1989)*, pp. 115–125.

Coordinated petrologic and spectroscopic analyses were undertaken for a specially prepared 1-cm chip of regolith breccia 60019. The mineralogy of several large clasts (>1 mm) and matrix areas of this sample were analyzed in thin section. The mafic minerals of each large clast were readily identified from spectral reflectance measurements of the same class, and mineral abundance was shown to be directly related to absorption strength. Although most clasts of 60019 are noritic in composition, the presence of abundant olivine and/or high-Ca pyroxene in several clasts is easily noted spectroscopically, based on the wavelength and strength of absorption bands near 1 and 2 μm. The origin of an unusual absorption feature near 0.6 μm in an anorthositic clast was determined by petrographic analysis to be due to very fine-grained translucent ilmenite. The 60019 matrix is dark and glassy, and although a variety of clasts occur on all scales, particulate powders of 60019 are all very similar and have spectral properties that indicate a noritic breccia bulk composition. The spectral homogeneity of direct powders from this complex regolith breccia indicates that the variety of distinct lithologies inferred from remote spectroscopic measurement of unsampled sites across the Moon must reflect basic variations in local rock types.

Premo, W. R., Tatsumoto, M. and Wang, J.-W. (U.S. Geological Survey, Denver Federal Center, Denver, CO 80225): 'Pb Isotopes in Anorthositic Breccias 67075 and 62237: A Search for Primitive Lunar Lead', in *Proceedings of the 19th Lunar and Planetary Science Conference (1989)*, pp. 61–71.

A major obstacle in lunar U-Pb chronology has been the elusiveness of the primitive or "initial" lunar Pb isotopic composition and U/Pb value and therefore the Pb evolution during the early history of the Moon. In order to better understand the lunar Pb isotopic evolution, the U-Th-Pb systematics of "primitive" Apollo 16 anorthositic breccias 67075 and 62237 were studied. For 67075, a whole-rock and several mineral fractions including plagioclase, a pyroxene-olivine mixture, and opaques were analyzed. When plotted, the Pb isotope data for acid-leached residues from 67075 do not form a linear trend as expected, but instead lie within or on a triangle formed by plagioclase, opaques, and pyroxene-olivine mixture. These results indicate either mixing of different Pbs consistent with the polymict, brecciated nature of the sample, or they may indicate that xenocrystic pyroxene (and possibly olivine) were incorporated into a plagioclase melt at about 4.24 Ga, an age that corresponds to the intercept of the tie line of plagioclase and the opaques. This age is similar to a previously reported $^{40}Ar/^{39}Ar$ age for the same sample. For 62237, whole-rock, plagioclase, pyroxene, olivine, and a magnetically-separated mixture were analyzed. As with the Pb isotopic data from 67075, residues of sample 62237 do not form a linear array, but instead lie within or on a triangle formed by plagioclase, olivine, and pyroxene. A similar agreement for mixed Pbs can be made for 62237. Uranium-lead data from plagioclase and opaque separates of 67075 define concordia intercepts at 4.35 and 4.09 and, although the precision level precludes any definite age data from 62237, the U-Pb results from both 67075 and 62237 are in general consistent with the "cataclysm array" of Terra *et al.* (1974). Using the measured $^{238}U/^{204}Pb(\mu)$ values for plagioclase and some mafic mineral fractions, calculated first-state μ values for both two-stage and three-stage Pb evolution equations range between 250 and 625 assuming a lunar origin age 4.56 Ga and a primary lunar differentiation age of 4.36 Ga. We suggest the Moon had a high μ value (>300) from the outset, that early cumulates differentiated from the lunar primary magma ocean may have had a μ value of ~20–50, and that late cumulates consequently had high μ values (>100).

Ryder, G. (Lunar and Planetary Institute, Houston, TX 77058): 'Mare Basalts on the Apennine Front and the Mare Stratigraphy of the Apollo 15 Landing Site', in *Proceedings of the 19th Lunar and Planetary Science Conference (1989)*, pp. 43–50.

Olivine-normative mare basalts are present on the Apennine Front as crystalline particles and shocked or shock-melted fragments. Picritic basalts, which may be related to the olivine-normative basalts by olivine accumulation, not only occur on the Front but such samples so far recognized are confined to it. Mare volcanic and impact glasses also occur on the Front; all are olivine-normative, though none are quite the equivalent of the typical olivine-normative mare group. The quartz-normative mare basalts are not present (or are extremely rare) on the Front either as crystalline basalt or shocked or glass equivalents. These observations are consistent with the olivine-normative mare basalts being both local and the youngest flows at the site, and the fragments being emplaced on the Front by impacts. The picritic basalts raise the distinct possibility that the olivine-normative basalts also ponded on the Front. An influx of olivine-normative basalts from exotic sources (e.g., a ray from Aristillus) is inconsistent with their abundance, their dominance in the mare soil chemistry, and their age, isotopic, and trace element similarities with the quartz-normative basalts. However, the thermal histories of the olivine-normative basalts require elucidation.

Simon, S. B., Papike, J. J., Shearer, C. D., Hughes, S. S. and Schmitt, R. A. (Institute for the Study of Mineral Deposits, South Dakota School of Mines and Technology, Rapid City, SD 57701): 'Petrology of Apollo 14 Regolith Breccias and Ion Microprobe Studies of Glass Beads', *in Proceedings of the 19th Lunar and Planetary Science Conference, (1989)*, pp. 1–17.

Comparisons of mineral chemistries, glass chemistries, and bulk compositions of ten Apollo 14 regolith breccias with Apollo 14 soils show that nine of the ten are of local origin. Data from these local breccias can therefore be used to improve our understanding of regolith evolution at the Apollo 14 site and on the Moon in general. Results show that the major changes in the regolith since the formation of the breccias are an increase in maturity, an increase in glasses with "Fra Mauro basalt" composition, and decreases in feldspathic (anorthostic gabbro) and mare glasses. The Fra Mauro glasses have soil-like compositions and are accumulating in the regolith, whereas the feldspathic and mare glasses are being gardened and diluted in the regolith. Ion probe analyses show that the Na-, K-rich Fra Mauro glasses are KREEPy ($\sim$200–500$\times$ chondrite), whereas the Na-, K-poor feldspathic glasses have low REE abundances and positive Eu anomalies. ZNa-, K-poor, REE-rich glasses are also observed and show that decoupling of K and REE is possible, probably by silicate-liquid immiscibility and/or differential volatilization. Breccia 14315 is different from the other breccias in terms of mineral and glass populations, bulk chemistry (richer in Al_2O_3, lower in MgO, K_2O), and REE and other lithophile abundances (lower). These observations indicate a source (probably exotic to the site) with a larger non-KREEPy highland plutonic component than the other breccias. The chemical uniformity of the local breccias and their similarity to the soils show that the regolith at the Apollo 14 site has been chemically homogeneous since before the formation of the breccias.

Spudis, P. D., Hawke, B. R. and Lucey, P. G. (Branch of Astrogeology, U.S. Geological Survey, Flagstaff, AZ 86001): 'Geology and Deposits of the Lunar Nectaris Basin', in *Proceedings of the 19th Lunar and Planetary Science Conference (1989)*, pp. 51–59.

In order to better understand the lunar basin-forming process and the regional geologic setting of the Apollo 16 landing site, we have studied the geology and composition of Nectaris basin deposits. The deposits outside the basin rim are the radially lineated Janssen Formation and the hummocky Descartes material; those inside the basin include massifs and a hummocky or knobby unity. The Nectaris basin has five rings, 240, 400, 620, 860 (main rim), and 1320 km in diameter. The regional composition of Descartes material and the hummocky unit, as determined from orbital chemical data and Earth-based reflectance spectroscopy, is that of anorthositic norite to noritic anorthosite. Several outcrops of nearly pure anorthosite have been identified in several locations including the walls of Kant crater, in an inner ring of the basin, and in the crater Bohnenberger F. A relatively mafic area of the basin interior deposits has been shown to consist of noritic material, suggesting that a previous interpretation of this unit as a site of volcanic resurfacing is unlikely. The bulk of the Apollo 16 sample collection comes from a complex megabreccia of broadly anorthositic composition that was ultimately derived from the Nectaris basin. It is possible that Nectaris basin melt may have been collected at the Apollo 16 site in the form of "VHA basalt," an aluminous variety of low-K Fra Mauro basalt; if so, the Nectaris basin formed 3.92 b.y. ago. The Nectaris impact can be modeled as a proportional-growth crater. This analysis suggests that the Nectaris excavation cavity was about 470 km in diameter and as deep at 55 km, and that the total excavated volume was between 6.3 and 9.2×10^6 km^3.

Stone, J. and Clayton, R. N. (Enrico Fermi Institute, University of Chicago, Chicago, IL 60637): 'Nitrogen Isotopes in Drive Tube 79002/79001: Regolith History and Nitrogen Isotopic Evolution in the Solar Wind', in *Proceedings of the 19th Lunar and Planetary Science Conference (1989)*, pp. 285–295.

Variations in abundance and isotopic composition of nitrogen in 79002/79001 drive tube samples result from mixing of two soil components: one mature, N-rich, and isotopically light, resembling breccia material in the core, and the other immature, N-poor, and isotopically heavy. That these materials are common to a soil at each stratigraphic level in the core suggests widespread distribution in the local regolith. Preservation of mixing correlations involving nitrogenisotopic compositions and cosmogenic ^{15}N concentrations suggests relatively recent mixing, perhaps in association with emplacement of the core stratigraphy. Characteristics of nitrogen release from the end member materials, relationships between their nitrogen contents and maturity, and contrasts in their cosmogenic ^{15}N contents are consistent with models involving secular increase of the ^{15}N/^{14}N ratio of the solar wind.

Warren, P. H., Jerde, E. A. and Kallemeyn, G. W. (Institute of Geophysics and Planetary Physics, University of California, Los Angeles, CA 90024): 'Lunar Meteorities: Siderophile Element Contents, and Implications for the Composition and Origin of the Moon', *Earth and Planetary Science Letters* **91** (1989), 245–260.

Six lunar meteorites have thus far been discovered in Antarctica. Although these meteorites are undocumented lunar-geographic provenance, all other available lunar samples (obtained from the Apollo and Luna programs) came from a relatively minuscule region of the central nearside, around which a polygon could be drawn covering just 4.7% of the lunar surface. The five lunar meteorites that are now well-studied represent at least two but probably three separate lunar source craters: ALHA81005 and Y791197 are probably from separate craters, and compound meteorite Y82192/6032 is certainly from a crater of its own. At least ALHA81005 and Y79197, and probably also (at least in a loose sense) Y82192/6032, are highlands regolith breccias. Thus, their compositions may be appropriately compared with compositions of Apollo and Luna highlands regolith samples. Compared with average highlands regolith samples from the central nearside Apollo sites, lunar meteorites have lower concentrations of siderophile elements in general, and especially Au, Ge and Ni. Among anothositic Apollo samples (i.e., mainly those from Apollo 16), Au/Ir and to a lesser extent Ge/Ir ratios tend to be hyperchondritic. Most previous models for lunar regolith siderophile geochemistry assumed that the Apollo 16 samples are representative of the overall lunar highlands. Such models tended to conclude that the hyperchondritic Au/Ir and Ge/Ir ratios were consequences of variations in the compositions of Moon-striking projectiles as a function of time. It was even speculated that these temporal variations were consequences of the heterogeneous accretion of a Moon with a general enrichment in refractory elements.

The lunar meteorities suggest that hyperchondritic Au/Ir and Ge/Ir are not general features of the highlands, but peculiarities of the Apollo 16 region, or more generally, the central nearside. The high Ni contents of the Apollo 16 megaregolith, substantially in excess of the Ni implied by a model in which all meteoritic debris has an H-chondritic Ni/Ir ratio, have been interpreted to imply that the Mg-rich fraction of the lunar crust is extremely Ni-rich, and thus similar in siderophile geochemistry to terrestrial komatiites. This coincidence has been interpreted as confirmation that the Moon formed by modified fission from the Earth's mantle, after core formation (plus late-accretion effects) had established the final siderophile pattern of the Earth's mantle. However, the lunar meteorites (and a survey of data for the Luna 20 highlands regolith sample) suggest that the high Ni content of the Apollo 16 regolith is strictly a peculiarity of the Apollo 16 region, and not a general feature of the Moon's crust. The anomalous siderophile composition of the central nearside regolith probably stems from a combination of regional heterogeneity in cratering-projectile compositions, plus regional enrichments in relatively "labile" siderophile elements (most notably Au, Ge, and perhaps to a certain extent Ni), which might be loosely correlated with the anomalously high concentration of KREEP over the central nearside.

2. PLANETS (Articles about more than one body)

Breus, T. K., Bauer, S. J., Krymskii, A. M. and Mitnitskii, V. Ya. (Space Research Institute, Academy of Sciences of the USSR, Moscow): 'Mass Loading in the Solar Wind Interaction with Venus and Mars', *Journ. Geophys. Res.* **94** (1989), 2375–2382.

An analysis of available experimental data and theoretical concepts indicates that the interaction of the solar wind (SW) on the subsolar side with Venus, which has no intrinsic magnetic field, and with Mars, which has a small intrinsic magnetic field, is determined by the solar wind dynamic pressure with a contribution from the neutral planetary atmosphere to this interaction. The pattern of the SW interaction with these planets is different in principle for high and low dynamic pressures of the SW and is related to the varying intensity of ion formation processes (the SW Mass loading effect) in the vicinity of the SW obstacle boundary, which moves for different SW dynamic pressures into regions of different neutral atmosphere density. For moderate or high SW dynamic pressures, the subsolar Martian magnetosphere is also affected by this process. Results of numerical simulations of the SW-Mars interaction for a magnetospheric obstacle boundary at an altitude of 300 km are presented. To estimate the relative role of photoionization and charge exchange processes and their effect on the shock front position, different versions of the mass loading effect were separately calculated.

