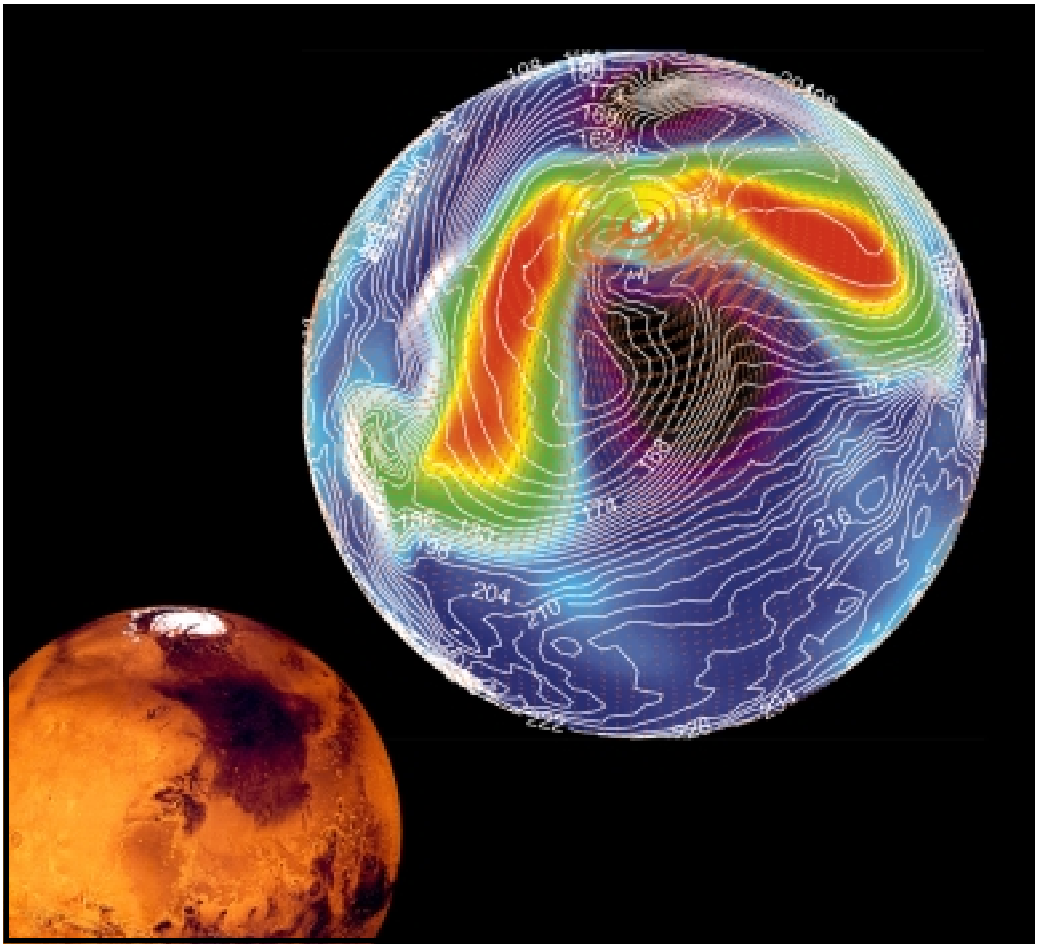

Mars Atmosphere Model. Credit: J. Hollingsworth, R. Haberle, and J. Schaeffer

Planetary Systems Branch (SST) 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

Deputy Chief, Planetary Systems Branch (SST)

PARTICLE-GAS DYNAMICS IN THE PROTOPLANETARY NEBULA

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

“Primitive”or unmelted asteroids, from which the planets were built, are represented in the meteorite record as a vast data set that has had little context for interpretation. The accretion of these primitive bodies from small grains and mm-sized, melted ‘’chondrules” almost certainly occurred in the presence of gas. Study of this stage is complicated by the feedback effects of the gas on the particles, and vice versa. Ames’ efforts focus on numerical modeling of particle-gas interactions in turbulent flows, and understanding meteorite properties in the light of theoretical models.

