Planetary Systems Branch

Overview

The overall research effort in the Planetary Systems Branch is directed at acquiring new, fundamental knowledge about the origins of stars and planetary systems and life itself. These studies are an integral part of NASA's overarching thrust in Astrobiology. Principal research programs include studies of the formation of stars and planets and the early history of the solar system, studies of planetary atmospheres and climate, investigation of the dynamics of planetary disks and rings, work on problems associated with the Martian surface including resource utilization and environments for the origin of life, and other programs (chiefly theoretical) involving stellar and planetary dynamics, radiative processes in stars and the interstellar medium, and investigation of the physical and chemical conditions in molecular clouds and star formation regions. Scientists in the branch also support NASA flight missions through participation on various mission science teams. The primary product of the Branch is new knowledge about the nature of the universe, presented and published in the open literature.

Bruce F. Smith

Chief, Planetary Systems Branch

KEPLER MISSION TO FIND EARTH-SIZE PLANETS: A STATUS REPORT

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Small rocky planets at orbital distances from 0.9 to 1.2 AU are more likely to harbor life than the giant gas planets that are now being discovered with the Doppler-velocity technique. Technology based on transit photometry can find smaller, Earth-like planets that are a factor of several hundred times less massive than Jupiter-like planets. The Kepler Mission is designed to discover hundreds of Earth-size planets in and near the habitable zone (HZ) around a wide variety of stars. It was selected as Discovery Mission #10 in December 2001.

The instrument is a wide field-of-view (FOV) differential photometer with a 100 square degree field of view that continuously and simultaneously monitors the brightness of 100,000 main-sequence stars with sufficient precision to detect transits by Earth-size planets orbiting G2 dwarfs. The brightness range of target stars is from visual magnitude 9 through 14. The photometer is based on a modified Schmidt telescope design that includes field flatteners near the focal plane. Figure 1 is a schematic diagram of the photometer.

Approximately 100,000 target stars must be monitored to get a statistically meaningful estimate of the frequency of terrestrial planets in the HZ of solar-like stars. In particular even if every such star has such a planet, only about 500 planets will be discovered because the geometrical probability that the planets' orbit will be aligned well enough to show transits is only about 0.5%. In the 100 sq degree Kepler FOV, there are approximately 450,000 stars brighter than 15th magnitude. To find 100,000 useful targets, all of these must be classified with respect to spectral type and luminosity class because no catalogs with this information exist. This is a formidable task that must be completed before launch. Hence three small studies have been funded this year to find the quickest and least expen-

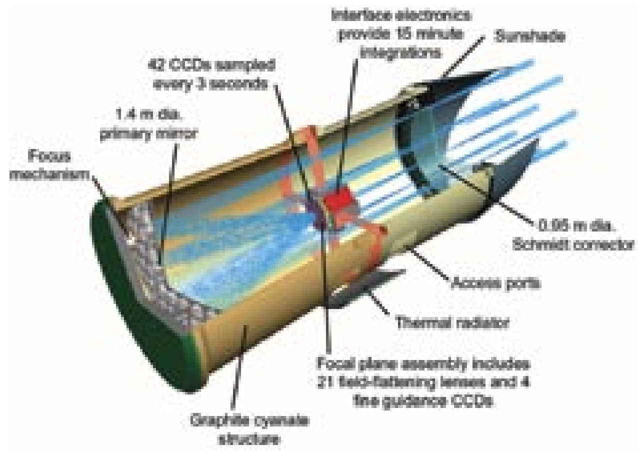

Figure 1. Schematic diagram of Kepler photometer.

sive method. Two of the studies will use multi-band photometry and ground-based telescopes with large fields of view. The third study will use a combination of multi-fiber spectroscopy at a 6.5 m telescope and the results of recently published catalogs of infrared stellar measurements and reduced proper motions to identify and eliminate those stars of little interest. Results of the three studies are due in December.