Brophy, T. G. and Esposito, L. W. (Laboratory for Atmospheric and Space Physics, University of Colorado, Boulder, Colorado 80309): 'Simulation of Collisional Transport Processes and the Stability of Planetary Rings', *Icarus* **78** (1989), 181–205.

A model kinetic equation is solved numerically for a flattened Keplerian disk using a phase-space fluid method which models the particle transport process as a Markov process. Ringlets composed of single-sized particles and ringlets composed of two different-sized particles are investigated. The accuracy of the new computational method is verified by close agreement with the analytical results of F. H. Shu and G. R. Stewart (*Icarus* **62**, 360–383 (1985)), P. Goldreich and S. Tremaine (*Icarus* **34**, 227–239 (1978)), W. R. Ward (*Geophys. Res. Lett.* **8**, No. 6, 641–643 (1981)), and D. N. C. Lin and P. Bodenheimer (*Astrophys. J.* **248**, L83–L86 (1981)), and the simulations of Spaute and Greenberg (*Icarus* **70**, 289-302 (1987) and J. M. Petit and M. Henon (*Astron. Astrophys.* **199**, 343–356 (1988). The generally accepted theory of viscous spreading (e.g., N. Borderies, P. Goldreich, and S. Tremaine, is verified for the special case of ringlets where all the particles are the same size. Ringlets composed of two components of particle size evolve in such a manner that the lighter particles are confined by the heavier particles. Some implications are that (1) a natural mechanism may sharpen the optical depth profile of edges even in the absence of an external forcing mechanism under some conditions and (2) in some cases intermediate optical depths are dynamically preferred. Simulation of the dominant features of observed planetary rings (sharp edges, micro-structure) may have been excluded by some of the simplifying assumptions of analytic theories, such as single-sized particles and the existence of a simple scalar viscosity.

Cintala, M. J., Hörz, F. and See, T. H. (NASA Johnson Space Center, Houston, TX 77058): 'Impact Cratering in Low μ Gravity Environments: Results of Reconnaissance Experimentation on the NASA KC-135A Reduced-Gravity Aircraft', in *Proceedings of the 19th Lunar and Planetary Science Conference (1989)*, pp. 627–639.

A program of flight experimentation was performed on the NASA KC-135A Reduced-Gravity Aircraft to evaluate the potential for conducting impact experiments in reduced-gravity environments and to collect impact-cratering data at gravity levels below 1 *g*. Lead pellets were launched into coarse-grained sand at velocities ranging from ~65 m/sec to 130 m/sec while the gravitational acceleration was maintained at levels between 0.59 *g* to 0.05 *g*. A total of 64 craters were studied and, after allowance is made for the atmospheric pressure over the target (0.83 atm), their diameters are found to have been consistent with scaling predictions made on the basis of ground-based experimentation. Formation times were also obtained for 33 of these craters and constitute a distribution that is somewhat different from that described by the ground-based data. Nevertheless, the KC-135 data set as a whole falls on the trend formed by the ground-based results. The overall agreement between the two data sets attests to the stability of the aircraft as a platform for impact experimentation.

Cole, S., 'Rediscovering Venus and Jupiter', *Astronomy* **17**(1) (1989), 23–31.

MAGELLAN's state-of-the-art radar mapping of Venus and GALILEO's intricate flybys through the Jovian system will give us the best look yet at these planets.

Cynn, H. C., Boone, S., Koumvakalis, A., Nicol, M. and Stevenson, D. J. (Department of Earth and Space Sciences, University of California, Los Angeles, CA 90024): 'Phase Diagram for Ammonia-Water Mixtures at High Pressures: Implication for Icy Satellites', in *Proceedings of the 19th Lunar and Planetary Science Conference (1989)*, pp. 433–441.

The $(NH_3)_X(H_2O)_{1-X}$ phase diagram for $0 \leq X \leq 0.50$ has been reexamined at temperatures from 125 K to 400 K and at pressures to 6.0 GPa using diamond-anvil cells. By electroplating the gasket materials with gold, complicated reactions between sample solutions and gasket materials, which affected earlier studies, have been avoided. Sample pressures were determined using the ruby-luminescence technique, and phase assignments were made using optical characterization. Phase assignments were confirmed by Raman spectroscopy. At room temperature the stable phases observed were fluid, high pressure ices (VI and VII), and ammonia monohydrate, $NH_3 \cdot H_2O$. The Ice VI and Ice VII liquidi at 295 K were extrapolated to intersect at $X = 0.26 \pm 0.01$ and 2.1 GPa. At room temperature, the eutectic for Ice VII and $NH_3 \cdot H_2O$ was observed at 3.3 ± 0.2 GPa, and extrapolation of the room temperature liquidus indicates that the cotectic composition is near $X = 0.45$. Near $X = 0.33$, the stable phases were high pressure ices (VI, VII, and VIII), $NH_3 \cdot H_2O$, and another phase tentatively identified as ammonia dihydrate, $NH_3 \cdot 2H_2O$. At this composition, the Ice VI liquidus and the congruent melting curve of $NH_3 \cdot 2H_2O$ intersect at 1.8 ± 0.2 GPa and 252 ± 5 K, and the Ice VII liquidus is approximately linear with a slope of 0.016 ± 0.002 GPa K^{-1}. To within the uncertainty of the experiment, the Ice VI liquidus continues smoothly from the Ice VII liquidus. The quadruple point among $NH_3 \cdot H_2O$, $NH_3 \cdot H_2O$, Ice VI, and fluid is located at 250 ± 5 K and 1.9 ± 0.3 GPa, with the accompanying double cotectic at a composition of $X = 0.36 \pm 0.01$. The eutectic for $NH_3 \cdot H_2O$ and Ice VII is approximately linear with a slope of 0.033 ± 0.003 GPa K^{-1}. We have applied these data to the interior of Titan in a manner similar to the analysis of Lunine and Stevenson (1987). The main implication of these results is that Titan is likely to have a thicker NH_3–H_2O ocean than previously suspected, because the stability field of $NH_3 \cdot 2H_2O$ is smaller than previously supposed. Implications for methane and ammonia volcanism on Titan are briefly discussed. The experimentally observed reactivity between the liquid and iron (for example) may also have implications for planetary and satellite evolution.

Donn, B. and Meakin, P. (NASA Goddard Space Flight Center, Greenbelt, MD 20771): 'Collisions of Macroscopic Fluffy Aggregates in the Primordial Solar Nebula and the Formation of Planetesimals', in *Proceedings of the 19th Lunar and Planetary Science Conference (1989)*, pp. 577–580.

Small grains some tens of nanometers in radius tend to stick very readily. This produces very low-density fractal aggregates up to several millimeters diameter. As these particles grow, the fractal structure is distorted and the density increases. It is expected that aggregates of meter dimensions will have substantially higher densities and a value of 0.2 g cm^{-3} has been adopted. Such bodies are very compressible, unlike the usual assumption of close-packed, dense bodies that have been made in studies of planetary accumulation. These fluffy aggregates will capture smaller ones in a collision, leading to an effective growth process. The collision mechanism has been analyzed under some simplifying assumptions: (1) all objects are uniform density spheres; (2) collisions have small impact parameters; and (3) the effect of the impact is restricted to a cylinder with the cross-section of the smaller body. The smaller object penetrates the larger until all the kinetic energy of the collision is dissipated by the work done in the penetration and resultant compression of the material. This calculation is based on published experiments on the static compaction of low-density powders. The present analysis suffers from an ignorance of the mechanical behavior of fluffy aggregates and the limited range of experimental results. This report represents a first attempt to treat the problem. The results of representative collisions are summarized in Table 1. These show that the penetration is only a fraction of the radius of the impacting body. Two procedures to improve these calculations are under way. One is a series of experiments on the mechanical properties of fluffy aggregates and their response to impacts. The second is an improved treatment of collisions without the restrictive assumption.

Durham, R. and Chamberlain, J. W. (Department of Space Physics and Astronomy, Rice University, Houston, Texas 77521): 'A Comparative Study of the Early Terrestrial Atmospheres', *Icarus* **77** (1989), 59–66.

A one-dimensional radiative-convective model of the atmosphere is used to determine the levels of CO_2 needed to maintain the climatic conditions thought to have existed on Mars, Earth, and Venus 4.0 byr ago. The range of possible atmospheric compositions is large for any one planet, but narrows considerably when the composition must be compatible with conditions on all three planets. From a comparative analysis of the planets, we estimate that 4.0 byr ago the surface partial pressure of CO_2 on Mars was between 1.3 and 2.1 bars and its partial pressure on Earth may have been as high as 14 bars. The Earth and Martian atmospheres were very stable and would not have gone into a moist or runaway greenhouse state even if the CO_2 partial pressure were equivalent to 100 bars on Earth. On the other hand, because of its proximity to the Sun, the Venus atmosphere was very susceptible to the rapid photodissociation of water vapor and the subsequent escape of hydrogen for surface pressures less than 11 bars. At partial pressures greater than 15 bars of CO_2, the increased albedo of Venus due to Rayleigh scatterin becomes a dominant factor and the Venus atmosphere becomes stable. This stabilizing effect of Rayleigh scattering in massive CO_2 atmospheres, along with the relative distances of the Earth and Venus from the Sun, can account for the very divergent evolutions of the terrestrial atmospheres.

Feldman, W. C., Drake, D. M., O'Dell, R. D., Brinkley, F. W., Jr. and Anderson, R. C. (Los Alamos National Laboratory, Los Alamos, New Mexico): 'Gravitational Effects on Planetary Neutron Flux Spectra', *Journal of Geophysical Res.* **94** (1989), 513–525.

The one-dimensional diffusion accelerated neutral-particle transport (ONEDANT) code is augmented to explore the effects of gravity on neutron flux spectra near planetary surfaces. The lifetime of the neutron is also explicitly accounted for. The results show a qualitatively new feature in planetary neutron leakage spectra in the form of a component of returning neutrons having kinetic energies less than the gravitational binding energy (0.132 eV for Mars). The net effect is an enhancement in flux at the lowest energies that is largest at and above the outermost layer of planetary matter. This effect diminishes with increasing depth. Fluxes for kinetic energies larger than the gravitational binding potential are minimally changed by gravity. All energy spectra can be well characterized by a model consisting of the super-position of relatively simple thermal and epithermal functions that are completely specified by four parameters; the thermal and epithermal amplitudes, α and β, respectively; the thermal temperature, T_α; and the epithermal power law exponent, p. Instrumental parameters for the initial version of the neutron mode of the Mars observer gamma ray spectrometer are used to demonstrate the ability to use measured, count rates to determine thermal and epithermal amplitudes.

Goguen, J. D., Hammel, H. B. and Brown, R. H. (Institute for Astronomy, University of Hawaii, Honolulu, Hawaii 96822): 'V Photometry of Titania, Oberon and Triton', *Icarus* **77** (1989), 239–247.

V filter photometry with the 2.2-m University of Hawaii telescope on Mauna Kea obtained during 1982–1983 is analyzed to determine the phase angle and orbital brightness variations of Titania, Oberon, and Triton. The unit distance opposition magnitudes and phase coeficients ($\alpha < 3°$) are Titania, $V(1, 0) = 1.016 \pm 0.042$, $\beta = 0.102 \pm 0.021$ mag/deg; Oberon, $V(1, 0) = 1.231 \pm 0.035$, $\beta = 0.103 \pm 0.018$ mag/deg; Triton $V(1, 0) = -1.236 \pm 0.041$; $\beta = 0.027 \pm 0.035$ mag/deg. The phase coefficients for Titania and Oberon are comparable to those observed for asteroids at similar small phase angles. Measurements made at $\alpha = 0.°06$ show an ~0.2-mag additional increase in brightness similar to that reported in the near-infrared by R. H. Brown and D. P. Cruikshank ((1983), *Icarus* **55**, 83–92). The small phase coefficient for Triton indicates the light may not be scattered from a low-albedo, porous regolith, but suggests a high-albedo surface, a significant atmosphere, or a smooth surface, e.g., an ocean. Orbital light curves are less than 0.1 mag in amplitude for Titania, Oberon, and Triton. The Titania data agree well with photometry at phase angles $\geqslant 0.°8$ from the Voyager 2 imaging experiment (J. Veverka, P. Thomas, P. Helfenstein, R. H. Brown and T. V. Johnson, 1987, *J. Geophys. Res.* **92** 14,895–14,904).

Hayakawa, M., Mizutani, H., Kawakami, S. and Takagi, Y. (Department of Earth Sciences, Nagoya University, Nagoya, Japan): 'Numerical Simulation of Collisional Accretion Process of the Earth', in *Proceedings of the 19th Lunar and Planetary Science Conference (1989)*, pp. 659–671.