Ames’ “turbulent concentration” theory (TC), introduced several years ago, shows how particles of a specific size / density combination are concentrated by orders of magnitude in weak nebula turbulence. The theory makes specific predictions as to the relative abundance distribution of the concentrated particles. Predictions of the shape of the size distribution are in very good agreement with observed particle size distributions in primitive chondrites, thus revealing the fingerprints of TC. We developed a multifractal theory to predict the magnitude of turbulent concentration at much higher Reynolds numbers than achievable numerically, but the concentration factor can be so large that the local particle mass density can exceed that of the gas, and the feedback effect of the particle phase on damping the gas turblence must be considered before further modeling efforts can proceed. To better understand the effects of heavy mass loading on turbulence and TC, we are developing a cascade model of the process which is capable of reproducing the way concentrations of particles emerge as energy flows down the turbulent cascade, or inertial range. The cascade model is parametrized by partition functions or “multipliers” which are only statistically defined, but whose probability distribution function can be fit to our numerical results for mass-loaded turbulent fluids. That is to say, the multipliers appropriate for densely particle-enriched regions where the turbulent kinetic energy and / or vorticity might be damped, could be different from the multipliers in “normal” regions where mass loading is negligible. We are now determining the dependence of these multipliers on the local gas and / or particle density properties, making extensive use of new runs of a scalar field particle code (rather than the previous Lagarangian particle code) on the Ames Origins 2000 facility.

This year, Ames researchers also developed a scenario to help explain a new phenomenon found in chondritic meteorites by collaborators at Stanford and the University of Hawaii. The observation is an abundant class of Iron-Nickel metal grains with chemical and crystallographic properties that define their growth and cooling times simultaneously. The scenario developed visualizes a very hot, early, perhaps inner stage of the protoplanetary nebula, rather different from the environment in which more familiar chondrites form. In this dense, hot region, strong convection plumes rise towards the surface of the nebula, cooling and condensing small metal and silicate particles much as raindrops or hailstones condense in upwelling thunderstorm plumes on Earth. Some fraction of these objects are dispersed outwards to cooler regions before being downdrafted again to their destruction. While the theory is adequate to explain some properties of these unique meteorites, it is clear that deeply puzzling aspects remain unexplained. ❑

PLANETARY RINGS

J.N. Cuzzi, I. Mosqueira, M. Showalter, F. Poulet

In addition to the natural curiosity inspired by their exotic appearance, planetary rings present a unique dynamical laboratory for understanding the properties of collisional particle disks which might help us understand the accretion of the planets. Ames scientists are involved in a number of different aspects of planetary ring studies.

An ongoing Hubble Space Telescope (HST) program to observe the rings while they “open up” as seen from Earth over the last five years (see Figure 14) has produced over 100 images in a variety of filters. Analysis of these images using a newly developed surface scattering code has led us to the conclusion that the increasing redness of the rings which we found occurs as the angle between the Sun and Earth increases, is caused by unusually rough surfaces on the ring particles. This supports the concept that a ring “particle” is actually an ensemble or aggregation of smaller “particles” - a lumpy snowman-like of fractal structure. Further analysis will help us gain insight into how this structure varies across the rings, on scales that can never be observed directly (tens of meters or less). In addition, this modeling and analysis has established that the abrupt brightening of the rings as the Sun-ring-Earth angle gets very small, which has been previously ascribed to the disappearance of shadows, is more likely due to optical interference effects within the grainy surface of individual particles. This result helps us reconcile the brightening with dynamical expectations that the ring particles are collapsed into a fairly thin, dense layer due to inelastic collisions rather than being many particles thick as had been previously thought. We also hunted down a discrepancy between Voyager and HST color observations of the rings, tracing it to an incorrect Voyager calibration. We can now compare Voyager and HST color data directly, and find that the two data sets are in very good agreement from the standpoint of spatial color variations. We find that variations of color, which trace out particle compositional variations, vary with radius and ring opacity in a way that is quite unusual and will be addressed in future analysis.

The systems of large (and small) regular moons that orbit the gas giant outer planets have always been cited as “solar systems in miniature” but their own origin has remained a puzzle. One recent area of interest is the two outer Galilean moons of Jupiter (Ganymede and Callisto), which are of very similar mass and size, yet have very different internal structure. We have developed a two-stage accretion scenario, which postulates a long-lived, secondary accretion stage only for Callisto involving debris which forms in a very extended disk of material extending far out beyond the boundaries of the current satellite system. A small amount of gas remaining in this disk causes solid material to drift slowly inwards onto the outermost moon, accreting without providing much heating. In addition, a study of the thermal internal evolution of a realistic Callisto was carried out, including ice phase change boundaries and plastic ice convection, showing that a sufficiently slow accretion rate would indeed preclude melting of the icy component and prevent complete differentiation of the icy and rocky material.