Phase B work started in March of 2002. Since then a new management team from the NASA Jet Propulsion Lab (JPL) was chosen to provide overall mission management. The JPL team members have been smoothly integrated with those at NASA Ames and the Ball Aerospace & Technology Corporation. Their addition greatly strengthens the Kepler Mission by providing great depth in mission management and engineering.

In the fall of 2002, 30 CCD detectors were ordered from each of two vendors. This "twin buy" approach insures that the large number of detectors required for the Kepler focal plane will be available even if one of the two vendors runs into difficulties. In April of this year all mechanical grade detectors were received. Minor difficulties were found, but all were acceptable. Delivery of the evaluation grade detectors is expected to start in May 2003. These will be tested to demonstrate that they correctly respond to electronics, have the appropriate sensitivity, and produce photometrically stable results.

Competition to build both the 0.95m Schmidt corrector and the 1.4m primary mirror for the photometer optics was won by the Brashear Corporation in May 2003. Delivery is expected in 2005. Negotiations for other long-lead items such as the Ka- and X-band travelling-wave tube amplifiers (TWTAs) needed for the telemetry link are in progress.

The first major review of the mission, the systems requirement review, will be held this October. In summary, the Kepler Mission is on schedule for a 2007 launch.

PLANETARY RINGS

J. N. Cuzzi, I. Mosqueira, and F. Poulet

Saturn's rings are one of the main targets of the upcoming Cassini mission to Saturn. In addition, rings provide a unique dynamical laboratory for understanding the properties of particle disks, which will help us understand the accretion of the planets.

Models we have developed for the way in which grainy, icy surfaces (or "regoliths") scatter light have been applied to model the composition of Saturn's rings in a quantitative way for the first time. One very interesting result of this research is that the tendency for regolith grains to scatter light in the forward direction, deeper into the surface, has been greatly underestimated in the most popular previous models. This has led to overestimates of the amounts of nonicy contaminants required to be mixed into these surfaces in order to explain their colors. Application of the new models to two "Centaurs", or icy bodies orbiting between Saturn and Uranus, leads to Carbon/Water Ice mass ratios which are 30 times smaller than previously believed. These models, applied to Saturn's rings, imply that only a few percent of the rings can be composed of materials other than water ice (i.e., amorphous Carbon; reddish "Tholin"-like organics). In addition, modeling of newly obtained, very high spectral resolution data from NASA's Infrared Telescope Facility, in combination with these models, indicate that the Carbon is distributed differently on a microscopic level withni the regolith in some rings than in others—perhaps indicating that it was formed in situ by radiation darkening, or that it was more finely pulverized by meteoroid impacts.

Other research has focussed on the origin of the regular satellites of the gas giant planets, which can be considered "miniature solar systems." The research is unique in that it attempts to explain the regular satellite systems of Jupiter, Saturn and Uranus within the same general scheme, merely by varying local conditions such as temperature and gas density. It includes satellitesimal migration due to gas drag and tidal torques, and forms satellites by a combination of "particle-in-a-box" binary accretion and drift augmented accretion in an extended, two-component planetary subnebula. The dense inner disk is set by the location to which the nearby, sun-orbiting gas and debris falls inward, while the much less dense outer disk extends to the location of the irregulars, and arises as a result of later infall from further distances.

This model forms Ganymede and Titan in the inner disk in one to ten thousand years and ten to a hundred thousand years respectively, and Callisto and Iapetus in the outer disk, both in about a million years. Callisto is formed out the volatile-rich condensables present in the extended, low density outer disk; its very long formation timescale is tied to the disk clearing time, which is the time it takes for gas drag to clear the circumplanetary disk of solids. The different formation material and timescale of Callisto relative to Ganymede may explain the high volatile content of Callisto compared to Ganymede, as well as Callisto's partially differentiated state (in contrast, Ganymede is fully differentiated). Formation of Hyperion in resonance can be explained by the steep density gradient between the inner and outer disks, as had been suggested without context by some earlier studies. The model also makes several predictions about the composition and interior structure of Titan, Iapetus, the icy inner saturnian satellites and the rings, which may soon be tested by Cassini.

