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We report on a recent comprehensive and quantitative reassessment of the hazard posed by Near-Earth Objects (NEOs). This hazard originates from three distinct impact-related phenomena. We estimate, in the mean, 60(+45/-25) fatalities per year from direct blast effects, 180(+200/-120) people displaced per year from impact tsunami inundation, and 1000(+2050/-700) fatalities per year from global climatic disruption. Of these hazards, the global threat is largely associated with impacts by kilometer-plus diameter objects. These larger objects are far fewer and much easier to discover than the sub-km objects that are primarily responsible for the blast and tsunami risks. We find as a result that current survey efforts are making substantial progress in reducing the global hazard, in terms of fatalities per year, and should retire over 90% of it before 2008, but that little progress can be expected in removing the hazard from sub-km impactors. By 2008 the remaining global hazard will be on par with the remaining sub-km hazard and a more capable survey will be required to preserve momentum in NEO hazard retirement.

P51E-02 0935h INVITED

A Study to Determine the Feasibility of Extending the Search for NEOs to Smaller Limiting Diameters: Report of a NASA Science Definition Team

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In 1998, NASA formally commenced efforts toward the goal of finding and determining the orbits of at least 90% of all near-Earth asteroids with diameters 1 Km or larger by 2008. The 1 km diameter metric was chosen after considerable study indicated that an impact of an asteroid greater than 1 km would likely cause a worldwide catastrophe and could potentially result in worldwide damage up to and including extinction of the human race. The NASA commitment has resulted in the funding of several focused asteroid search efforts that are making considerable progress toward the 90% by 2008 goal. To date, more than 50% of the expected population of these large asteroids capable of passing near the Earth has been discovered and the discoveries continue at a high rate. While the current goal covers the larger objects, which could cause global devastation, it is silent on the much more numerous smaller objects (between 50 meters and 1 km diameter) that could cause local or regional damage should they impact. Given the significantly larger population of Near Earth Asteroids (NEAs) with decreasing diameter, it is much more likely that civilization will experience the impact of an asteroid smaller than 1 km than a larger event. In addition, the public and the science community are beginning to see more information on objects with smaller diameters. Because the current asteroid survey programs are designed to find the "large" threatening objects, they now search a large enough portion of the sky each month that many smaller objects are found as well. These detections are expected, and should be viewed as an indication of the increasing capabilities of the search programs; however, in some cases the discoveries have been interpreted by the press and public as surprising and threatening. Since the existing search programs are making good progress toward meeting the current goal, given the emerging discussion of smaller objects it is natural to ask what, if any, action should be taken to catalogue or warn against potential impacts of objects smaller than 1 km in diameter. From August 2002 to June 2003, NASA commissioned a Science Definition Team to develop an understanding of the threat posed by smaller objects and to assess methods of detecting them and providing warnings of any potential impacts. The Team provided recommendations to NASA and outlined an executable approach to addressing any recommendations made. Specifically, the team was chartered to address the following questions: 1. What are the smallest objects for which the search should be optimized?
2. Should comets be included in any way in the survey?
3. What is technically possible?
4. How would the expanded search be done?
5. What would it cost?
6. How long would the search take?
7. Is there a transition size above which one catalogs all the objects, and below which the design is simply to provide warning? The Team has conducted an in-depth analysis of the asteroid impact hazard and methods for characterizing the risk by discovering and cataloguing the potentially hazardous asteroid population. A cost/benefit approach was used to analyze the effectiveness of a broad range of search methods and technology and to provide answers to the seven specific questions stated above. *This work was sponsored by NASA under Contract F19628-00-C-2002. "Opinions, interpretations, conclusions, and recommendations are those of the author and are not necessarily endorsed by the United States Government."