Ames maintains the Planetary Data System’s Rings Node (http://ringmaster.arc.nasa.gov/), which archives and distributes ring data from NASA’s spacecraft missions and from Earth-based observatories. We now have on line the entire archive of images from the Voyager missions to the giant planets, with catalogs to help users find the images they need. We have also produced interactive search and geometrical visualization utilities to assist Cassini scientists in planning observations of the rings during the upcoming tour (2004-2008). Ames also provides the Cassini project with the Interdisciplinary Scientist for Rings and Dust, who chaired the Rings Discipline Working Group this year as it worked through initial ring science sequence planning. ❑

Figure 14: HST observations of Saturn since 1996, during which time the ring opening angle has increased from about 4 degrees to about 24 degrees. Data of this quality is available to us in over eight color filters. Voyager data is of higher spatial resolution, but only three filters are available - fortunately they are nearly identical to three of the HST filters.

VORTEX EVOLUTION IN A PROTOPLANETARY DISK

Sanford Davis

The theory that planets form from a thin disk of dust and gas was first proposed in the 18th Century and is now a generally accepted fact. The process by which planets actually emerge from this tenuous state is a subject of intense current study. Recent research points to vortex motion as a possible intermediary where dust particles are captured, concentrated, and finally accumulated by gravitational attraction. These mass accumulations gradually grow to kilometer-sized objects (planetesimals) and ultimately to full-sized planets. Assuming that the disk can support a turbulent flow, it was shown that vortices arise naturally and persist as long as turbulent energy is present. Other possibilities are that vortices arise from certain instabilities in the rotating disk or from external impacts of clumpy infalling gas. In either case, coherent vortices could lead to important and far-reaching processes in the protoplanetary disk.

A research study is underway to determine the effect of vortices on the wave structure in a typical disk which may also play a role in the planet-formation process. It is well known that discrete vortices in a sheared flow do not retain their coherence. This coherence time depends on the local shear rate, the strength, and the size of the vortex. During the shearing epoch, and depending on the nature of the medium, a vortex can emit a variety of wave systems. In this study, the equations of motion have been simulated using a high-resolution numerical method to track Rossby and acoustic/shock waves. Rossby waves are slowly moving waves of vorticity generated in flows with large-scale vorticity gradients. Acoustic waves are waves of expansion and contraction that occur in all compressible media. The protoplanetary disk is a rotating compressible gas with a radially variable rotation rate. It can support both wave systems.

A typical result from the simulation is shown in Figure 15. It is a sequence of snapshots of the perturbed vorticity defined as the difference between the total vorticity and the baseline flow. This baseline flow is a Keplerian flow (rotational velocity = const x (radius)$^{-1/2}$) and the initial vortex is shown in the third quadrant in Figure 15(a). The vortex becomes elongated about its initial location at $r = 4$ (blue-red streaks on the white circle in Figure 15(b)) and both inward and outward-bound counterclockwise spiral vorticity waves are spawned. The outward-bound waves evolve to an axisymmetric wave pattern (“circularization”) with shock waves (Figure 15(d)). It is interesting that the vortex-induced waves can induce a supersonic radial flow. Another wave system (Rossby waves) appears in the region $r < 10$. The shock waves are axisymmetric while the Rossby waves have a cosine angular dependence. Each wave system has a characteristic radial speed.

In follow-up work we will augment the numerical simulations with particle and/or granular gas models to examine the effect of these vorticity-induced waves on particle migration, accumulation, and (possibly) planetesimal formation. ❑