PARTICLE-GAS DYNAMICS IN THE PROTOPLANETARY NEBULA

J. N. Cuzzi, R.C. Hogan, S. S. Davis, and A. R. Dobrovolskis

"Primitive" or unmelted asteroids, from which the terrestrial planets were built, are represented in the meteorite record as a vast and complex set of "chondrites."

The interpretation of this unique look into the environment preceding planet formation has suffered for lack of a coherent theoretical context. Accretion of these primitive chondrites from small grains and mm-sized, melted silicate “chondrules” almost certainly occurred in the presence of gas, where subtle feedback effects occur between gas and particles.This research focusses on theoretical modeling of particle-gas interactions in turbulent nebula flows, and understanding meteorite properties in the light of these models.

Building on past results in this line of research, Ames researchers have developed new analytical models of particle velocities in the early solar nebula. These models encapsulate complex physics into simple, but still rigorous, closed-form analytical expressions suitable for general use. One of the first uses of the new results has been as part of a new model of the formation and redistribution of one key component of meteorites—the oldest, highest-temperature mineral condensates called Calcium-Aluminum-rich inclusions (CAIs). The models predict a significant enhancement of the inner nebula in silicates and Carbon for the first hundred thousand years of nebula history, due to drifting meter-sized rubble. This region, for this time, is likely to be the CAI formation zone. It is becoming evident that CAIs, found ubiquitously in primitive chondrites, are 1–3 million years older than the bulk of the other mineral objects in the same rock. It has long puzzled meteoriticists as to why these older fragments are not lost into the sun during this several million year hiatus. Our models show that turbulent diffusion of CAIs outwards in the nebula, subsequent to their formation, can explain their persistence for several million years. The enhancement of the formation zone in silicates explains the abundance of CAIs in meteorites quantitatively, and its enhancement in Carbon apparently helps explain their chemical and isotopic properties.

This year, Ames researchers also developed a novel cascade model for turbulence, which is capable of reproducing the statistical properties of fully 3D direct numerical simulations (DNS) and extending them to far higher Reynolds numbers. The goal of the model is to make quantitative estimates of the tendency of turbulent concentration of particles to produce planetesimals with the observed properties. Our model is a two-phase, coupled cascade which calculates both particle concentration and local vorticity, with their spatial correlations included. These two properties determine the tendency towards gravitational instability of dense regions. Furthermore, the effects of particle mass loading on the cascade—leading to a tendency for particle concentration to saturate at some high level - are modeled using characteristic “partition rules” obtained from 3D simulations of turbulence under mass loaded conditions. The cascade code is running on Ames’ Origins 2000 1024 node machine, and is capable of reaching Reynolds numbers of over a million with reasonable run times. For comparison, 3D DNS models struggle to reach Reynolds numbers of several thousand.

THE PASCAL MARS SCOUT MISSION

Robert M. Haberle

The next major advance in our understanding of the meteorology and climate of Mars will come from in-situ measurements taken by a global network of long-lived landers. The National Research Council has recommended to NASA that in developing its long term science goals for Mars exploration, such a mission should be given high priority. During most of fiscal year 2002 Ames Research Center, along with industry partners Ball Aerospace, Lockheed Martin Advanced Technology Center, and ITT Aerotherm Corporation, developed a network mission concept to propose to NASA’s Mars Scout program. The mission is named after Blaise Pascal, the 17th century French scientist who pioneered measurements of atmospheric surface pressure, the most important meteorological parameter.