The formation process of the Earth from 10^{10} plantesimals of 8 km in diameter in a gas-free environment was studied numerically using the method developed originally by Greenberg *et al.* (1978) in which planetesimals are treated as "particles in a box" and are distributed into size groups (size bins) according to the respective masses of planetesimals. The evolution of the size and velocity distribution of the planetesimal swarm in the Earth zone was simultaneously calculated taking into account impact fragmentation, cratering erosion, rebound, and coagulation. Major revisions were made to Greenberg *et al.*'s numerical scheme including the mesh size of the size bin, which was found to affect the growth time significantly, and the scaling laws on the impact process, which were obtained on the basis of recent experimental and theoretical studies. The present results show: (1) In the Earth region, a body of about 5000 km in diameter is produced in 10^7 years. A simple extrapolation of the growth curve of the proto-Earth indicates that the formation time of the full-size Earth is about 10^8 years. (2) The random velocities (relative to Keplerian orbits) of small planetesimals become 1 to 5 km/s at $t = 10^7$ years due to the gravitational scattering effect. The high velocities of small planetesimals cause destructive elimination of medium-size bodies. (3) At the final stage of Earth's accretion, the planetesimal mass distribution becomes bimodal: a small-size group and a large-size group of planetesimals. The small-size group represents planetesimals smaller than 10 m in diameter and the large-size group represents those larger than a few hundred kilometers in diameter. The Earth grows by gradual and calm accumulation of planetesimals of the small-size group and infrequent but violent collisions with planetesimals of the large-size group.

Heisler, J. and Tremaine, S. (Steward Observatory, University of Arizona, Tucson, AZ 85721): 'How

Dating Uncertainties Affect the Detection of Periodicity in Extinctions and Craters', *Icarus* **77** (1989), 213–219.

Claims of a highly significant detection of a period of 25–30 myr in the records of major extinction events and large craters have prompted us to examine how dating errors degrade a periodic signal. We ran Monte Carlo simulations in which we placed eight events at equal time intervals and then displaced each event by a random error chosen from a normal distribution. If the r.m.s. error is greater than about 13% of the period, the periodic data is usually no longer distinguishable from random data at the 90% confidence level. At present, the r.m.s. dating errors in extinction episodes and craters over the last 250 myr are *at least* 6 myr or $\geqslant$20% of a 25- to 30-myr period. We conclude that even if a periodicity were present, it would not normally be detected at a statistically significant level by the tests used in the literature. The apparent periodicity is probably due to a statistical fluke or subjective bias.

Horedt, G. P. (DFVLR, Wessling, F. R. Germany): 'Models of Evolutionary Tracks of Planetary Satellites', *Astron. Astrophys.* **209** (1989), 411–422.

Satellite formation is studied within the scenario of collisional capture of planetesimals by an accreting planet. We calculate the capture probability of planetary satellites by free-free and bound-free collisions among planetesimals within the planet's gravitational sphere of action. The possibility of satellite formation by near-grazing and/or destructive collisions between a planetesimal and the planet itself is discussed. A capture criterion for satellite formation by collisions between planetesimals is formulated. After capture the satellite evolves by coaccretion, being eventually crushed by collisions with heliocentric planetesimals, forming subsequently a circumplanetary ring. Circumplanetary rings are generally very short lasting objects, the crushed satellites being reaccreted after several 10^2–10^4 yr. We calculate evolutionary tracks for selected satellites formed by coaccretion, or accreting in circumplanetary rings. The surface density in the satellite systems of Jupiter, Saturn and Uranus is determined, masses, velocities, eccentricities and formation intervals being shown for selected satellites.

Hubbard, W. B. and Marley, M. S. (Department of Planetary Sciences, Lunar and Planetary Laboratory, University of Arizona, Tucson, Arizona 85721): 'Optimized Jupiter, Saturn, and Uranus Interior Models', *Icarus* **78** (1989), 102–118.

We present models of Jupiter, Saturn, and Uranus which exactly match recent accurate determinations of these planets' gravitational harmonics. The models are computed to third order in the rotational disturbance to the total potential and are based upon a method for inverting the gravitational data. For Jupiter and Saturn, a range of gravity models is calculated to test the possibility of a reduction of density in the outer layers due to helium depletion. The results, which are based upon an improved equation of state for molecular hydrogen, indicate that major helium depletion has not occurred in the outer (molecular hydrogen) layers of Jupiter or Saturn, or if it has, that its effect on the density profile is masked by the presence of other, denser, components. Jupiter is found to be slightly enhanced in heavy elements with respect to solar composition, but the density profile of its hydrogen-rich layers generally agrees rather well with a theoretical profile for solar composition. The deviations from such a profile are more pronounced in the case of Saturn. Uranus models have considerable uncertainty; one successful model resembles the ice-rich model of M. Podolak and R. T. Reynolds (1987, *Icarus* **70**, 31–36), but is fitted to a newer value of J_4. Our Uranus model has a substantial enrichment of heavy elements at depth, but little separation of the ice from the rock component. All of the Jovian planets appear to have central cores of non-hydrogen–helium material which are of similar mass (about 10–15 Earth masses). For Jupiter and Saturn, our calculations yield a gravitational harmonic J_6 which is in agreement with observation, but suggest that this quantity, along with harmonics of higher degree and order, is likely to be more useful for constraining the nature of fluid currents in outer layers rather than deep static structure.

Jackson, A. A. and Zook, H. A. (Lockheed Engineering and Science Corp., Houston, TX 77058): 'A Solar System Dust Ring with the Earth as its Shepherd', *Nature* **337** (1989), 629–631.

Bodies orbiting in the gravitational fields of galactic, solar or planetary systems often suffer dissipative forces, including tidal interactions and drag resulting from motion through a gas or from collisions with dust grains. In the early solar nebula, gas drag induces resonance trapping, which may be of importance in the early accretional growth of planets. By means of numerical integrations, we show here that small dust grains can be temporarily captured into exterior orbit–orbit resonances with the Earth, lasting from less than 10,000 years to more than 100,000 years. Grains with radii of 30–100 μm, orbiting in planes less than 10° from the plane of the Solar System and with orbital eccentricities of less than 0.3, are captured most easily. We argue that there should be an approximately toroidal cloud of particles, derived mostly from the asteroid belt, trapped into a variety of these exterior resonances. The cloud is mostly beyond the Earth's orbit, but includes it.

Johnson, R. E. (Department of Nuclear Engineering and Engineering Physics, University of Virginia, Charlottesville, Virginia 22901): 'Application of Laboratory Data to the Sputtering of a Planetary Regolith', *Icarus* **78** (1989), 206–210.

Expressions for laboratory sputtering data are examined in order to describe the effective yield from a planetary regolith composed of, roughly, spherical grains. It is shown that for a fully exposed regolith the effective yield is of the order of 0.4–1 times the measured yield at normal incidence on a laboratory surface depending on the nature of the sputtering process.

Jones, D. L. and Diner, D. J. (Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA 91109): 'A Sub-Millimetre Aperture Synthesis Array for Nonsolar Planet Detection', *Nature* **337** (1989), 51–53.

The detection of Earth-like planets orbiting other stars has great scientific interest, but is a challenging observational goal. At wavelengths shorter than 4 μm a terrestrial planet would be about 10^{10} times fainter than a solar-type star, and at a distance of 10 parsecs the planet–star separation would never exceed 0.1 arcsec. At wavelengths longer than 50–100 μm the brightness ratio is reduced by four to five orders of magnitude. Here we consider the possibility of using aperture synthesis to image other planetary systems at sub-millimetre wavelengths (50–1,000 μm). This approach requires only a small increase in dynamic range over that already demonstrated by the Very Large Array at longer wavelengths.

Kaplan, G. H., Hughes, J. A., Seidelmann, P. K. Smith, C. A. and Yallop, B. D. (U.S. Naval Observatory, Washington, DC 20932): 'Mean and Apparent Place Computations in the New IAU System. III, Apparent, Topocentric and Astrometric Places of Planets and Stars', *Astron. J.* **97** (1989), 1197–1210.

A set of algorithms is presented for computing the apparent directions of planets and stars on any date to milliarcsecond precision. The expressions are consistent with the new IAU astronomical reference system for epoch J2000.0. The algorithms define the transformation between fundamental reference data, such as star and radio-source catalogs and planetary ephemerides, and astrometric observables.

Kerr, R. A., 'Does Chaos Permeate the Solar System?', *Science* **244** (1989), 144–145.

As faster computers allow celestial mechanicians longer looks at the behavior of the planets, chaos is turning up everywhere.

Lanzerotti, L. J. and Uberoi, C. (AT&T Bell Laboratories): 'The Planets' Magnetic Environments', *Sky & Telescope* 77 (1989), 149–152.

Large-scale magnetic organization of matter in the plasma state may be as common as the more familiar gravitational organization.

Laskar, J. (SCMC du Bureau des Longitudes, UA 707 du CNRS, Paris, France): 'A Numerical Experiment on the Chaotic Behaviour of the Solar System', *Nature* **338** (1989), 237–238.

Laplace and Lagrange made an essential contribution to the study of the stability of the Solar System by proving analytically that, to first order in the masses, inclinations and eccentricities of their orbits, the planets move quasiperiodically. Since then, many analytic quasiperiodic solutions have been sought to higher order. I have recently constructed an extensive analytic system of averaged differential equations containing the secular evolution of the orbits of the eight main planets, accurate to second order in the planetary masses and to fifth order in eccentricity and inclination, and including corrections from general relativity and the Moon. Here I describe the results of a numerical integration of this system, extending backwards over 200 million years. The solution is chaotic, with a maximum Lyapunov exponent that reaches the surprisingly large value of $\sim 1/5\,\mathrm{Myr}^{-1}$. The motion of the Solar System is thus shown to be chaotic, not quasiperiodic. In particular, predictability of the orbits of the inner planets, including the Earth, is lost within a few tens of millions of years. This does not mean that after such a short timespan we will see catastrophic events such as a crossing of the orbits of Venus and Earth; but the traditional tools of quanitative celestial mechanics (numerical integrations or analytical theories), which aim at unique solutions from given initial conditions, will fail to predict such events. The problem of the stability of the Solar System will have to be set up again, and the qualitative methods indicated by Poincaré definitely need to replace quantitative methods in this analysis.

Lellouch, E., Drossart, P. and Encrenaz, T. (Department de Recherches Spatiales, Observatoire de Paris-Meudon, France): 'A New Analysus of the Jovian 5-μm Voyager/IRIS Spectra', *Icarus* 77 (1989), 457–465.

Using improved laboratory data of ammonia, recorded at low temperature in the 5-μm region, a complete modeling of the Jovian spectrum has been performed in the spectral region 1900–2050 cm^{-1}, including the effects of NH_3, H_2O, PH_3, and a H_2–He continuum. A cloud layer is included at a temperature of 200°K. The synthetic spectra have been compared to IRIS data recorded in various locations on the Jovian disk. This work shows two significant correlations: (1) the abundances of NH_3 and H_2O are correlated; (2) the transmission of the cloud located at about 2 bars decreases as the abundances of NH_3 and H_2O increase. These correlations are not dependent upon the longitudinal location on the disk; in particular, the individual hot spots show no significant differences in gaseous composition. These results support the atmospheric model in which hot spots are regions of subsidence. The variations are consistent with observations of NH_3 in the centimeter range and previous observations of H_2O variations.

Lunine, J. I. and Hunten, D. M. (Lunar and Planetary Laboratory, University of Arizona, Tucson, AZ 85721): 'Abundance of Condensable Species at Planetary Cold Traps: The Role of Moist Convection', *Planetary and Space Science* 37 (1989), 151–166.

We examine the interplay of moist convection and particle growth in the tropopause region of the atmospheres of Earth, Uranus and Neptune, in an attempt to understand the diverse vertical distributions of these planets' major condensable species. On Earth, water is *undersaturated* in the lower stratosphere relative to the mixing ratio expected from average temperature profiles near the tropopause cold trap. On Uranus, methane is largely depleted in the upper stratosphere by photochemistry, but plausibly close to its saturated value at the tropopause. On Neptune methane is oversaturated by 2–3 orders of magnitude in the lower stratosphere. Paradoxically, moist convection has been invoked to undersaturate the Earth's stratosphere and oversaturate Neptune's. A simple one-dimensional model of moist convection is used to address this problem, along with analytic expressions for growth timescales of particles from the vapor. For the Earth, we also derive downward fluxes for Junge layer aerosols to assess their role in dehydrating the stratosphere. We reach the following conclusions. (1) The downward flux of aerosols is not sufficient to dehydrate the Earth's stratosphere by chemical dessication, but aerosols may play a role as nucleating particles for ice crystals in the cold anvil model of Danielsen (1982, *Geophys. Res. Lett.* **9** 605). (2) The source of Neptune's oversaturated stratosphere is convective penetration of the tropopause by methane moist convective columns. However, certain restrictive conditions are required to initiate and maintain moist convection. Conditions in the troposphere of Uranus, on the other hand, are not conducive to the initiation of moist convection, and gaseous methane closely follows the vapor pressure law. (3) The action of moist convection in undersaturating Earth's stratosphere while oversaturating Neptune's can be understood in terms of very different particle size distributions for the condensable on the two bodies. Methane particles remain small and are carried up through Neptune's columns; on Earth water droplets grow rapidly and fall out. Additionally, the conditions appropriate for radiative cooling of terrestrial anvils, which accounts for the undersaturation, do not apply on Neptune.

Matson, D. L. and Brown, R. H. (Jet Propulsion Laboraory, California Institute of Technology, Pasadena, California 91109): 'Solid-State Greenhouses and their Implications for Icy Satellites', *Icarus* **77** (1989), 67–81.

Subsurface heating by sunlight can considerably raise the temperatures of relatively translucent, high-albedo materials. We call this the solid-state greenhouse effect and apply it to the study of planetary surfaces. Of special interest to us in this paper are the frost and ice surfaces found on satellites in the outer Solar Systems. We compute temperatures as a function of depth for an illustrative range of thermal variables. We find that the surface regions and interiors of these bodies can be much warmer than previously expected. For example, in the case of Europa, thermal metamorphosis of the surface layer is indicated. We identified the solid-state greenhouse temperature as the relevant temperature to use for the upper-boundary condition for the calculations of the thermal state of the interior. Several mechanisms are identified whereby modest alteration of surface properties can substantially change the greenhouse and force an adjustment of interior temperatures.