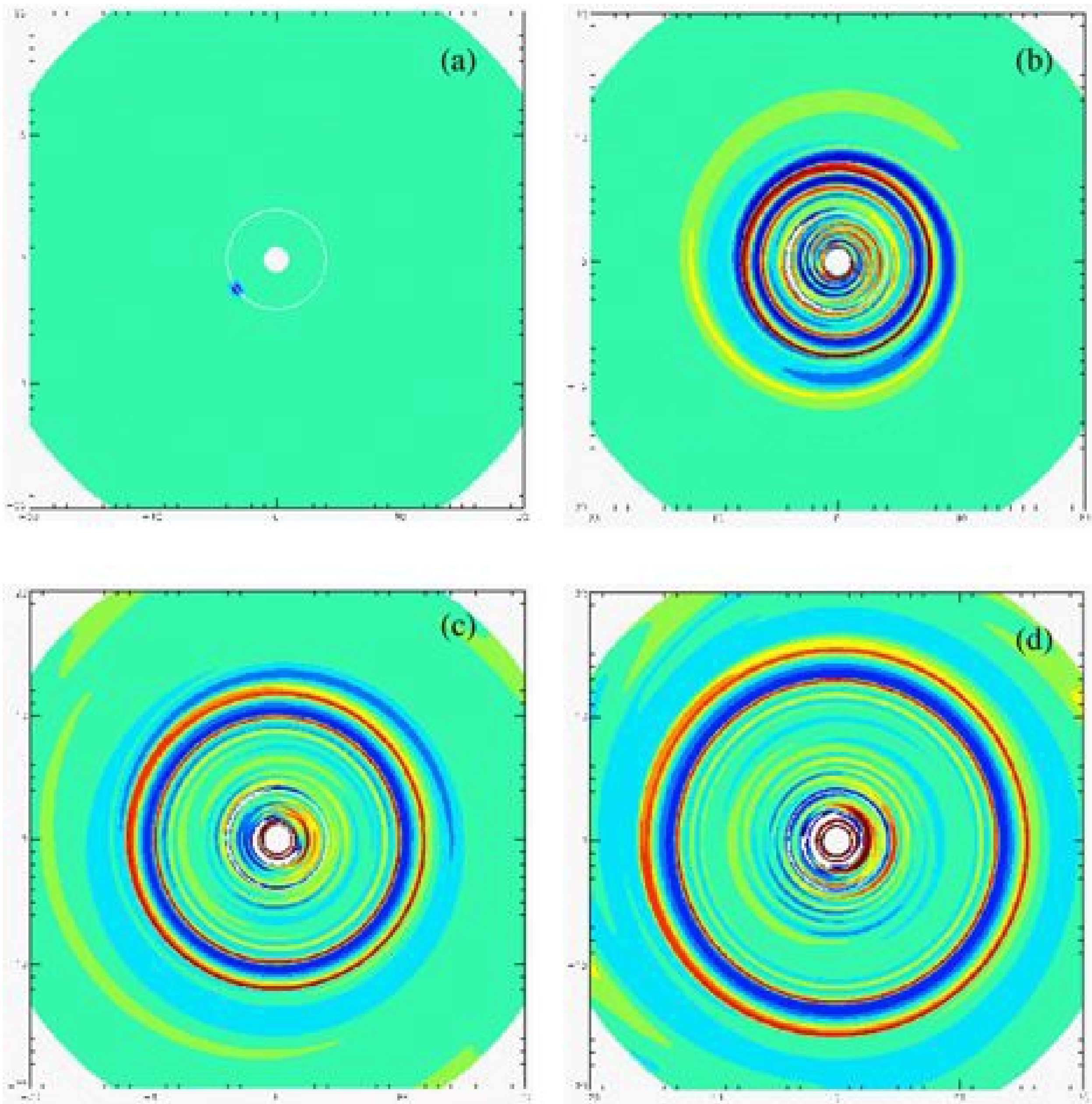

Figure 15: Perturbation vorticity bitmaps showing density (shocks) and Rossby waves. (a)-(d): 0, 16, 32, and 48 vortex revolutions respectively.

LIQUID WATER ON PRESENT DAY MARS?

Robert M. Haberle

Near surface environmental conditions on Mars today are generally considered inadequate to permit liquid water to exist in equilibrium with the atmosphere. Mean annual temperatures are about 50-60 K below the melting point, and mean annual surface pressures are very close to the triple point. Yet there are localized regions where for a few hours out of the day at the right time of year surface temperatures and pressures meet the minimum requirements for the existence of liquid water: pressures and temperatures above the triple point of water, but below the boiling point

That such conditions do in fact exist was determined using a validated General Circulation Model. The model predicts where and for how long liquid water could exist each Martian year. For pure liquid water the model predicts that there are five regions where liquid water might occur: between 0° and 30° N in the plains of Amazonis, Arabia, and Elysium; and in the Southern Hemisphere impact basins of Hellas and Argyre. The combined area of these regions represents 29% of the planet's surface area. In the Amazonis region, these requirements are satisfied for a total integrated time of 37 sols each Martian year. In the Hellas basin, the number of degree-days above zero is 70, which is well above those experienced in the dry valley lake region of Antarctica.