The Pascal mission delivers 18 small weather stations to the surface of Mars. The weather stations are distributed all around the planet so global scale phenomena can be sampled. Each station conducts meteorological measurements for at least 3 Mars years (a Mars year is equivalent to 687 Earth days). These measurements include pressure, temperature, sky opacity, wind speed, and water vapor concentration. A panoramic camera system periodically images the surrounding terrain to look for changes in the scene due to wind activity. In addition to these measurements, each weather station

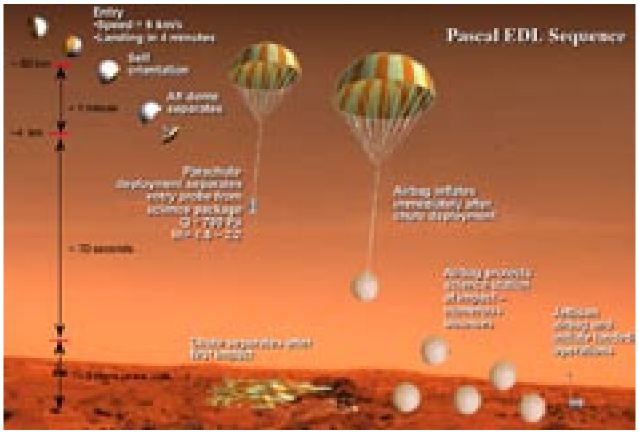

Figure 1. Pascal entry, descent, and landing (EDL) sequence.

measures the temperature structure of the atmosphere, and takes pictures of the ground during its descent to the surface. All operations are autonomous. Communications to and from the Earth takes place through a relay orbiter provided by NASA's Mars Exploration Program or those from other countries.

A carrier spacecraft begins releasing and targeting the probes to the surface of Mars when it is about 40 days from encountering the planet. The targeting and release sequence takes about 15 days to complete. Figure 1 shows the entry, descent, and landing sequence. After releasing all the probes, the carrier spacecraft flys by Mars and begins to orbit the sun. Each probe enters the atmosphere at an altitude of approximately 150 km. The probes orient themselves so that the aeroshell is facing forward. The aeroshell provides thermal protection as the probes slow down in the atmosphere. At 10 km altitude, a parachute is deployed to further slow the probes to approximately 25 meters per second (50 miles per hour). Just before impact an airbag inflates and the parachute is jettisoned. After several bounces the probe comes to rest and the airbag is jettisoned. The camera system is then deployed and autonomous operations commence.

The Pascal mission seeks to understand the long-term global behavior of weather systems on Mars, how they interact with the surface, and how they control the planet's climate system. The science objectives are (1) measure the seasonal cycles of dust, water vapor, and carbon dioxide, (2) measure the surface signature of the planet's weather systems, (3) understand how these systems control the planet's climate and modify its surface, and (4) provide a basis for comparative planetary meteorology. The Pascal mission provides a long-term continuous presence on the surface of Mars not possible in previous missions.

THE CENTER FOR STAR FORMATION STUDIES

D. Hollenbach and K. R. Bell

The Center for Star Formation Studies, a consortium of scientists from the Space Science Division at Ames and the Astronomy Departments of the University of California at Berkeley and Santa Cruz, conducts a coordinated program of theoretical research on star and planet formation. The Center, under the directorship of D. Hollenbach (NASA Ames), supports postdoctoral fellows, senior visitors, and students, meets regularly at Ames to exchange ideas and to present informal seminars on current research, hosts visits of outside scientists, and conducts a week-long workshop on selected aspects of star and planet formation each summer.

In June 2002 the Center, along with the Institute of Astronomy and Astrophysics in Taiwan, co-hosted an international workshop entitled "Magnetohydrodynamics, Radiation Diagnostics, and Chemistry of Star Formation," which was held in Taiwan. The weeklong workshop had approximately 150 attendees, and included an invited talk by D. Hollenbach on "Molecular and Dust Emission from Disks Around Low Mass Stars"