McKinnon, W. B. (Department of Earth and Planetary Sciences and McDonnell Center for the Space Sciences, Washington University, Saint Louis, Missouri 63130): 'Impacts Giveth and Impacts Taketh Away', *Nature* **338** (1989), 465–466.

Milani, A. (Department of Astronomy, Cornell University, Ithaca, NY 14853): 'Emerging Stability and Chaos', *Nature* **338** (1989), 207–208.

Morgan, T. H., Zook, H. A. and Potter, A. E. (NASA Johnson Space Center, Houston, TX 77058), 'Production of Sodium Vapor from Exposed Regolith in the Inner Solar System', in *Proceedings of the 19th Lunar and Planetary Science Conference (1989)*, pp. 297–304.

We have calculated the likely supply of sodium to the lunar exosphere by impact vaporization, by charged particle sputtering, and by photon stimulated desorption. These were each compared to the supply of sodium needed to maintain the observed sodium exosphere about the Moon. The two processes already known to act on the lunar regolith, impact vaporization and charged particle sputtering, appear to be sufficient to explain the observed column density of sodium in the lunar atmosphere. Photon-stimulated desorption, given the estimates for the yield of sodium due to this process available in the literature would produce 100 to 1000 times more sodium than is observed. If impact vaporization is the main source of sodium to the atmosphere of Mercury, then sodium photo-ions in the exosphere of Mercury are efficiently recycled to the planet.

Nishiizumi, K., Kubik, P. W., Elmore, D., Reedy, R. C. and Arnold, J. R. (Department of Chemistry, University of California, San Diego, La Jolla, CA 92093): 'Cosmogenic ^{36}Cl Production Rates in Meteorites and the Lunar Surface', in *Proceedings of the 19th Lunar and Planetary Science Conference (1989)*, pp. 305–312.

Activity-vs.-depth profiles of cosmic-ray-produced ^{36}Cl were measured in metal from two cores each in the St. Severin and Jilin chondrites and in bulk soil from lunar core 15008. Production of ^{36}Cl in these samples ranges from high-energy reactions with Fe and Ni to low-energy reactions with Ca and K and possibly neutron-capture reactions with ^{35}Cl. The cross-sections used in the Reedy-Arnold model for neutron-induced reactions were adjusted to get production rates that fit the measured ^{36}Cl activities in St. Severin metal and in the lunar soil of core 15008. The ^{36}Cl in metal from St. Severin has a fairly flat activity-vs.-depth profile, unlike most other cosmogenic nuclides in bulk samples from St. Severin, which increase in concentration with depth. In metal from Jilin, a decrease in ^{36}Cl was observed near its center. The length of Jilin's most recent cosmic-ray exposure was ~0.5 m.y. Lunar core 15008 has an excess in ^{36}Cl of about 4 dpm/kg near its surface that was produced by solar-proton-induced reactions. The calculated production rates are consistent with the measured trends in 15008.

Noll, K. S., Geballe, T. R. and Knacke, R. F. (Lunar and Planetary Laboratory, University of Arizona, Tucson, AZ 85721): 'Arsine in Saturn and Jupiter', *Astrophys. J.* **338** (1989), L71–L74.

We have a prominent absorption feature in Saturn and Jupiter near 4.7 μm that is coincident with the ν_3 Q-branch of AsH_3. A smaller absorption at the location of the ν_1 Q-branch of AsH_3 is also observed in Saturn. Based on the two spectral coincidences and agreement of the band structure, we conclude that AsH_3 is present in both atmospheres. The mole fractions of AsH_3 are determined to be $q\text{AsH}_3 = 1.8^{+1.8}_{-0.9}$ pbb in Saturn and $q\text{AsH}_3 = 0.7^{+0.7}_{-0.4}$ ppb in Jupiter, and are probably representative of the As/H ratio in the gaseous envelopes of these planets. Arsenic is significantly enriched over the solar abundance in both planets. Mass-dependent compositional gradients in the atmospheres are ruled out. The ratio of the abundances in the planets, which can be computed without making absolute abundance determinations, suggest that AsH_3 is almost a factor of 2 higher in Saturn than in Jupiter. The observed enrichments are consistent with the core instability model for the formation of the giant planets. Models of arsenic chemistry that predict strong depletions of AsH_3 at temperatures below 370 K are not consistent with the observations, suggesting that vertical convection or perhaps some other mechanism inhibits depletion.

Nuth, J. A. and Moore, M. H. (Astrochemistry Branch, NASA Goddard Space Flight Center, Greenbelt, MD 20742): 'Proton Irradiation of SiH_4-$Fe(CO)_5$-H_2O Ices: Production of Refractory Silicates and Implications for the Solar Nebula', in *Proceedings of the 19th Lunar and Planetary Science Conference (1989)*, pp. 565–569.

We report the results of a number of experiments in which SiH_4-$Fe(CO)_5$-H_2O ice mixtures were irradiated by 1 MeV protons at 15 K and then warmed to room temperature in approximately 50 K steps. The properties of a sample were monitored by observing its infrared absorption spectrum as a function of its processing history. In each experiment in which ice samples containing SiH_4 were irradiated, a refractory amorphous silicate residue remained after warming to room temperature. In addition to the usual broad silicate features at 10 and 20 microns, features due to water or hydroxyl at 3 and 6.2 microns, and a feature due to CO at 5 microns, we observed a surprisingly stable infrared feature at 4.6 microns, attributed by us to the SiH stretching fundamental. This feature is similar to an as yet unidentified infrared feature observed in the protostellar source W33A. Confirmation of the presence of residues from processes complex ices in such a protostellar source might suggest that similar materials were present in the solar nebula as well. We discuss the limitations of the present experimental data and the possibility that such processes would lead to the synthesis of large organic molecules, unique silicate crystal structures, the efficient trapping of noble gases and other volatiles, and isotopic fractionation of oxygen in the grain mantles.

Pospieszalska, M. K. and Johnson, R. E. (Department of Nuclear Engineering and Engineering Physics, University of Virginia, Charlottesville, Virginia 22901): 'Magnetospheric Ion Bombardment Profiles of Satellites: Europa and Dione', *Icarus* **78** (1989), 1–13.

The spatial dependence across a satellite surface of the ion bombardment/implantation rate is calculated for satellites imbedded in planetary magnetospheric plasmas. These bombardment profiles are created by tracking ions in the plasma onto the surface of the object using an appropriate description of the ion motion. A parameter study is made indicating the general dependence on ion gyroradius and pitch angle. It is shown that access to the leading hemisphere depends strongly on the pitch angle distribution and that the gyromotion can cause differences in the bombardment of the inner and outer hemisphere. Profiles are then calculated for sulfur ions incident on Europa and oxygen ions incident on Dione using reasonable speed and pitch angle distribution. The results indicate that the longitudinal dependence of the UV absorption seen by Voyager closely follows the sulfur ion implantation profile at Europa if the hot plasma measured by LECP is not dominated by sulfur. This would appear to confirm that the feature is produced by ion bombardment. It is also found that for the assumed pitch angle distribution the dominant sputtering component at Dione bombards that surface nearly isotopically. This affects the analysis of the surface reflectance properties and the calculation of the heavy ion plasma source distribution.

Schenk, P. M. (Department of Earth and Planetary Sciences and McDonnell Center for the Space Sciences, Washington University, Saint Louis, MO 63130): 'Crater Formation and Modification on the Icy Satellites of Uranus and Saturn: Depth/Diameter and Central Peak Occurrence', *Journ. Geophysical Res.* **94** (1989), 3813–3832.

Depth/diameters (d/D) for fresh craters on the intermediate-sized icy satellites of Uranus and Saturn have been determined using photoclinometry and shadow lengths, and are compared with similar measurements on the terrestrial planets. Simple bowl-shaped craters on icy satellites, including those on Miranda for which the highest resolution data are available, are systematically 20–40% shallower than on the terrestrial planets. This pronounced difference between crater depths on icy and rocky surfaces indicates that differences in impact velocity or surface gravity are not as important as the differences in mechanical properties between ice and "rock" in controlling simple crater morphology. Experimental impact studies indicate that differences in material properties such as angle of internal friction can control crater depth. Alternatively, breccia lenses may be thicker in icy satellite simple craters. Complex craters on the icy satellites become significantly deeper with increasing crater diameters, unlike complex craters on terrestrial planets, which are nearly constant in depth. Central peaks, and hence floor rebound, are also volumetrically and morphologically more prominent than wall slumping (rim collapse) on the icy satellites. The magnitude of viscous relaxation of very large craters (e.g., Herschel and Odysseus) on the icy satellites can be estimated from extrapolation of the d/D fits at smaller crater diameters. The transition diameter from simple to complex morphology is inversely correlated with gravity, as it is on the terrestrial planets, but at significantly smaller diameters than would be expected from a simple extrapolation of the terrestrial trend. Thus crater modification, especially floor rebound, is easier to initiate on icy satellites. Estimated effective cohesions for shocked icy material are lower by a factor of 10–20 relative to rock, although estimated effective viscosities are similar. The distinct, systematic differences between crater morphology on icy and rocky worlds indicate that gross material property differences between rock and ices play a key role in crater formation and modfication, but gravity is still the primary driving force.

Smith, W. H., Schempp, W. V., Simon, J. and Baines, K. H. (Department of Earth and Planetary Sciences, Washington University, St. Louis, MO 63130): 'D/H for Uranus and Neptune', *Ap. J.* **336** (1989), 962–966.

Searches for absorption features of HD near 6050 Å are reported for Uranus and Neptune. The existence of blends of the HD features with weak features due to minor species in the atmosphere of Uranus is demonstrated. These blends make the unambiguous identification of the weak HD features exceedingly difficult. The data are analyzed with inhomogeneous scattering models to ascertain a D/H upper limit for Uranus and Neptune of 10^{-4}, a factor of 2 smaller than the upper limit reported from CH_3D measurements.

Spahn, F. and Wiebicke, H.-J. (Institut für Kosmosforschung, Berlin, GDR): 'Long-Term Gravitational Influence of Moonlets in Planetary Rings', *Icarus* **77** (1989), 124–134.

The long-term influence of the gravity of moonlets or satellites on the radial density structure of planetary rings has been calculated, numerically combining the results of test-particle calculations with the requirement of conservation of mass in the ring. Significant stable features of the density structure, caused by multiple scattering of the ring particles on the moonlet, have been obtained which are in good agreement with observations of "hyperfine" structure of the rings of Saturn and Uranus.

Taylor, S. R. (Research School of Earth Sciences, Australian National University, Canberra, Australia): 'Growth of Planetary Crusts', *Tectonophysics* **161** (1989), 147–156.

The planets and satellites of the Solar System show much diversity, but most have formed crusts which differ substantially from their bulk compositions. Three principal types of crust may be broadly distinguished: primary, formed after accretional heating (e.g., lunar highlands); secondary, formed following partial melting in planetary mantles (e.g., lunar maria, terrestrial oceanic crust); and tertiary, formed by processing of secondary crusts, of which the continental crust of the Earth is the only identifiable example. Crustal growth before 3800 m.y. was complicated by the heavy planetesimal bombardment: active erosion on the Earth is likely to have destroyed the brecciated rubble resulting from over 200 Mare Orientale-scale events in this period. The Mercurian crust is probably primary, perhaps analogous to the lunar highlands. In contrast, the observable Martian and Venusian crusts are secondary, dominated by basaltic volcanism. The icy crusts of the satellites of the outer planets are mixtures of both primary and secondary crusts, with complex histories. Ganymede is of special interest in displaying a secondary (grooved terrain) water ice crust which has split an older more heavily cratered, possibly primary crust. Slight expansion has resulted probably from polymorphic transitions from high density ice VIII to low density ice I. The primary lunar crust, 12% of lunar volume, grew in 10^8 years; secondary crusts derived by partial melting of mantles grow at a much slower rate – total production of terrestrial oceanic crust over 4000 m.y. is only 2% of planetary volume, whereas terrestrial continental crustal growth is even slower, producing over the same period a volume only about 0.33% that of the Earth. Crustal growth on the other planets appears to be an irreversible process, without evidence of recycling. No evidence for massive planetary expansions, as required by expanding earth hypotheses, is apparent on the other planets or satellites of the Solar System.

Thomas, P. C. (Center for Radiophysics and Space Research, Cornell University, Ithaca, New York 14853): 'The Shapes of Small Satellites', *Icarus* **77** (1989), 248–274.

Improved measurement techniques allow quantitative testing of the physical significance of the shapes of small satellites such as the possible occurrence of equilibrium ellipsoid forms. Shapes of the small satellites of Mars, Jupiter, Saturn, and Uranus have been measured using limb coordinates from spacecraft images. Limb-derived ellipsoidal models can measure volumes of irregular objects accurately: ellipsoidal models of Phobos and Deimos derived from limb coordinates are nearly identical to those obtained independently from stereogrammetry (Duxbury and Callahan 1988). These ellipsoidal approximations, however, are incomplete descriptions of the shapes of small satellites in that average residuals are much larger than measurement errors. Ellipsoidal models of eight small satellites compared with equilibrium ellipsoids show that shapes of even moderately irregular satellites are poor predictors of mean densities. Icy satellites smaller than mean radius (R_m) ~ 150 km are irregularly shaped and have limb roughnesses of several percent of mean radius (RMS residuals .03–.08 R_m). There is no trend in roughness with size below $R_m = 150$ km. Larger icy satellites are ellipsoidal and have limb roughnesses below 0.01 R_m. "Rocky" satellites of $R_m = 6$–110 km are also irregularly shaped; the only larger rocky satellites are the Moon and Io ($R_m = 1740$ and 1820 km) which have roughnesses well below 0.01 R_n, Data on rocky satellites combined with published data for Ceres and Juno (Millis *et al.* 1981, 1987) suggest a gradual transition from irregular to ellipsoidal rocky objects. Limb topography and images suggest that the small satellites retain impact scars of diameter of up to 1.7 times the satellite mean radius. These large indentations are the primary difference in shape between small and large satellites.