Whether liquid water ever forms in these regions depends on the availability of ice and heat, and on the evaporation rate. The latter is poorly understood for low-pressure CO_2 environments, but is likely to be so high that melting occurs rarely, if at all. However, even rare events of liquid water formation would be significant since they would dominate the chemistry of the soil, and would have biological implications as well.

Interestingly, these regions are remarkably well correlated with the location of impact craters that appear to have been filled with lakes at some time in the past. Approximately 86% of the more than 100 impact crater lakes lie within the model-predicted regions where conditions for liquid water are favorable. The lakes do not exist today, but appear to have existed within the last several billion years, and some appear to have existed within the last several hundred million years. The reason for this amazing correlation is not known. ❑

THE CENTER FOR STAR FORMATION STUDIES

D. Hollenbach, K.R. Bell, and G. Laughlin

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 2000 the Center worked together with researchers from the Arcetri Observatory (Florence, Italy) to hold an international workshop entitled “High Mass Star Formation: An Origin in Clusters” The weeklong workshop, held in Volterra, Italy, had approximately 175 attendees, and included an invited talk by D. Hollenbach on “Star Formation and the Fluctuating Ultraviolet Field in the Galaxy.”

One focus of the NASA Ames portion of the research work in the Center in 2000 involved the effect of ultraviolet radiation from young massive stars on the interstellar medium of a galaxy. The interstellar medium of a galaxy is the gas and dust which lie between the stars. Most of the gas is hydrogen; the dust mass is only about 1% of the gas mass. The gas and dust reside in various components, often characterized by the gas density in the component. The densest and coldest component is the molecular clouds; this component forms stars..Diffuse clouds are less dense than molecular clouds, they are primarily cold atomic hydrogen. The warm medium consists of neutral and ionized gas at very low density and relatively high temperature. The star formation rate in a galaxy depends on the rate at which molecular clouds can be formed, since only this component forms stars. The molecular clouds are thought to form by the coalescence of diffuse clouds into opaque, self-gravitating clouds. However, high rates of star formation leads to high populations of massive stars which radiate copious ultraviolet flux. The ultraviolet flux in turn heats up the diffuse clouds in the interstellar medium and transforms them into warm medium. Since warm medium is unlikely to form molecular clouds, the lack of diffuse clouds cuts off the supply of molecular clouds in a galaxy which cuts off the star formation rate. This then provides a self-regulation mechanism which controls the rate of star formation in a galaxy.

Another focus of the Ames portion of the Center research in 2000 involved a collaborative theoretical study of the conditions which determine whether a collapsing molecular cloud core of gas and dust gives rise to a single star surrounded by planets or to a binary star system. This work focused on the realization that the molecular cloud cores that precede star formation can have equilibrium configurations that are non-axisymmetric (lopsided). An analytical study carried out by the Center reported on the discovery and the properties of a sequence of these unusual egg-shaped equilibrium configurations. The analysis shows that these configurations can collapse in a way that may naturally produce either binary or single stars, depending on the initial degree of distortion.

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). ❏

THE FORMATION AND DYNAMICS OF PLANETARY SYSTEMS

Gregory Laughlin

In the past year, progress was made in a number of areas bearing on the overall problem of planetary systems formation and evolution. Specific topics of research have ranged from the earliest stages of star formation through the long term fate of the Earth, and are described in four peer-reviewed research papers.

In the present-day solar system, the sun contains 99.9% of the mass, whereas the planets contain the bulk of the system angular momentum. The clouds of gas and dust which collapse to form star-planet systems, however, are essentially in uniform rotation. One of the major unsolved puzzles in the theory of star and planet formation thus involves the detailed mechanism by which mass is transported inwards onto the protostar while angular momentum is simultaneously pushed outwards. It is believed that spiral gravitational instabilities play a key role in eliciting angular momentum transport, but a full description of how spirals grow and operate on a global scale (i.e. throughout the entire protoplanetary disk) is not understood. Considerable theoretical progress was made in this area by performing a stability analysis of idealized singular isothermal disks. This research, carried out and published in collaboration with researchers at UC Berkeley, Arcetri (Italy), and UNAM (Mexico), has clearly explained the role of the co-rotation amplifier in allowing spiral waves to grow. This in turn gives us a clearer theoretical picture of the very earliest stages of star and planet formation.