One focus of the NASA Ames portion of the research work in the Center in 2002 involved the study of the ultraviolet radiation field in galaxies which is produced by relatively short-lived massive stars. Stars in galaxies form by the gravitational collapse of portions of giant molecular clouds (GMCs), and the star formation in these GMCs produces a range of stellar masses, including massive stars with masses 10 to 100 times as massive as the Sun. Although these stars are less numerous than solar-type stars, they are incredibly luminous, nearly 105 times as luminous as the Sun, and they dominate the production of ultraviolet radiation in galaxies. The GMCs form out of an assemblage of more diffuse, cold atomic clouds in galaxies, and the amount of diffuse cold clouds is determined by the ultraviolet radiation field. If the ultraviolet radiation field is high, the heating caused by these energetic photons will warm the cold clouds to extremely high temperatures of 104 K and cause them to expand and dissipate. In this way, the rate of star formation in a galaxy is self-regulated. If stars form too rapidly, there will be a large population of massive stars, a resultant high ultraviolet field, and a consequent destruction of the very clouds which lead to star formation. Hence, the star formation rate will be forced to slow down. On the other hand, if the star formation rate is low, the ultraviolet field is low, and there is little heating of the diffuse gas in the interstellar medium. In this case, the gas cools, forms copious cold clouds, which conglomerate to form GMCs, and which then ultimately lead to higher star formation rates.

Another focus of the Ames portion of the Center research in 2002 involved a study of dust particles at the surface of a protoplanetary disk. Radiation from this layer produces infrared emission that reveals mineralogical, chemical, and morphological properties of the dust. Long term monitoring of a dozen young star/disk systems has revealed several whose infrared emission changes dramatically from month to month. This unexpected short term variability may mean that both dust population and disk structure are evolving very rapidly in the planet-forming regions of young Sun-like systems.

The theoretical models of the Center have been used to interpret observational data from such NASA facilities as the Infrared Telescope Facility (IRTF), the Infrared Astronomical Observatory (IRAS), the Hubble Space Telescope (HST), and the Infrared Space Observatory (ISO, a European space telescope with NASA collaboration), as well as from numerous ground-based radio and optical telescopes. In addition, they have been used to determine requirements on future missions such as the Stratospheric Observatory for Infrared Astronomy (SOFIA) and the Space Infrared Telescope Facility (SIRTF).

HEARING THE LESSONS BROWN DWARFS TEACH

Mark Marley, Richard Freedman

One of the central goals for NASA's Space Science Enterprise is the direct detection of extrasolar planets. Jupiter-like planets are an easier target than terrestrial planets, of course, and as such will serve as a stepping stone on the path to finding "pale blue dots," or extrasolar Earth-like planets. Even obtaining the first image of an extrasolar Jupiter will require large ground or space based telescopes, a new generation of instruments, and an optimal strategy. In fact one of the key science goals of the James Webb Space Telescope is to directly image extrasolar giant planets in the solar neighborhood. The strategy is to image these planets at the favorable wavelength of five microns, where models predict the planets to be particularly bright and the glare from their primary star to be less troublesome.

Although no giant planets have yet been imaged, hundreds of brown dwarfs have been found. These objects, which are more massive than planets, but less massive than stars, serve as pathfinders to the extrasolar giant planets. They have roughly the same radii, the same composition, and the same atmospheric temperature conditions as, at least some, extrasolar planets. As such they provide test cases which illuminate the optimal observing strategy.

At the conditions prevalent in cool brown dwarf atmospheres, chemical equilibrium arguments suggest that most carbon atoms should be found in the form of methane, CH_4. Methane, along with water and ammonia, the other major atmospheric constituents, absorb relatively little near five microns. This absorption minimum is responsible for the opening of the "window" in this spectral region. The window allows bright flux from deeper, hotter regions of the atmosphere to escape to space. Thus the prediction that extrasolar giant planets should be bright at five microns. However, a key result from the past year of observations and interpretation of brown dwarfs has been that these objects are dimmer than predicted by models in this crucial spectral region.