P51E-03 0950h INVITED

Beyond Spaceguard: Steps Toward Protecting Planet Earth, and Stepping Stones on the Path to Exploration

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Asteroids and comets are not well understood, but their hazard is mitigable if we take time to learn their structural mechanical properties, and in turn how to divert them (if we have secured adequate lead time) or to disrupt them if not. NASA has already taken a primary role in the scientific exploration of near-Earth objects, or NEOs. Because there is no central entity assigned the task of NEO hazard mitigation, it was recently recommended by a major scientific workshop (see http://www.noao.edu/meetings/mitigation) that NASA, guided and aided by close international cooperation, assume a leadership role in quantifying the population and physical diversity of near-Earth objects that may collide with our planet. While it has acquired political and societal impetus, NEO science is fundamental solar system exploration. Beyond posing a threat, these building blocks of planets record the solar system's origin and evolution, offer potential resources for solar system exploration, and have been a critical component of terrestrial biology. It is therefore natural that mitigation technology be rooted in fundamental planetary exploration, and in the coming decades the paths may be identical. Techniques for this exploration will be presented, and the fruits of knowing how to manipulate a dangerous asteroid will be described.

P51F MCC: 2000 Friday 1020h

The Young Solar System II *(joint with NG)*

Presiding: **L W Esposito,** Laboratory for Atmospheric and Space Physics, University of Colorado**; R Canup,** Southwest Research Institute

P51F-01 1020h

Time and Length Scales for Planetary and Satellite Gas Disk Clearing

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Observationally, the maximum ages of T Tauri stars that show evidence for disks is $\sim 10^6 - 10^7$ years (Strom et al. 1989). On the other hand, a time of $10^6 - 10^7$ years is needed for giant planet formation through core accretion depending on gas opacity (Pollack et al. 1996; Hubickyj, private communication). One approach to satisfy these constraints involves matching the planetary formation timescale to the unrelated timescale of disk clearing due to turbulent viscosity. In this model, the above agreement of timescales is a coincidence. In contrast, Goodman and Rafikov (2001) considered the possibility that the acoustic waves launched by small (a few Earth mass) planets introduce an effective viscosity that clears the disk in the required timescale. However, such objects are likely to drift in an be lost due to Type I migration (Ward 1997) before the gas disk (where most of the angular momentum of the system is stored) evolves. Mosqueira and Estrada (2003b) (in the context of satellites, but the same argument would apply to planets; see Mosqueira and Estrada, this conference) advanced a related mechanism involving those objects large enough to stall and open a gap in the disk (Rafikov 2002). Here we investigate the possibility that the tidal torque of planets and giant planet satellites clears the gas disk in which they formed in timescales of $\sim 10^6$ years and $\sim 10^5$ years respectively. Also, such a gas clearing mechanism may only be effective to a distance possibly connected with the region where solids are stranded following gas dissipation ($\sim$ 40 AU at the edge of the Kuiper belt for the solar system, and the region where regular satellites are found for satellite systems), i.e., outside this region gas would linger and rocky bodies formed there would be removed by gas drag or tidal torques. This work was supported by the National Research Council and a NASA PGG grant.

P51F-02 1035h

Planet Embryos in Vortex Wombs

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One of the enduring puzzles in the formation of planetary systems is how millimeter-sized dust grains agglomerate to become kilometer-sized, self gravitating planetesimals, the "building blocks" of planets. One theory is that the dust grains settle into the mid-plane of the protoplanetary disk (thin, cool disk of gas and dust in orbit around a newly forming protostar) until they reach a critical density that triggers a gravitational instability to clumping. However, turbulence within the disk is likely to stir up the dust grains and prevent them from reaching this critical density. A competing theory is that dust grains grow by pairwise collisions, forming fractal structures. It is unclear, however, how robust such structures would be to successive collisions. A new and exciting theory is that vortices in a protoplanetary disk may capture dust grains at their centers, "seeding" the formation of planetesimals. We are investigating the dynamics of 3D vortices in protoplanetary disks with a parallel spectral code on the Blue Horizon supercomputer. Some of the lingering questions we address are: What is the structure of 3D vortices in a protoplanetary disk? Are they columns that extend vertically through the disk, through many scale heights of pressure and density? Or are they more "pancake-like" and confined to the mid-plane? Are the vortices stable to small perturbations, such as vertical shear? Are 3D vortices robust and long-lived coherent structures? Do small vortices merge to form larger vortices the way vortices on Jupiter do?