A second line of inquiry has developed a way to constrain the conditions under which our own solar system formed. The outer giant planets in our solar system all have nearly coplanar, circular orbits. This orderly configuration indicates that the Sun and the planets have always existed in relative isolation. Had another stellar system passed within several hundred astronomical units of the Sun, gravitational perturbations would have scattered the outer planets (particularly Neptune) into highly eccentric, inclined orbits. An extensive set of Monte-Carlo star-planet scattering calculations has shown that the solar system likely formed in an aggregate containing fewer than 1500 stars, and thus was not born in a dense stellar cluster (resembling, say, the Trapezium region in Orion). Primitive meteorites, however, contain daughter products of extinct radioactive elements which have half lifes of one million years or less. In order to explain the presence of such short-lived isotopes in meteorites, it has been proposed that either (1) the pre-solar nebula was enriched by a nearby supernova explosion, or alternately that (2) X-ray flares associated with the nascent sun were able to create radioactive atoms via processes such as spallation. The new research strongly favors scenario (2), since the presence of a nearby supernova would imply that the sun formed in a very massive aggregate of stars, and this possibility is effectively ruled out by the Monte-Çarlo calculations.

A third focus of the research effort examined the emerging correlation between high stellar metallicity and the detected presence of an extrasolar planet. Now that more than 70 extrasolar planets have been found, it is possible to evaluate the emergence of statistical trends. An analysis of volume-limited samples of stars in the solar neighborhood demonstrated that stars with metal content >50% higher than solar are 10 times more likely to harbor a short-period planet than the average star in the solar neighborhood. This finding can be exploited to find extrasolar planets with less effort, thus saving large amounts of time on instruments such as the Keck Telescope. A catalog of 200 highly metal-rich stars was compiled, and within 6 months, 5 planets have been detected in this catalog. Two were found by the Marcy group, two were found by Swiss researchers, and one was found by Ames researchers (HD 20675b, to be confirmed and announced in Fall, 2001). ❑

STABILITY OF UPSILON ANDROMEDAE'S PLANETARY SYSTEM

Jack J. Lissauer, Eugenio Rivera

The objectives of this project are to study the dynamical properties of planetary systems that are consistent with the observational data on the three-planet system orbiting the nearby main sequence star Upsilon Andromedae. We find that systems with the planetary masses and orbital parameters that provide the best fit to stellar radial velocity observations made at Lick observatory through either February 2000 or July 2000 are substantially more stable than systems with the parameters originally announced in April 1999. Simulations using the February 2000 parameters are stable for planetary masses as much as four times as large as the observational lower bounds (which are obtained by assuming that the Solar System lies in the orbital plane of the Upsilon Andromedae planetary system). In relatively stable systems, test particles (which can be thought of as representing asteroids or Earth-like planets that are too small to have been detected to date) can survive for long times between the inner and middle planets as well as several astronomical units or more exterior to the outer planet, but we could find no stable orbits between the middle and outer planets. ❑

THE ORGANIC REFRACTORY MATERIAL IN THE DIFFUSE INTERSTELLAR MEDIUM: MID-IR SPECTROSCOPIC CONSTRAINTS

Yvonne J. Pendleton and Louis J. Allamandola

Through an analysis of the 4000 to 1000 cm^{-1} (2.5 to 10 micron) region of the spectrum of diffuse interstellar medium (DISM) dust compared with the spectra of thirteen laboratory produced chemical candidates which serve as analogs to the interstellar material, we have found that the organic refractory material in the diffuse interstellar medium is predominantly hydrocarbon in nature, possessing little nitrogen or oxygen, with the carbon distributed between the aromatic and aliphatic forms. Long alkane chains $H_3C\text{-}(CH_2)_n$- with n much greater than 4 or 5 are not major constituents of this material.

Spectral analysis of the DISM allows us to place significant constraints on the likelihood of the proposed materials to be present in the diffuse interstellar medium. The spectra of candidate materials are evaluated using four spectral characteristics based on the interstellar data. Comparisons to laboratory analogs indicate the DISM organic material resembles plasma processed pure hydrocarbon residues much more so than energetically processed ice residues, which were previously thought to be relevant analogs. This result is consistent with a birth site for the carrier of the 3.4 micron band in the outflow region of evolved carbon stars, rather than in the icy mantles of dense cloud dust.