The most likely explanation for this unexpected diminution in brightness is an enhanced abundance of carbon monoxide, CO, in these atmospheres. Although methane is the favored reservoir of carbon at low temperatures high in the atmosphere, CO is favored deeper in the atmosphere. Strong vertical flows in the atmosphere can transport CO from the deep, unobservable, regions up to the observable atmosphere. Once there the tendency of carbon monoxide to absorb near five microns muffles the otherwise bright emitted flux. A similar phenomenon is seen at Jupiter where CO is detectable in this same spectral region.

The fact that some cool brown dwarfs are substantially (by up to 60%) dimmer than expected implies that this same phenomenon may be ubiquitous, and also affects the atmosphere of extrasolar giant planets. If so the planets will be dimmer and more difficult to detect than had previously been expected.

Continuing research will focus on better understanding the reason for the flux diminution in brown dwarfs and providing guidance for efforts to directly detect extrasolar giant planets.

CLUSTER DETECTION IN GALAXY SURVEYS

Jeffrey D. Scargle, Christopher E. Henze, Creon Levit, Michael Way, Bradley Jackson

This collaboration developed a novel way to detect and characterize structure in three dimensional point data, and applied the methodology to analyze large new data sets from astronomical surveys of the constituents of the Universe. This application resulted in an objective procedure for identifying galaxy clusters without imposing assumptions about cluster shape, and without fixing ahead of time the number of clusters - thus removing limitation affecting most previous cluster detection studies.

The procedure is based on a 3D segmentation model, in which the data space is partitioned into subregions such that the point density is well modeled as being constant over each such subregion. The computational procedure is to find the optimum such partition, meaning the one that maximizes a goodness of fit quantity. The Bayesian posterior probability of the model, given the point data, was adopted as this fitness measure.

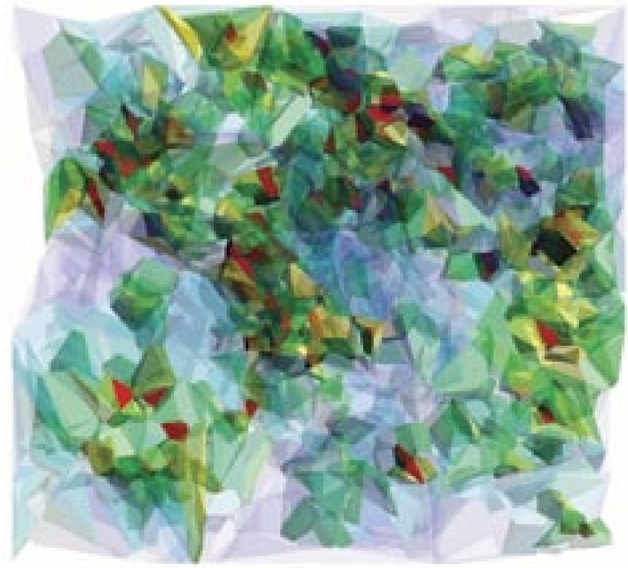

Fig. 1: Results of the segmentation analysis of a small cube of data from the Sloan Digital Sky Survey Early Release Data. The color scale indicates density of galaxies per unit volume of space, with red being the highest density, then yellow, green, and light blue, with violet being the least dense (and roughly representing a uniform background of non-clustered galaxies on which the other structures are superimposed.

The complexity of the space of possible models was reduced by positing that the partition elements consist of finite collections of data cells - that is, regions of the data space closest to a given data point, the so-called Voronoi tessellation of the space. This excellent approximation reduces the size of the search space from highly infinite to a finite one—albeit exponential in the number of data points.

The solution to this combinatorial optimization problem is obtained by a simple adaptation to higher dimensionality of an exact 1D algorithm developed in an earlier phase of the work. The adaptation is based on a mathematical result, called the intermediate density principle—which allows the data cells in any dimensional space to be ordered by cell volume and then treated as a 1D sequence. The final algorithm finds the global optimum partition of the data in time proporational to the square of the number of data points.