P51F-03 1050h

Is Hydrodynamic Escape from Small Orbit Extrasolar Planets Fast or Slow? New Solution of Hydrodynamic Equations and Its Applications

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Hydrodynamic escape has important applications in the formation and evolution of planetary atmospheres. Solutions to the time-independent hydrodynamic equations are difficult to find due to the existence of a singularity point. New method to solve time-dependent hydrodynamic equations is developed and validated. When applied to extrasolar planets under intense radiation from parent stars (HD209458b), we tried to answer the following 2 questions: 1) are these planets undergoing hdyrodynamic escape; 2) how fast are they losing their mass. Simulation results are compared with observations.

P51F-04 1105h

TIDAL DISRUPTION OF PRIMORDIAL PLANETARY BODIES

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Introduction: We evaluate the tidal disruption of planetary embryos from dynamical, geophysical and meteoritical perspectives. It is widely believed that the present population of asteroids (and thus most meteorites) derive from material that survived intense (99.9%) mass depletion in the protoplanetary disk between Earth and Jupiter. According to this scenario, about one in a thousand bodies survived scattering, close encounters and mergers to become the ancestors of the present main belt and the precursors of meteorites. Close tidal encounters were inevitable, because a deep Roche encounter *near* a growing planet is about as likely as accretion *onto* the same planet. **Process and Implications:** This "long march" took its toll on the survivors, which begat the present asteroids and meteorites. Specifically, for very weak bodies (rubble piles, or those with deep regolith) and for gravity-dominated bodies with viscosity less than ($\nu_{lim} \sim \sqrt{G}\rho^{3/2}R^2$ 10^{11} poise for 100 km radius), an encounter with periapsis $< 0.5R_{roche}$ results in catastrophic removal of half the original mass [1]. Even partially molten silicate bodies have sufficiently low viscosity to undergo disruptive tidal deformation. Abundant mantle water at this early phase lowers viscosity and enhances disruption energetics. Our dynamical calculations show that a few percent of the surviving primordial asteroids underwent catastrophic tidal disruption during encounters with the transitory main-belt embryos [c.f. 2], if a majority were either partially molten or rubble piles during the first 3 Ma. Melting and differentiation of asteroid parent bodies took place during this time [3], so planetary mantles may have been tidally stripped in a process that may have been as common as giant collisions. Tidal disruption produces a symmetric chain of fragments. In models of tidal disruption [1], differentiated bodies pull apart into one or more central cores almost devoid of mantle rock, flanked by core-free bodies of diminishing size away from the center. The process need only occur a few times to resolve dilemmas associated with iron and stony-iron meteorites and their parent bodies. **Thermodynamics:** Tidal disruption induces pressure-release melting and brings core and mantle material into sudden close association across wide surface area. Silicate and iron mix as the core and deep mantle are brought, in the course of hours, to low pressure. Melts degas abruptly and generate turbulence. The shock-free disruption and mixing of parent materials can explain highly varying cooling rates within a single meteorite taxonomic type, and mantle-removal of classic M-type asteroids such as Psyche and Kleopatra without invoking intense impact bombardment that would have easily removed Vesta's crust. We also contemplate a planetary precursor phase where accretion and gravitational equilibrium are sporadically upset by pressure release events and violent degassing. **References:** [1] Asphaug, E. and W. Benz 1996, Icarus 121, 225-248. [2] Morbidelli, A. et al. 2000, MAPS 35, 1309-1320. [3] Keil, K. 2000, P&SS 48, 887-903.