Valentin, J. R. (Solar System Exploration Branch, NASA Ames Research Center, Moffett Field, CA 94035): 'Multiplex Gas Chromatography: An Alternative Concept for Gas Chromatographic Analysis of Planetary Atmospheres', *LG-GC* **7** (1989) 248–250, 252, 254–257.

Warren, P. H. (Institute of Geophysics and Planetary Physics, University of California, Los Angeles, CA 90024): 'Growth of the Continental Crust: A Planetary-mantle Perspective', *Tectonophysics* **161** (1989), 156–199.

This paper addresses the *net* growth through time of the total continental crust (CC), not be confused with sporadic growth of individual continental masses (e.g., by accretion of island arcs), a process that does not necessarily require *net* growth. Geochemists tend to emphasize differences between CC and oceanic crust (OC), but from a whole-planet perspective CC and OC are remarkably similar in composition and density. The CC/OC distinction is canonically defined in terms of elevation. However, the Earth's bimodal elevation pattern clearly reflects a genetic distinction. The OC participates directly in mantle convection, whereas the CC is the remaining, relatively stable portion of the crust. The Earth's advective cooling mechanism requires massive subduction of lithosphere, which due to the inherent buoyancy of crust tends to require a low crust/total lithosphere thickness ratio. Given relatively constant lithosphere thickness (except near thermally buoyant mid-ocean ridges), the Earth responds by heaping most of its crust into a few thick continents, allowing subduction to freely operate over a large area of relatively thin crust. This crustal thickness bimodality engenders the bimodal elevation pattern.

Prevailing wisdom tends to hold that the rate of CC growth has been slow and ongoing; typical models show CC volume roughly proportional to $1/h$, where h is the total heat generation by the Earth's K, Th and U. However, such models are generally vague as to the mechanism that supposedly holds back growth, even after 4.5 Ga. The strong T-dependence of mantle rheology probably ensured that the mantle took only a few million years to cool within a few hundred degrees of its modern T. Gradual compositional evolution of the CC from a plausible initial composition (e.g., basaltic, anorthositic) might have slightly lowered the mean CC density, but this effect is of second-order importance in comparison to the general increase in crust/total lithosphere thickness ratio (for any given crustal thickness) engendered by temporal cooling of the mantle. Intense cratering, occurring, coevally with early intense crust/mantle recycling, probably reconstituted virtually all of the CC extant prior to ~3.9 Ga, but CC was probably not recycled into the mantle any faster than it was regenerated.

Wetherill, G. W. and Stewart, G. R. (Department of Terrestrial Magnetism, Carnegie Institution of Washington, Washington, D.C. 20015): 'Accumulation of a Swarm of Small Planetesimals', *Icarus* **77** (1989), 330–357.

The stage of planetesimal accumulation in which ~10-km planetesimals in the vicinity of 1 AU grow into "planetary embryos" greater than 10^{25} to 10^{27} g in mass has been studied using the methods of gas dynamics. Particular attention is given to identifying the circumstances for which runaway growth results in the formation of a relatively small number (e.g., 30) of massive ($\sim 4 \times 10^{26}$ g) embryos in the terrestrial planet region on a time scale of 10^5 to 10^6 years. It is found that under the assumptions made by the Moscow (Safronov and others) and Kyoto (Hayashi and others) "schools," no runaways are found, in agreement with the conclusions of these investigators. In contrast, when more plausible physical processes are included, e.g., the importance of equipartition of energy in gravitational encounters, the presence of "seeds" in the initial distribution, enhancement of the gravitational cross section above the two-body value at low velocity, and fragmentation, runaways in the terrestrial planet region are found to be very probable on a time scale of about 10^5 years. The final stage of planetary accumulation may then consist of the accumultion of these embryos into the present planets on a time scale of 10^7 to 10^8 years. At larger heliocentric distances the planetesimal evolution could be different; circumstances may have existed in which runaway growth of Jupiter prevented runaways in the asteroid belt.

3. JUPITER

Barrow, C. H. and Desch, M. D. (Max-Planck-Institut für Aeronomie, Katlenburg-Lindau, F. R. Germany): 'Solar Wind Control of Jupiter's Hectometric Radio Emission', *Astron. Astrophys.* **213** (1989), 495–501.

New results are presented on the control of the Jovian hectometric radio emission (HOM) by the solar wind, demonstrated from Voyager 1 and Voyager 2 observations. Using the method of superposed epochs, it is found that the higher energy HOM is correlated with the interplanetary magnetic field (IMF) magnitude as well as with the solar wind density and pressure. The correlation appears to be enhanced when the interplanetary magnetic sector structure is well-defined. The results suggest that higher energy HOM is most likely to occur when the IMF magnitude and the solar wind density are increasing towards their maximum values as a sector centre approaches Jupiter. Similar calculations, made previously for the Io-independent decametric radio emission (Non-Io DAM), are compared with these results. Unlike the Non-Io DAM, the HOM shows little indication of correlation with the solar wind velocity although both radio components appear to be influenced by the IMF and somehow associated with sector structure. Also, the Non-Io DAM is most likely to occur immediately after the sector centre has passed Jupiter. The lowest frequency radio observations of Jupiter made from the Earth, at 5 to 7 MHz during the period 1961–65, are re-examined in an attempt to shed further light upon the question as to whether or not the HOM is really a separate component of radio emission or merely a low frequency extension of the DAM. Occurrence probability profiles in System III Central Meridian Longitude suggest that the HOM may, at times, extend up to some 7 MHz and then be observable from the Earth if receiving conditions are favourable.

Bolton, S. J., Gulkis, S., Klein, M. J., de Pater, I. and Thompson, T. J. (Space Physics and Astrophysics Section, Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California): 'Correlation Studies Between Solar Wind Parameters and the Decimetric Radio Emission from Jupiter', *Journal of Geophysical Research* **94** (1989), 121–128.

Results of a study comparing long-term time variations (years) in Jupiter's synchrotron radio emission with a variety of solar wind parameters and the 10.7-cm solar flux are reported. Data from 1963 through 1985 were analyzed, and the results suggest that many solar wind parameters are correlated with the intensity of the synchrotron emission produced by the relativistic electrons in the Jovian Van Allen radiation belts. Significant nonzero correlation coefficients appear to be associated with solar wind ion density, ram pressure, thermal pressure, flow velocity, momentum, and ion temperature. The highest correlation coefficients are obtained for solar wind ram pressure (NV^2) and thermal pressure (NT). The correlation analysis suggests that the delay time between fluctuations in the solar wind and changes in the Jovian synchrotron emission is typically about 2 years. The delay time of the correlation places important constraints on the theoretical models describing the radiation belts. The implication of these results, if the correlations are real, is that the solar wind is influencing the supply and/or loss of electrons to Jupiter's inner magnetosphere. We note that the data for this work spans only about two periods of the solar activity cycle, and because of the long time scales of the observed variations, it is important to confirm these results with additional observations.

Huang, T. S. and Hill, T. W. (Department of Space Physics and Astronomy, Rice University, Houston, Texas 77251): 'Corotation Lag of the Jovian Atmosphere, Ionosphere, and Magnetosphere', *Journ. Geophys. Res.* **94** (1989), 3761–3765.

We modify the Jovian ionosphere-magnetosphere coupling model presented by Hill (1979) to include rotational slippage of the neutral atmosphere at ionospheric heights, relative to a frame of reference corotating rigidly with Jupiter. In the modified model, as altitude increases, the drift velocities of neutrals and ions relative to the corotating frame increase from zero at the bottom of the ionosphere to their respective maximum values at the top, and the corotation lag of the magnetosphere is enhanced for a given rate of mass loading of the magnetosphere. The height variations of the drift velocities of neutrals and ions in the ionosphere and the enhancement factor for the corotation lag of the magnetosphere are related to the atmospheric eddy diffusion coefficient at ionospheric heights. On the basis of ionospheric properties deduced from measurements of Pioneer 11, Voyager 1, and Voyager 2, we derive height profiles of ion and neutral drift speed for various possible values of the eddy diffusion coefficient. If we accept the ion injection rate from Io (10^{29} ions/s) and the ion transport rate through the Jovian magnetosphere (3×10^{28} ions/s), corresponding to the observed values of the corotation lag of the Io torus ($\delta\omega_I = 0.04\omega_J$) and the critical distance for magnetospheric corotation ($L_0 = 20$), respectively, the effective ionsopheric conductance is reduced by a factor of the order of 10, resulting in an enhanced corotation lag, for a given rate of mass loading, by the same factor compared to earlier models. The eddy diffusion coefficient in the high-latitude ionosphere is inferred to be $\sim 10^{13}$ $n_n^{-1/2}$ m$^{1/2}$/s, or about a factor of 20 larger than the value inferred from Voyager measurements at near-equatorial latitudes.

Jones, D. and Leblanc, Y. (Space Plasma Physics Group, British Antarctic Survey, NERC, Cambridge, U.K.): 'Analysis of Jovian Kilometric Radiation Simultaneously Observed by Voyagers 1 and 2', *Adv. Space Res.* **8** (1989), 453–457.

Broadband Jovian radio emission in the kilometric wavelength range (bKOM) observed by the Voyagers 1 and 2 (V1 and V2) planetary radioastronomy, PRA, experiments have been analysed for the period January to December 1979 which includes the Jupiter encounters. The pre-encounter observations were made on a nightside, the difference in local time between the two spacecraft being about one hour. It is therefore possible to study local time, and source – observer distance effects. bKOM beaming exhibits large temporal variations. The beaming is believed to arise from the manner in which the source electrostatic upper-hybrid waves are converted to electromagnetic radiation in the plasma density gradient at the Io plasma, and temporal variations in the beaming are expected to reflect fluctuations in the Io torus. Remote-sensed density profiles have been computed from V1 and V2 simultaneous bKOM observations and compared with in situ measurements by V1 when it passed through the torus. Good agreement is found between the density gradients obtained, and the in situ measurements. The differences between V1 and V2 profiles may possibly be explained by the difference in local time of the two spacecraft. The computed profiles from dayside and nightside observations are nearly coincident. A large temporal variability of the Io torus density, or of the latitudinal position of the source, is apparent.

Magalhães, J. A., Weir, A. L., Conrath, B. J., Gierasch, P. J. and Leroy, S. S. (NASA/Ames Research Center, Moffett Field, CA 94035): 'Slowly Moving Thermal Features on Jupiter', *Nature* **337** (1989), 444–447.

Obtaining measurements of winds on the jovian planets – Jupiter, Saturn and Uranus – at depths other than the level of the observed visible clouds has long been a problem preventing an understanding of the dynamics of these deep atmospheres. Measurements of horizontal thermal structure on Jupiter suggest that the observed zonal (west–east) jet system decays slowly above the visible clouds, persisting over many pressure-scale heights. The ubiquitous visible cloud cover, believed to be composed of ammonia ice crystals lying somewhere between the 700-mbar and 300-mbar pressure levels, prevents direct sensing below these levels, so the depth of the wind system remains unknown. Here we report that maps of upper troposphere temperatures derived from Voyager 1 and Voyager 2 infrared interferometer spectrometer (IRIS) spectra shown large-scale features which move very slowly; the motion is very different from the inferred local fluid velocity. We suggest that these features may be indicative of a deeply-rooted fluid dynamical regime beneath the surface meteorology, although other explanations are possible.

Prange, R. and Elkhamsl, M. (L.A.S.–L.P.S.P., Verrières le Buisson, France): 'Modeling of the Longitudinal Variations of the Jovian Auroral Precipitations: Preliminary Results', *Comptes Rendus de l'Academie des Sciences, Ser. II.* **308** (1989), 723–729.

We present the preliminary results of a simplified model which represents, as a function of longitude, the quasi-trapped density and precipitation flux of particles drifting perpendicularly to the Jovian magnetic field. For both hemispheres, we study the location and intensity of the precipitation peaks of electrons and ions, as well as their dependence on the L-shell parameter, and we briefly show the influence of the angular distribution of the injection mechanism. The results are compared to the intensity variations observed from space in the Jovian auroral oval in the far UV.

Rucker, H. O., Ladreiter, H. P., Leblanc, Y., Jones, D. and Kurth, W. S. (Space Research Institute, Austrian Academy of Sciences, Observatory Lustbuehel, Graz, Austria): 'Jovian Plasma Sheet Density Profile from Low-Frequency Radio Waves', *Journ. Geophys. Res.* **94** (1989), 3495–3503.

By using planetary radio astronomy (PRA), plasma wave system (PWS), and magnetometer (MAG) data from Voyager 1 and 2 (V1 and V2), essential features of the night side Jovian plasma sheet are derived, and the density gradient of the corotating plasma structure in the middle Jovian magnetosphere is calculated. The PRA experiment gives information about the plasma wave polarization. To determine the density profile of the plasma sheet, we have derived the hinge point position of the plasma disc from MAG data and used the low-frequency cutoffs observed at three frequencies (562 Hz, 1 kHz, and 1.78 kHz) from the PWS experiment. We show that the hinge point position varies with the solar wind ram pressure, and the plasma disk thickness decreases with distance up to about $60R_J$. The average thickness for an isodensity contour corresponding to 1 kHz is $3.29R_J$ for V1 and $3.16R_J$ for V2.