The algorithm was applied to the early release data from the Sloan Digital Sky Survey (www.sdss.org). A small sample result is shown in the first figure. The raw data consist of the positions on the sky and redshifts of a large sample of galaxies. Converting the redshifts to distances, using the Hubble relationship, yields a true 3D distribtion of tens of thousands (ultimately millions when the survey is complete) of galaxies. The optimal partition in to collections (called blocks) of 3D Voronoi cells, colored according to the spatial density of galaxies averaged over each block, are shown in the figure. We are experimenting with scientific visualization techniques to render the true distribution more comprehensible, including the use of the NAS HyperWall to explicate correlations between the spatial, spectral, color and brightness data available for each galaxy.

THE CHEMISTRY AND MINERALOGY OF ATACAMA DESERT SOILS

Brad Sutter

The Atacama Desert of northern Chile is the driest desert in the world. While Mars is vastly more dry and cold than the Atacama, the Atacama environment may be one of the best terrestrial Mars analog environments accessible to researchers. The objective of this work was to examine the soils of the hyper-arid Atacama Desert to provide insight as to what soil properties maybe found on Mars.

Three soils were examined that occur along a south to north transect (Copiapo → Altimira → Yungay) in the Atacama that coincides with decreasing moisture levels (~15mm to ~2 mm yr^{-1}, south to north). Total chemical analyses were used to calculate strain (i.e. volume change) and the open-system mass-transport function. The Yungay and Altimira soils expanded over 400% while the Copiapo soil collapsed by as much as 48%. The expansion of the Yungay and Altimira soils may be the result of the additions of sulfate, nitrate, and chloride from aerosol inputs from wind redistribution of playa salts, volcanic activity, and marine influences. Apparently, the higher level of precipitation at the Copiapo site caused leeching, and the sulfate, nitrate, and chloride additions could not accumulate to levels high enough, thus the Copiapo soil collapsed. The lack of significant precipitation at the Yungay and Altimira soils allows for additions of sulfate, nitrate, and chloride to remain, which resulted in soil expansion.

The results of this work suggest that there is a critical water balance for soil formation (precipitation – evapotranspiration) at which the long-term accumulation of atmospherically-derived elements (e.g., sulfate, nitrate, and chloride) exceeds weathering losses, and landscapes undergo continual dilation (e.g., Yungay soil) as opposed to collapse (e.g, Copiapo soil). The critical climatic cutoff point is likely to be quite arid. In the Atacama Desert, the crossover point between the accretion vs. the loss of soluble atmospheric inputs such as sulfate is somewhere between 2 and 15 mm of precipitation per year. Elevated levels of sulfur and chlorine found at the Viking and Pathfinder sites suggesting aerosol input coupled with the extreme aridity of Mars indicates that Martian soils may have undergone volumetric expansion similar to what has occurred in the Atacama.

Currently, the rare earth elements of the above soils as well as soil chemical data just received from soil horizons deeper than what was discussed above are being examined to provide more insight into the soil expansion and contraction properties of Atacama soils. Future work will examine Atacama soils developed on volcanic materials farther from the coast in an effort to obtain a better analog to Mars soils.

HEAT FLOW AND DEGASSING IN MANTLE CONVECTION

Kevin Zahnle, Norman H. Sleep, and Francis W. H. Nimmo

That the Earth's mantle convects is not in doubt. But whether it convects as a whole, in layers, or in some more complex pattern is a matter of debate. In whole mantle convection the continents and atmosphere are extracted from the mantle as a whole. The remaining "depleted" mantle is to first approximation statistically well-mixed and fairly sampled by volcanism. More subtle views of whole mantle convection regard the mantle as a poorly stirred cauldren of primitive materials, depleted materials, and convectively-entrained materials from the surface (e.g. subducted continental materials and subducted MORB) and from the core-mantle boundary. In layered convection the mantle convects in two layers, which may be loosely termed "upper mantle" and "lower mantle." By construction the lower mantle is not easily depleted and does not easily degas. In traditional layered convection, the layering is identified with and possibly caused by (or at least modulated by) the solid state phase transition that occurs 660 km below the surface. More modern versions of layered convection move the barrier to mixing to much greater depths and have asserted that compositional differences between upper and lower mantle materials can maintain distinctive unmixed mantle reservoirs.