The organic signatures of extragalactic dust, carbonaceous chondritic material, and E. coli bacteria have also been compared because these have been discussed in the literature as relevant to the diffuse interstellar medium. The organic material extracted from the Murchison carbonaceous meteorite and the spectrum of E. coli bacteria reveal spectral features in the 5-10 micron region that are absent in the DISM. Although the presence of unaltered circumstellar components in the Murchison meteorite has been established through several lines of evidence, it is unclear whether or not the aliphatic component which gives rise to the 3.4 micron band is in that category. Considering the complete 2-10 micron wavelength region, there is no spectral evidence for a biological origin of the 3.4 micron interstellar absorption band. The similarity of the aliphatic CH stretch region of dust from our own galaxy compared with that of distant galaxies suggests that the organic component of the ISM is widespread and may be an important universal reservoir of prebiotic organic carbon. ❑

CRATERING RATES ON SYNCHRONOUSLY ROTATING SATELLITES

Kevin Zahnle and Paul Schenk

Impact cratering of synchronously-rotating satellites is expected to occur faster on the leading hemisphere than on the trailing hemisphere. This occurs because the satellite's orbital velocity around the planet is generally large compared to the space velocities of comets and asteroids. The relationship between comets and moons is broadly akin to that between flies and windshields. As it is with cars, the predicted asymmetry is large, with cratering rates at the apex of motion (the center of the leading hemisphere) typically 30-80 times greater than at the antapex. However, the expected asymmetry is at best poorly expressed on actual satellites, with the alarming exception of Triton, where the observed asymmetry is apparently too great. The failure to observe the seemingly inevitable suggests that some of these satellites have led, and may still be leading, interesting lives.

This study used a suite of Monte Carlo simulations to better determine how cratering rates vary across the surfaces of synchronous satellites. The method generates orbits randomly from ancestral distributions that arguably are isotropic, or nearly so; assign to each orbit an impact probability and to each a possible impact site and appropriate crater diameter; while also allowing practical treatment of many effects that would be dauntingly difficult to treat analytically. An empirical fit to the suite of numerical experiments is that the cratering rate

$$\dot{N} \propto \left(1 + \frac{v_{orb}}{\sqrt{2v_{orb}^2 + v_\infty^2}} \cos\beta\right)^{2.0+0.47\gamma}$$

where v_{orb} refers to the circular orbital velocity of the satellite and v_{∞} refers to the characteristic encounter velocity of the ecliptic comet with the planet; the angle β is the angular distance measured from the apex of motion; and the parameter g is the power law exponent describing the assumed cumulative size distribution of the impactors, $N(>d) \propto d^{-\gamma}$, where d is diameter. The expression works well for 1<γ<4; real solar system populations typically have 1.5<γ<3.

As noted above, the predicted cratering asymmetries are not seen in fact. Most synchronous satellites are effectively saturated with impact craters, for which no signature of a leading/trailing cratering asymmetry is to be expected. The three interesting exceptions are Ganymede and Europa, moons of Jupiter, and Triton, chief moon of Neptune. Europa has few impact craters and no obvious leading/trailing asymmetry. But this is not surprising, because Europa's icy shell is decoupled from the interior by a liquid water ocean: it would be relatively easy for the shell to rotate nonsynchronously. Ganymede is a more interesting case. Careful analysis reveals that Ganymede does preserve a four-fold asymmetry between fore and aft. This is much less than the 60-fold asymmetry expected but in the right direction; a possible interpretation is that Ganymede once rotated nonsynchronously but does so no longer. This in turn implicates a once thicker liquid water ocean for Ganymede, a conclusion in harmony with other clues that Ganymede was once much more like Europa than it is now.

Finally, there is Triton. Triton revolves in a retrograde orbit around Neptune. It appears to be a captured comet that melted as its orbit tidally evolved from a highly eccentric ellipse to a circle. Triton has very few craters. Its surface is obviously geologically young, probably no older than Europa's. Essentially all of its impact craters are on its leading hemisphere. In particular, a lack of craters near β=90° appears to be real, as this region (facing Neptune) was the part of Triton seen best by the Voyager 2 spacecraft. This cratering pattern is too asymmetric to be accounted for by comets or other objects that orbit the sun. Required rather are objects in prograde orbit around Neptune. Such objects would strike Triton mostly head-on, and the resulting craters would be mostly confined to the leading hemisphere. The origin of the implied swarm of prograde, Neptune-orbiting debris is an open question. The alternative explanation is that Triton has been capriciously resurfaced so as to look to us, from the one viewpoint of the Voyager 2, as if it had run face-first into a swarm of debris. ❑