Smith, W. H., Schempp, W. V. and Baines, K. H. (Department of Earth and Planetary Sciences, Washington University, St. Louis, MO 63130): 'The D/H Ratio for Jupiter', *Ap. J.* **336** (1989), 967–970.

Observations of Jupiter's spectrum near the $R_5(0)$ HD line at 6063.88 Å are reported. A feature with an equivalent width of 0.065 ± 0.021 mÅ is coincident with the expected line. This feature is compared with HD profiles computed for inhomogeneous scattering models for Jupiter to yield a range for the Jovian D/H ratio of $1.0\text{–}2.9 \times 10^{-5}$. This D/H ratio is in the lower range of previously reported D/H values for Jupiter and corresponds to an essentially solar D/H ratio for Jupiter. The detection of HD features in the presence of probable blends with spends features of minor atmospheric hydrocarbon molecules is discussed. Such blends may make unambiguous identification of HD features difficult.

Summers, D., Thorne, R. M. and Mei, Yi (Department of Mathematics and Statistics, Memorial University, St. John's, Newfoundland): 'Jupiter's Radiation Belt Ions: A Comparison of Theory and Observation', *Geophysical Research Letters* **16** (1989), 231–234.

We construct radial profiles for the Jovian radiation belt flux-tube content Y^* from the reported phase-space density of energetic particles obtained from the Voyager 1 LECP data over the range $L = 6$ to $L = 9$. These experimental profiles are compared with theoretical solutions for Y^* from our interchange-diffusion models of the coupled radiation belt and Iogenic ion populations, which incorporates the pressure gradient of the radiation belt ions and spatially-varying forms for the precipitation loss-rate of the radiation belt ions and the concomitant height-integrated Pedersen ionospheric conductivity. Subject to certain limitations of the Voyager 1 data, the model solutions are found to be consistent with the data for a variety of input parameters. Model solutions are also found corresponding to radition belt ions in the energy range $1(\text{MeV/G}) \leq \mu \leq 10(\text{MeV/G})$ (which was not sampled by Voyager) that are expected to be mainly responsible for the auroral energy input. Comparison of our theoretical profiles with the data implies that the energetic radiation belt ions should have a peak loss rate within a factor of three of that for strong diffusion scattering.

4. SATELLITES OF JUPITER

Arlot, J.-E., Thuillot, W. and D'Ambrosio, V. (SCMS du Bureau des Longitudes, UA 707 du CNRS, Paris, France): 'An Analysis of the Observations of the Mutual Events of the Galilean Satellites of Jupiter Made in 1985 at the Observatoire de Haute Provence', *Astron. Astrophys.* **213** (1989), 479–486.

Mutual eclipses and occultations of the Galilean satellites of Jupiter occurred in 1985. These photometric phenomena are of great interest for astrometry because of the accuracy of their observations, and a campaign have been organized in France. This paper presents the results that we have obtained and the analysis of these observations that we realized at the Observatoire de Haute Provence (OHP). Eleven mutual eclipses and seven mutual occultations were observed and are discussed.

Drobyshevski, E. M. (A. F. Ioffe Physical-Technical Institute, USSR Academy of Sciences, Leningrad, USSR): 'Jovian Satellite Callisto: Possibility and Consequences of its Explosion', *Earth, Moon and Planets* **44** (1989), 7–23.

The numerous poorly understood differences between Ganymede and Callisto (the difference in the densities, in the degree of cratering and topography of the surface, the existence proper of craters and a difference of their distribution from that typical of bodies in the inner Solar System, etc.) find readily an explanation within the hypothesis of an explosion of Ganymede's icy envelope saturated by products of the volumetric electrolysis of ice. Similar explosions underwent earlier the ices on Io and Europa, and more recently, on Saturn's satellite Titan. One cannot exclude the possibility that the envelope of Callisto is also saturated by the electrolysis products and is only awaiting a strong impact which would trigger its explosion.

The consequences of such an explosion would be devastating for the Earth's biosphere. About 10^9 ice fragments $\phi \geq 0.3$ km would appear in the orbits of Jovian comet family. Every day, a body causing an explosion $\gtrsim 1$ Mt of TNT equivalent would fall on the Earth, once a year – $\gtrsim 10^3$ Mt, and once in a man's life. $\gtrsim 10^5$ Mt. Apart from purely impact effects (super-tsunami, heating of the atmosphere) and the poisoning of the air by such compounds as HCN, CO, etc., impacts in excess of 10^5 Mt could produce a 'nuclear winter' phenomenon resulting from the appearance of huge amounts of dust in the atmosphere.

Such impact-related catastrophies led in the past to changes of geological epochs. An analysis is given of possible impact sources. The ~30 Myr intervals between mass extinctions can be accounted for by purely random collisions, with only large impacts being capable of producing (1) a nuclear 'superwinter' leading to a global catastrophe and (2) an ejection from the Earth of the Aten-type asteroids leading to subsequent secondary mass bombardment. A possibility is pointed out of the appearance of rare (once in about 10^8 yr) short-period comet showers originating from the detonation of the ices still remaining in the large Trojans.

The high priority of a mission to Callisto to determine the degree of saturation of its ices by the electrolysis products and to evaluate its potential hazard for mankind is validated.

Howell, R. R., Nash, D. B., Geballe, T. R. and Cruikshank, D. P. (Institute for Astronomy, University of Hawaii, Honolulu, Hawaii 96822): 'High-Resolution Infrared Spectroscopy of Io Possible Surface Materials', *Icarus* **78** (1989), 27–32.

We have obtained new spectra of Io in 3.5- to 4.2- and 4.5- to 5.4-μm regions with a resolution ($\lambda / \Delta \lambda$) of roughly 500. The Io spectra cover a range of longitudes, and times from 1983 through 1985. Laboratory spectra of various materials have also been obtained. In this wavelength region are located several strong bands of SO_2, known to be a major component of Io's surface, as well as the bands of several potential surface materials. In the Io spectra we identify several new features attributable to SO_2, and have obtained strengths of the ^{33}S, ^{34}S, and ^{18}O isotopic bands, which appear normal. We place limits on the amounts of Na_2SO_3, and Na_2SO_4 present. Finally, we use the data to place limits on the SO_2 gas abundance in Io's atmosphere.

McGrath, M. A. and Johnson, R. E. (Department of Astronomy, University of Virginia, Charlottesville, Virginia): 'Charge Exchange Cross Sections for the Io Plasma Torus', *Journ. Geophys. Res.* **94** (1989), 2677–2683.

An impact parameter method for calculating cross sections as a function of incident ion energy is used in conjunction with an improved exchange energy formulation to update several of the charge exchange cross-sections currently used in Io plasma torus modeling. New cross sections for $S^+ + S^{2+} \rightarrow S^{2+} + S^+$ and Na^+ on neutral targets, useful in analyzing the fast Na jets observed at Io, are also calculated.

Tittemore, W. C. and Sinton, W. M. (Department of Earth, Atmospheric, and Planetary Sciences, Massachusetts Institute of Technology, Cambridge, MA 02139): 'Near-Infrared Photometry of the Galilean Satellites', *Icarus* **77** (1989), 82–97.

Near-infrared lightcurves and phase coefficients at 2.2, 3.8 and 4.8 μm for the Galilean satellites are presented. The geometric albedo of Io, as determined here, includes emission from volcanoes, especially at 3.8 and 4.8 μm. No major outbursts were detected during the period of observation, 1982–1983, covered by this paper. A broad peak in the 4.8-μm albedo at longitude $\approx$270–280° is attributed primarily to volcanoes other than Loki. Results for Europa and Ganymede, showing a trend of decreasing albedo with increasing wavelength, are consistent with icy surfaces for these satellites. For Ganymede, the phase coefficient depends strongly on the wavelength in the near infrared, and has the extremely high value of 0.083 mag/deg at 4.8 μm. Results for Callisto are consistent with observations of other dark solar system objects at visual wavelengths.

Wright, A. N. and Schwartz, J. (Astronomy Unit, School of Mathematical Sciences, Queen Mary College, University of London, London, U.K.): 'The Transmission of Alfvén Waves through the Io Plasma Torus', *Journ. Geophys. Res.* **94** (1989), 3749–3754.

In this paper we study the nature of Alfvén wave propagation through the Io plasma torus. A one-dimensional model is used with uniform magnetic field and exponential density decrease to a constant value. The solution can be expanded near the center of the torus and far away from the torus to give propagating Alfvén waves. The time-averaged Poynting flux is independent of position and, in the near and far limits, is equivalent to the sum of Poynting fluxes carried by individual wave trains. In this fashion it is possible to calculate the fraction of energy that is transmitted or reflected by the change in Alfvén speed through the torus, for a given wave train near Io. The solution is sensitive to the distant (or asymptotic) Alfvén speed. A lower limit for this speed can be found from the density decrease alone. Using this value we find, in accord with previous work, that there is negligible wave reflection. A more realistic asymptotic Alfvén speed takes into account the increase in field strength along the Io flux tube. This larger Alfvén speed value yields a significant reflection coefficient, and the result is in good agreement with our previous numerical solution. Our results imply that Io's Alfvén waves may not propagate completely through the plasma torus, and thus WKB theory and ray tracing may not provide meaningful estimates of the energy transport.

5. MARS

Arvidson, R. E., Guinness, E. A., Dale-Bannister, M. A., Adams, J., Smith, M., Christensen, P. R. and Singer, R. B. (McDonnell Center for the Space Sciences, Department of Earth and Planetary Sciences, Washington University, St. Louis, Missouri): 'Nature and Distribution of Surficial Deposits in Chryse Planitia and Vicinity, Mars', *Journal of Geophysical Research* **94** (1989), 1573–1587.

Color images of bright red dust deposits at the Mutch memorial Station were acquired at variable incidence angles during sol 611 (subsolar longitude ~70°, northern spring season). After removing effects due to atmospheric scattering and absorption, the data were used to estimate the independent variables in the Hapke (1986) photometric function. In blue, green, and red coordinates the vector representing the space radiance factor of the landing site extracted from Viking orbiter images acquired on sol 609 is separated by a Euclidean distance of only units and an angle of only 1.5° from the vector estimated from the station data for the orbiter lighting and viewing geometries. This result implies that light reflected from dust exposures dominates the orbiter signal; multiplicative and additive atmospheric terms cancel one another and surface roughness is a second-order effect in the orbiter data. Dust radiance factors computed from station data are most like laboratory spectra for fine-grained Hawaiian palagonite and are indistinguishable from Earth-based spectra of classical bright areas. Color composites of orbiter images show that the dust is found immediately south of Acidalia Plantitia and in association with topographic barriers such as craters and cliffs. Examination of Viking infrared thermal mapper data shows that the dust deposits typically do not have distinctive thermal inertia signatures, implying that the deposits are optically thick (hundreds of micrometers) but thinner than the diurnal thermal skin depth (centimeters). Dark gray material with thermal inertia values ($8-12 \times 10^{-3}$ cal cm^{-2} s$^{-1/2}$ K^{-1}) indicative of sand grain sizes (0.5–1.5 mm) dominates the Acidalia Planitia lowlands and parts of Kasei Vallis. This material also occurs as dark streaks extending from craters in Xanthe Terra and Oxia Palus. Space radiance factors of dark gray material are similar to spectra of mafic rock mixed with a minor amount of palagonitelike material. Material that is darker than but just as red as the dust deposits occurs in Lunae Planum, Xanthe Terra, and Oxia Palus, areas of intermediate elevation. Multiple phase angle orbiter images suggest that the dark red exposures are a mixture of bright red and dark gray materials, with the dark red exposures being relatively rough at a subpixel scale as compared to exposures of the other two materials. thus only two types of materials can be detected in the data covering the study area: palagonitelike dust and mafic rock fragments. Thermal inertia values ($4-8 \times 10^{-3}$ cal cm^{-2} s$^{-1/2}$ K^{-1}) for the dark red material are consistent with the presence of fine to medium sand size particles (0.10–0.5 mm); such material should be easily moved by winds. The lack of aeolian features implies that the dark red deposits are not composed of loose material. Rather, they are probably more eroded versions of blocky soil or duricrust (cemented dust and rock fragments) exposed at the station. both bright red dust (aeolin suspension load) and dark gray materials (saltation, traction loads) migrate over the dark red substrate. The overall distribution of the surficial units is controlled by topography at a variety of length scales. Lower wind threshold friction velocities associated with higher atmospheric densities in lowlands keep dust from accumulating and duricrust from forming, while higher threshold velocities in highlands lead to net accumulation of dust. Local topographic obstacles (craters, walls, ridges) perturb wind flow and lead to local accumulation or erosion at a variety of elevations. In addition, the bright red dust ubiquitously found between exposures of dark gray and dark red materials may accumulate as the wind velocity gradient decreases at the transition from smoother dark gray exposures to rougher dark red exposures. The distribution of the materials must also be modulated by climatic variations induced by quasi-periodic oscillations in obliquity, eccentricity and spin axis direction, constraining these surficial deposits to be $\leqslant 1$ Ma.

Beish, J. D., Parker, D. C. and Hernandez, C. E. (Association of Lunar and Planetary Observers): 'The Red Planet Shows Off', *Sky & Telescope* **77** (1989), 30–35.

Mar's best apparition of a lifetime kept observers glued to their eyepieces watching the planet's seasonal changes.

Bell, J. F. and McCord, T. B. (Planetary Geosciences Division, Hawaii Institute of Geophysics, University of Hawii, Honolulu, Hawaii 96822): 'Mars: Near-Infrared Comparative Spectroscopy during the 1986 Opposition', *Icarus* **77** (1989), 21–34.