A great many geophysical, seismological, and geochemical arguments have been made to all sides of this debate that do not need to be summarized here. Suffice it to say that seismological evidence against layering at 660 km, the traditional boundary between the upper and lower mantle, is strong, yet good indirect arguments for layering remain. One such argument involves a heat flow paradox: Earth seems to be cooling much faster than it is being heated by the decay of radioactive elements. (The important radioactive elements are uranium, thorium, and a rare isotope of potassium.) Such a mismatch is not expected in conventional whole mantle convection, but it is reasonable in layered convection, because the lower mantle can better store old heat. Second, radioactive decay produces, among other products, the inert gases helium and argon. The amount of argon in the atmosphere and the amount of helium currently being degassed from the Earth's mantle are both smaller than expected of a well-mixed mantle. The mantle helium flux in particular agrees with what is expected from a small isolated upper mantle. A well-known but ambiguous third argument for layering exploits the relative fluxes of radiogenic (^{4}He) and nonradiogenic (^{3}He) helium. In this argument relatively high ^{3}He/^{4}He ratios associated with Ocean Island Basalts (OIBs) are attributed to high ^{3}He/^{4}He material from the lower mantle. The idea is that the lower mantle is less degassed, and so retains a relatively higher amount of the nonradiogenic ^{3}He. This is something of a pyrrhic victory given that the quantity of helium in OIBs is smaller, and sometimes much smaller, than in the more voluminous Mid-Ocean Ridge Basalts (MORBs). The observed relationship is opposite what one expects from a helium-rich lower mantle source.

The failure to establish the existence of a material boundary at 660 km has led layering's advocates to consider alternative topologies. These are loosely lumped together under the label of "lava lamp layering." The key features of these newer models is that the upper mantle is made bigger and deeper, the lower mantle shrinks accordingly, and the distinction is maintained by modest compositional differences. (The lava lamp itself is a misleading but established analogy, misleading because the lava lamp comprises immiscible fluids but the mantle does not.) The new layering represents something of a compromise. It retains in diluted form most of the advantages and the disadvantages of both of its antecedents.

We construct self-consistent degassing and thermal history models for Earth in whole mantle and lava lamp style convection. Whole mantle solutions for argon, helium, CO_2, and the temperature of the Archean upper mantle can be obtained only if (i) helium and argon are some 4–6 times more compatible with the mantle (i.e. more readily retained by the mantle during magmatic processes) than is typical of incompatible "elements" such as CO_2; and (ii) heat flow has been roughly constant over geologic history. The sense of paradox in whole mantle convection stems from (i) the presumption that a rare inert element ought to degas as agressively as an extremely incompatible element; and (ii) the expectation, based on applying the conventional equations of parameterized convection to plate tectonics, that heat flow is strongly coupled to the mantle's temperature in a way that guarantees that heat flow tightly tracks the heating provided by the decay of radioactive elements. Neither of these presumptions is founded well enough to rule out whole mantle convection. The newer versions of layered convection, in which the depleted (upper) mantle comprises ~60% of the whole, may seem better. These allow higher noble gas degassing efficiencies, although still less than half that of CO_2. By setting the ratio of upper to lower mantle to 60:40, the new layering gives self-consistent abundances for Th, U, and K in the continents, MORBs, and lower mantle. This addresses a problem that whole mantle convection can address only by making recourse to heterogeneities. As in whole mantle convection, the new layered convection requires that heat loss be a weak function of mantle temperature. This is a paradox that apparently cannot be resolved by mantle topology alone but may instead require a more subtle understanding of how plate tectonics actually work.