Near-infrared (0.7–2.5 μm) spectral observations of Mars during the 1986 opposition were carried out at the Mauna Kea Observatory utilizing the University of Hawaii 2.2-m telescope. Spectra were obtained of several Martian locations using a continuously variable filter (CVF) spectrometer with a resolution of $\sim 1.25\%$ ($\Delta\lambda/\lambda$). During two separate runs in June and August, approximately 60 distinct spots between 354° W and 163° W and 32° N and 52° S were observed at an angular resolution of $\simeq 0.5$ to 1.5 arcsec, corresponding to a spatial resolution on Mars of $\simeq 200$ to 460 km, varying with nightly seeing conditions. These different spots fall roughly into a set of eight distinct geologic regions: volcanic regions, ridged plains, ridged volcanic plains, scoured plains, impact basins, channels and canyons, densely cratered regions, and layered terrain and ice. The spectra exhibit typical noise-related or weather-induced errors of less than 4% of the full-scale signal. To analyze these spectral data, spot-to-spot ratios, or relative reflectance spectra, were produced between spectra taken in different geologic regions. Spectral features observed in these ratios can act as indicators of mineralogic differences between areas under consideration.

Perhaps the most striking result obtained from the many ratios taken close in time and under similar viewing geometries was the consistent lack of noticeable differences between spectra taken of areas which, in geologic maps and viking orbiter images, appear to have very different morphologies. This observation leads to several possible conclusions: (a) The spectral feature differences are below the detection limit of these measurements. (b) The spatial resolution of spots observed on Mars was not high enough to merit comparison with medium- to high-resolution Viking Orbiter images and geologic maps (i.e., the local morphology varies significantly within the aperture region and a mixing or averaging effect operates to reduce the spectral feature differences). (c) All of these regions are the same spectrally in the near-infrared. It is likely that all three of these effects operate to some degree to prevent spectral features from being observed among the areas measured. Possibility (c) may best explain these results, as it is consistent with several previous studies indicating a grossly uniform mantle of global dust over much of the observed surface. The message to Mars orbiting spectroscopy experiments such as Mars Observer VIMS is that the spectral differences are small (only a few percent of the continuum) or nonexistent among many areas on Mars on the scale of several hundred kilometers.

Burt, D. M. (Department of Geology, Arizona State University, Tempe, AZ 85287): 'Iron-rich Clay Minerals on Mars: Potential Sources or Sinks for Hydrogen and Indicators of Hydrogen Loss over Time', in *Proceedings of the 19th Lunar and Planetary Science Conference (1989)*, pp. 423–432.

Although direct evidence is lacking, indirect evidence suggests that iron-rich clay minerals or poorly-ordered chemical equivalents ("palagonite") are widespread on the martian surface. Such clays (or other Fe and OH-bearing phases) can act as sources or sinks for hydrogen ("hydrogen sponges"). Ferrous clays can lose hydrogen, and ferric clays (especially dehydrogenated "oxy-clays") gain it by the coupled substitution $Fe^{3+}O(Fe^{2+}OH)_{-1}$, equivalent to minus atomic H. This "oxy-clay" substitution (H_2-loss) involves only proton and electron migration through the crystal structure, and therefore occurs nondestructively and reversibly, at relatively low temperature. The reversible, low-temperature nature of this reaction contrast with the irreversible nature of destructive dehydroxylation (H_2O-loss) suffered by clays heated to high temperatures. In theory, metastable ferric oxy-clays formed by dehydrogenation of ferrous clays over geologic time could, if exposed to water vapor, extract the hydrogen from it, releasing oxygen. Did this happen during the viking gas exchange experiments on Mars? The observations are otherwise difficult to explain. In any case, this class of reaction is of potential interest for the electrolysis-free generation of oxygen and hydrogen for propellant use (although relatively large masses of soil would need to be treated to produce a significant return).

Chapman, M. G. and Scott, D. H. (U.S. Geological Survey, Flagstaff, AZ 86001): 'Geology and Hydrology of the North Kasei Valles Area, Mars', in *Proceedings of the 19th Lunar and Planetary Science Conference (1989)*, pp. 367–375.

Geologic mapping of the north Kasei Valles area at 1:500,000 scale has provided new information regarding the geologic and hydrologic history of the large Kasei outflow channel system. The age of the system in the map area can be determined relative to geologic units that range in age from the early intermediate (Early Hesperian) to the very young (Late Amazonian) periods of Martian history; Kasei erosion occurred during the Upper Hesperian. Many geomorphic features in the map area suggest changes in water level and multiple erosional events associated with the Kasei Valles channel. Later erosional events are indicative of spring sapping, small-scale groundwater runoff, and water-mobilized debris flow.

Christiansen, E. H. (Department of Geology, Brigham Young University, Provo, Utah 84602): 'Lahars in the Elysium Region of Mars', *Geology* **17** (1989), 203–206.

Photogeological studies of the Elysium volcanic province, Mars, shows that its sinuous channels are part of a large deposit that was probably emplaced as a series of huge lahars. Some flows extend 1000 km from their sources. the deposits are thought to be lahars on the basis of evidence that they were (1) gravity-driven mass-flow deposits (lobate outlines, steep snouts, smooth medial channels, and rough lateral deposits; deposits narrow and widen in accord with topography, and extend downslope); (2) wet (channeled surfaces, draining features); and (3) associated with volcanism (the deposits and channels extend from a system of fractures which also fed lava flows). Heat associated with magnatism probably melted ground ice below the Elysium volcanoes and formed a muddy slurry that isued out of regional fractures and spread over the adjoining plain. The identification of these lahars adds to the evidence that Mars has a substantial volatile-element endowment.

Clark, R. N. (U.S. Geological Survey, Denver, CO 80225): 'Drawing Mars from Video', *Sky and Telescope* **77** (1989), 476.

Clifford, S. M., Greeley, R. and Haberle, R. M. (Lunar and Planetary Institute, Houston, TX 77058): 'Evidence for the Abundance of Water on Mars Now and in the Past', *Earth in Space* **1**(6) (1989), 3–5.

Mars has long fascinated scientists and the public. As a result, it has been the target of a number of ambitious spacecraft missions, the most recent being that of Vikings 1 and 2 in 1976. Scientists have recently returned to the Viking data to learn more about the nature and evolution of Mars.

de Vaucouleurs, G. (Dept. of Astronomy, University of Texas, Austin, TX 78712): 'The Best Telescopic Pictures of Mars', *Sky & Telescope*, **77** (1989), 15–17.

New technology yields spaceprobe-quality pictures of the red planet.

Eberhart, J., 'The Martian Atmosphere: Old Versus New', *Science News* **135** (1989), 21.

Eberhart, J., 'A Different View of Mars', *Science News* **135** (1989), 75.

Radar maps of Mars.

Eberhart, J., 'Signs of Old Mars: Written in the Dust', *Science News* **135** (1989), 173.

Eberhart, J., 'Solving a Mystery in the Sands of Mars', *Science News* **135** (1989), 266.

Eicher, D. J. and Troiani, D. M. (Schaumburg, Illinois): 'Memories of Mars', *Astronomy* **17**(4) (1989), 74–79.

Observers had clear views of Mars during the 1988 opposition until November when global dust storms obscured must of the Red Planet.

Fourth International Conference on Mars, January 10–13, 1989, Tucson, Arizona, Program and Abstracts.

Grizzaffi, P. and Schultz, P. H. (Department of Geological Sciences, Brown University, Providence, Rhode Island 02912): 'Esidis Basin: Site of Ancient Volatile-Rich Debris Layer', *Icarus* **77** (1989), 358–381.

The interior plains of the Isidis impact basin on Mars contain land forms which have previously been interpreted as volcanic features. These landforms can be classified into two broad units: hillocky terrain and ridged terrain. Hillocky terrain, the most central unit, consists of isolated mounds commonly arranged in arcuate chains. Ridged terrain contains systems of parallel, curvilinear ridges and occurs in a narrow band almost completely encircling the hillocky terrain. Ridges range from approximately 10 to 40 km long, 0.5 to 1.0 km wide, and 0.15 to 0.3 km high. Ridge properties and their distribution within Isidis appear inconsistent with characteristics of typical volcanic fields on Earth and Mars. Alternatively, we suggest that the Isidis landforms reflect the deposition and subsequent removal of a thick layer of material within the basin. Crater statistics and the morphology of additional features within Isidis provide further evidence that a major resurfacing event occurred within the basin, although depositional and erosional processes are currently minimal. Terrestrial ice-cover disintegration results in the development of landforms such as moraines, kames, and eskers, and provides possible analogs for the features which occur in Isidis. The Isidis cover, however, probably contained a vast amount of debris, remained stationary throughout most of its existence and eventually sublimated, thus differing from most terrestrial glaciers. A global survey of Viking Orbiter images reveals ridges elsewhere on Mars with similar characteristics or spatial distribution, thereby indicating that the Isidis layer may have been part of a more widespread epoch of deposition. This epoch possibly coincided with the period of major outflow channel formation when subsurface volatiles were released.

Hartmann, W. K. (Planetary Science Institute, Tucson, AZ 85719): 'What's New on Mars?', *Sky & Telescope* **77** (1989), 471–475.

Henbest, N., 'Probe Reveals Mars May Have Radiation Belts', *New Scientist* **121** (1989), 34.

Larson, S. (Lunar and Planetary Laboratory, University of Arizona, Tucson, AZ 85721): 'Changing Views of Mars', *Planetary Report* **9**(2) (1989), 10–12.

Lellouch, E., Gerin, M., Combes, F., Atreya, S. and Encrenaz, T. (Departement de Recherches Spatiales, Observatoire de Paris-Meudon, France): 'Observations of the $J = 1 - 0$ CO Lines in the Mars Atmosphere: Radiodetection of ^{13}CO and Monitoring of ^{12}CO', *Icarus* **77** (1989), 414–438.

Repeated millimeter-wave observations of Mars, performed in September and October 1986 and January 1987, allowed a high-resolution recording of the $J = 1 - 0$ ^{12}CO line, and the first radio detection of ^{13}CO. In the hypothesis where the thermal profile has the structure measured by the *Viking* spacecrafts, our observations are not compatible with a terrestrial $^{12}C/^{13}C$ isotopic ratio. If the isotope ratio is assumed terrestrial, then the observations imply that the thermal profile is very different from the profile in dust-free conditions, especially in its lower part, and that the CO abundance could vary by a factor of about 2 over a period of a few months.

Lendroth, S., 'Mars Watch Chronicles', *Planetary Report* **9**(1) (1989), 20–21.

The opposition of 1988 allowed amateur astronomers to join professionals in advancing our knowledge of Mars. With good telescopes and advanced film and processing, some amateurs were able to obtain photographs equal to any taken before the age of spacecraft.

Martin, L. J. and James, P. B. (Lowell Observatory, Flagstaff, Arizona 86001): 'Persistent Dust Cloud Activity on Mars near Echus Chasma in 1978', *Icarus* **77** (1989), 35–58.

Clouds were recorded by Viking cameras during five out of six observations over the same side canyon of Echus Chasma during a period of over $3\frac{1}{2}$ months in 1978. Although these clouds were different from one another in appearance, all were bright through a red filter and are believed to be at least partially composed of dust. Two of them were also imaged in violet light, in which they were also bright; therefore, they may also have contained condensate. A plausible explanation for the formation of the dust clouds is drainage winds, which are also known to be active to the west, in the Tharsis region during this season. In this case, winds may have been flowing downslope from the north rim of Tithonium Chasma.

McGill, G. E. (Department of Geology and Geography, University of Massachusetts, Amherst, MA 010003): 'Buried Topography of Utopia, Mars: Persistence of a Giant Impact Depression', *Journ. Geophys. Res.* **94** (1989), 2753–2759.

Knobs, partially buried craters, ring fractures, and some mesas permit a qualitative determination of the topography buried beneath younger northern plains materials. These features are widely distributed in the Utopia area but are absent in a large, roughly circular region centered at about 48° N, 240° W. This implies the existence of a circular depression about 3300 km in diameter buried beneath Utopia Planitia that is here interpreted to represent the central part of a very large impact basin. The presence of buried curved massifs around part of this depression, and a roughly coincident mascon, lend further support. Present topography, areal geology, and paleotopography of buried surfaces all point to the persistence of this major depression for almost the entire history of Mars.

Melosh, H. J. and Vickery, A. M. (Lunar and Planetary Laboratory, University of Arizona, Tucson, AZ 85721): 'Impact Erosion of the Primordial Atmosphere of Mars', *Nature* **338** (1989), 487–489.

Abundant geomorphic evidence for fluvial processes on the surface of mars suggests that during the era of heavy bombardment, Mars's atmospheric pressure was high enough for liquid water to flow on the surface. Many authors have proposed mechanisms by which Mars could have lost (or sequestered) an earlier, thicker atmosphere but none of these proposals has gained general acceptance. Here we examine the proces of atmospheric erosion by impacts and show that it may account for an early episode of atmosphere loss from Mars. On the basis of this model, the primordial atmospheric pressure on Mars must have been in the vicinity of 1 bar, barring other sources or sinks of CO_2. Current impact fluxes are too small to erode significantly the present Martian atmosphere.

Morris, R. V., Agresti, D. G., Lauer, H. V., Newcomb, J. A., Shelfer, T. A. and Murali, A. V. (Planetary Science Branch, NASA Johnson Space Center, Houston,Texas 77058): 'Evidence for Pigmentary Hematite on Mars Based on Optical, Magnetic, and Mossbauer Studies of Superparamagnetic (Nanocrystalline) Hermatite', *Journ. Geophys. Res.* **94** (1989), 2760–2778.

Features attributed to ferric iron in remotely sensed spectral data of Mars and the magnetic nature of Martian soil at the Viking landing sites are consistent with the occurrence of hematite (α-Fe_2O_3) as both superparamagnetic (nanocrystalline) hematite (sp-Hm) and larger-diameter hematite (bulk-Hm) particles. These hematite particles most likely occur in pigmentary form, that is, as particles dispersed throughout the volume of a relatively spectrally neutral (silicate?) material. Likely physical forms of this pigmented volume include rocks, dust and soil particles, and coatings (weathering rinds) thereon. Accomodation of Martian data by hematite is a result of differences in optical and magnetic properties of sp-Hm and bulk-Hm particles. Optical, magnetic, and Mossbauer properties of sp-Hm particles dispersed within particles of high-area silica gel are reported in this study and compared to the corresponding properties of bulk-Hm powders. Samples were prepared by calcining (~550 °C) powders of high-area silica gel that had been impregnated with ferric nitrate solutions. The samples are classified according to type of Mossbauer spectrum observed at 293 K. (1) Type S + D samples, which by Mossbauer granulometry contain hematite particles both larger and smaller than 10(2) nm, are characterized by a hematite sextet plus superparamagnetic doublet. (Uncertainties are given in parentheses and refer to the final digit(s).) (2) Type D samples, which contain hematite particles smaller than 10(2) nm, are characterized by only a superparmagnetic doublet and so contain only sp-Hm. The presence of larger particles in type S + D samples is consistent with X ray diffraction data; the diffraction patterns of type S + D samples are characterized by a few, broad hematite lines, and type D samples have no lines because the particles are too small to coherently scatter X rays. Measurements of internal field strengths (H_{int}) at 22 K for both types S + D and type D samples show that H_{int} is not constant but decreases with decreasing particle diameter from 54.0 T for bulk-Hm to 46.6 T for 5.4-nm sp-Hm. This dependence implies that phase identifications based solely on comparisons to bulk values of H_{int} are equivocal when superparamagnetic particles are present. Sp-Hm (<10 nm diameter) is much more magnetic than bulk-Hm; the saturation magnetization at 293 K for type D samples is

7(2) A m^2/kg as compared to 0–0.5 A m^2/kg for bulk-Hm. Optical properties of type S + D samples are similar to those of bulk-Hm; in particular, a well-defined band minimum is present near 860 nm. Optical properties of type D samples, with only sp-Hm at 293 K, are significantly different in that a step-shaped feature instead of a well-defined band is centered near 860 nm. The transition from well-defined band to step-shaped feature occurs at a hematite particle diameter of ~10 nm. The position of the UV-visible absorption edge and the absorption strength at 860 nm depend on the number density of sp-Hm particles, the Fe_2O_3 concentration, and the physiochemical properties of the support material. For 7(2)-nm sp-Hm particles dispersed within silica gel particles (35- to 74-μm powder with 6-nm pore diameter) the absorption edge shifts toward the visible, and the absorption strength at 860 nm increases with increasing number density of the sp-Hm particles. Visually, the color change is from nearly white to tan to dark red. Optical properties of samples containing 7(2)-nm sp-Hm particles are essentially independent of temperature between 173 and 293 K.

Parker, D. C., Beish, J. F. and Hernandez, C. E., 'Mars' Grand Finale', *Sky and Telescope* **77** (1989), 369–372

Plumb, R. C., Tantayanon, R., Libby, M. and Xu, W.W. (Department of Chemistry, Worchester Polytechnic Institute, Worcester, Massachusetts 01609): 'Chemical Model for Viking Biology Experiments: Implications for the Composition of the Martian Regolith', *Nature* **338** (1989), 633–635.

The 1976 Mars Viking biology experiments were designed to detect life by observing the products of biochemical reactions. In the labelled-release (LR) experiments, about 25 nmol of ^{14}C-labelled gases evolved when regolith samples were moistened with nutrient solution. About 22% of the products reabsorbed upon second injection. As a biological test the LR results were positive, although the reabsorption was not readily explained. In the gas exchange (GEX) experiments, up to 800 nmol of O_2 gas was evolved when samples were humidified, suggesting that the Martian regolith might contain a strong chemical oxidant which caused the LR results. Several chemical models have been proposed but no self-consistent explanation of all of the observations has been achieved. Here we propose a chemical model for these biology experiments in which the reactants are an inorganic nitrate salt, which has been partly photolysed by ultraviolet light, and a sparingly soluble metal carbonate such as calcite. The model reproduces the main effects seen, indicating that nitrates are present in the Martian regolith as well as calcite (or some other carbonate with similar solubility).

Risner, G. K. (Athens, Ohio 45701): 'The Geohydrology of Mars', *Groundwater* **27** (1989), 184–192.

The recent advances in space science have now made it possible to construct models of the existence, volume, and hydrological cycle of the ground water of the planet Mars.

Outgassing models of water vapor indicate that the surface of Mars should be covered with water to a depth of 10 to 100 meters (1.4×10^{15} to 1.4×10^{16} m^3). Geomorphic evidence suggests a depth of at least 500 meters (7×10^{16} m^3) of water should occur over much of the planet, yet no surface water, other than glacial ice at the poles (2.3×10^{15} to 9×10^{15} m^3), exists today. Martian gravity, though only 40 percent of Earth's, would keep water from escaping the planet. A survey of surface and atmospheric water volumes indicates that the majority of water, 1.2×10^{16} to 6×10^{16} m^3, is hidden as ground water.

Hydrologic cycle models indicate that Mars has an active but near static hydrologic cycle, dominated by water discharge in desert lowland and water recharge at the ice-covered poles. Ground-water flow plays a major role in this system.

Scott, D. H. and Chapman, M. G. (U.S. Geological Survey, Flagstaff, AZ 86001): 'Geologic Setting of an Unusual Martian Channel: Hypotheses on Origin', in *Proceedings of the 19th Lunar and Planetary Science Conference (1989)*, pp. 377–382.

Several areas within the Memnonia region of Mars have been proposed as candidate sites for a Mars sample return mission. Geologic studies of these areas made from computer-enhanced high-resolution Viking images show that an assemblage of rocks having different ages and compositions are accessible to a roving vehicle. In addition, evidence of recent fluvial episodes is indicated by small channels that incise materials emplaced during the Amazonian Period. The channel discussed in this paper is located near the highland-lowland boundary in the Memnonia MC-16SW quadrangle of Mars. It is of particular interest because of distinctive morphologic characteristics compared to other martian channels. Although several hypotheses are advanced to explain the origin of the channel, none of the arguments are completely satisfactory. However, we believe that water mobilized from ice in the subjacent regolith (hypothesis 1) or that condensate water from highly volatile ash flows (hypothesis 2) are the most likely origins for the channel.

Tanaka, K. L. and Golombek, M. P. (U.S. Geological Survey, Flagstaff, AZ 86001): 'Martian Tension Fractures and the Formation of Grabens and Collapse Features at Valles Marineris', in *Proceedings of the 19th Lunar and Planetary Science Conference (1989)*, pp. 383–396.

The Griffith theory of brittle failure of intact rock, Byerlee's law for shear failure of fractured rock, and laboratory and field observations of the extensional deformation of rocks are used to construct simple failure enveloped for shallow crustal extension on Mars based on rock friction and tensile strengths. Results indicate that for likely intact Martian materials and conditions, including the possibility of pore-water pressure, tension cracks can be produced to substantial depths (as much as tens of kilometers). Weathering, erosion, and other processes have exploited tension cracks on Mars, enlarging them so they can be observed in Viking images. Joints apparently control yardang trends in the Medusae Fossae Formation, grooves in ridged plains and basement materials in Kasei Valles, and grooves between knobs and mesas of chaotic terrains. Contraction cracks produced by thermal stresses in ice-rich material produced patterned ground in Deuteronilus Mensae (polygons 50–300 m across); larger polygons in the northern plains (2–20 km), however, are probably narrow grabens in ice-rich material. Fissures formed in part by forceful magma injection and perhaps bulging during intrusion are prevalent on Martian volcanic shields. Structural deformation at Valles Marineris is proposed to be instigated by deep, intense tension fracturing in basement rocks (whose older fractures have been healed by carbonate cementation following heavy bombardment). Material overlying the fractures extends and forms grabens and further collapses to form pits and troughs, likely augmented by groundwater flow. Other pits and grabens associated with noctis Labyrinthus and Tharsis faulting may also be controlled tension fractures.

Thompson, T. W. and Moore, H. J. (Jet Propulsion Laboratory, Pasadena, CA 91109): 'A Model for Depolarized Radar Echoes from Mars', in *Proceedings of the 19th Lunar and Planetary Science Conference (1989)*, pp. 409–422.

We have modeled depolarized echoes of 12.6-cm radio transmissions backscattered from Mars. The model (1) reproduces the variations of the total radar cross-sections with longitude observed by Goldstone in 1986 along 7° S, (2) yields larger magnitudes of total radar cross-sections along 22° N than those along 7° S – in accordance with the 1980–1982 Arecibo observations, and (3) produces depolarized echo spectra that broadly match those observed by the Arecibo radar in 1980 and 1982. In our model, depolarized echoes from individual areas are assumed to be uniformly bright. Thus depolarized echo strength per unit surface area is given by $A \cos \theta$, where θ is the angle of incidence and A is a variable assigned to radar map units on a degree-by-degree basis. Best-fit values of A were found by trial and error. Although the model may not be an entirely unique solution, it quantifies the large variations that exist in the depolarized backscatter from Mars. Our model indicates that volcanoes and lava plains of the Tharsis-Alba Patera, Elysium, and Amazonis regions have the strongest depolarized echoes from the entire planet. Depolarized echoes from these volcanoes are 7.0 to 18.0 times the background, while those of the lava plains are 3.0 to 16.0 times the background. The northern low plains and canyons have depolarized echoes between the background and 4.0 times the background.

The cratered uplands have echo strengths near the background level, while the Arabia region has echoes 0.8 times the background. The background level would produce a total radar cross-section of 0.010 if all of Mars backscattered uniformly with the background level. We estimated rock populations for the Moon and Mars assuming depolarized radar echoes result from rocks with radii between 1/3 and 3 times the wavelength. The average lunar surfaces at all Surveyor landing sites (except Surveyor 7) and the old cratered terrains on Mars have 2% and 4% coverage with rocks of these sizes. The Viking landing sites and the Martian plains in general have about 10% rock coverage, as does the Surveyor 7 landing site. The highest percentage-rock-coverage for Mars occurs on volcanic constructs where rock coverages can be 50% or more.

Wilhelms, D. E. and Baldwin, R. J. (San Jose State University Foundation, c/o Geology Department, San Jose State University, San Jose, CA 95192): 'The Role of Igneous Sills in Shaping the Martian Uplands', in *Proceedings of the 19th Lunar and Planetary Science Conference (1989)*, pp. 355–365.

Relations among geologic units and landforms suggest that igneous sills lie beneath much of the intercrater and intracrater terrain of the Martian uplands. The igneous rocks crop out along the upland-lowland front and in crater floors and other depressions that are low enough to intersect the sills' intrusion horizons. We suggest that heat from the cooling sills melted some of the ice contained in overlying fragmental deposits, creating valley networks by subsurface flow of the meltwater. Terrains with undulatory, smooth surfaces and softened traces of valleys were created by more direct contact with the sills. Widespread subsidence following emplacement of the sills deformed both them and the nonvolcanic deposits that overlie them, accounting for the many structures that continue from ridged plains into the hilly uplands. Crater counts show that the deposits that became valleyed, softened, and ridged probably began to form (and to acquire interstitial ice) during or shortly after the Middle Noachian Epoch (3.8–3.9 aeons ago?), and continued to form as late as the Early Hesperian Epoch (began 3.5 aeons ago?). The upper layers of this deposit, many of the visible valleys, and the ridged plains and postulated sills all have similar Early hesperian ages. Continued formation of valleys is indicated by their incision of fresh-appearing crater ejecta. The dependence of valley formation on internal processes implies that Mars did not necessarily have a dense early atmosphere or warm climate.

Zimbelman, J. R., Clifford, S. M. and Williams, S. H. (Center for Earth and Planetary Studies, National Air and Space Museum, Smithsonian Institution, Washington, DC 20560): 'Concentric Crater Fill on Mars: An Aeolian Alternative to Ice-rich Mass Wasting', in *Proceedings of the 19th Lunar and Planetary Science Conference (1989)*, pp. 397–407.

Concentric crater fill, a distinctive martian landform represented by a concentric pattern of surface undulations confined within a crater rim, has been interpreted as an example of ice-enhanced regolith creep at midlatitudes (e.g., Squyres and Carr, 1986). Theoretical constraints on the stability and mobility of ground ice limit the applicability of an ice-rich soil in effectively mobilizing downslope movement at latitudes poleward of ±30°, where concentric crater filled is observed. High-resolution images of concentric crater fill material in the Utopia Planitia region (45° N, 271° W) show it to be an eroded, multiple-layer deposit. Layering should not be preserved if the crater fill material moved by slow deformation throughout its thickness, as envisioned in the ice-enhanced creep model. Multiple layers are also exposed in the plains material surrounding the craters, indicating a recurrent depositional process that was at least regional in extent. Mantling layers are observed in high-resolution images of many other locations around Mars, suggesting that deposition occurred on a global scale and was not limited to the Utopia Planitia region. We propose that an aeolian interpretation for the origin and modification of concentric crater fill material is most consistent with morphologic and theoretical constraints.