P51F-05 1120h

Are Giant Planet Satellites Mini-solar Systems?

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The regular satellites of Jupiter and Saturn exhibit a number of characteristics strongly suggestive of formation in a thin (aspect ratio $H/r \sim 0.1$) circumplanetary gas disk (Mosqueira and Estrada 2003a). Also, the mass ratio of the largest satellites to the primary $\mu \sim 10^{-4}$ lead one to think of these satellite systems as scaled-down solar systems. Yet, the larger mass ratio for the giant planets to the primary $\mu \sim 10^{-3}$ appears to limit the usefulness of the planet-satellite analogy. If gap-opening determines the final size of at least Jupiter (Lin and Papaloizou 1993), then significantly smaller objects would be unable to truncate the disk. There are, however, at least two significant difficulties with this point of view. First, the non-linear or thermal gap-opening criterion (Lin and Papaloizou 1993) does not yield a Jupiter mass. Second, the migration timescale due to planet-disk interactions (Ward 1997) is too fast for the formation of giant planets through the core accretion process (Pollack et. al 1996) despite recent work which has lengthened it by up to an order of magnitude (Tanaka et al. 2002, D'Angelo et al. 2002, Bate et al. 2003). An alternative viewpoint has accretion taking place in a weakly turbulent disk, and the survival of both planets and satellites a direct consequence of gap-opening. In this view at least the largest satellites (Mosqueira and Estrada 2003b) and planetary cores ($\sim 10M_{\oplus}$; Rafikov 2002) were able to open gaps in the disk. However, because the waves launched by such pertubers do not become non-linear immediately, the gap begins to form a distance away from the perturber given by the shocking length of acoustic waves (Goodman and Rafikov 2001; Rafikov 2002). Estrada and Mosqueira (2003) have suggested that the annulus of material adjacent to the proto-planet that immediately precedes the runaway gas accretion phase (Pollack et al. 1996) can be used to provide the mass needed to lead to the formation of a giant planet. If so, the dilemma posed by Type I migration (Ward 1997) is mitigated, and the analogy between satellites and planets gains currency. It is possible to argue that an alternative solution to this issue may involve lowering the migration rate even further, but one should keep in mind that slower migration might allow even smaller objects to open gaps. Here we look into the issues raised by this annulus of material in the satellite context, and argue that it may not prevent satellite survival. This work was supported by a NASA PGG grant and the NRC.

P51F-06 1135h

Constraints on the Galilean protosatellite disk from Jupiter's obliquity

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The obliquity of Jupiter is only 3 degrees. Although a small obliquity seems consistent with its gas accretion phase, there are processes that could have altered it after its formation. The current spin axis precession period of Jupiter is $\sim 4.5\langle\ 10^5$ years due mostly to the solar torque exerted on the Galilean satellites (*e.g.,* Ward 1975; Harris and Ward 1982; Tremaine 1991). However, this would have been up to $\sim O(10^2)$ shorter if a minimum mass pre-satellite disk had been present. If this disk were subsequently photoevaporated after the solar nebula itself was dissipated, Jupiter's precession frequency would have drifted through one of the mutual orbital precession frequencies of Jupiter and Saturn, *i.e.,* the so-called ν_{16} that describes the precession of their orbital nodes with a period of $P_{16} \sim 5\langle\ 10^4$ years. An adiabatic passage could generate an obliquity of 25.6 degrees (*e.g.,* Henrard and Murigande 1987). This could be avoided if passage is fast enough to be non-adiabatic, in which case the final obliquity is rate dependent (*i.e.,* Ward *et al.* 1976). If α_S denotes the spin axis precession parameter, which is a function of the circumplanetary disk and satellite masses in addition to the Jovian oblateness (*e.g.,* Ward 1975), and we define $\Omega_{pole}\{\Delta_S/\Delta_S$ and calculate its value to yield an obliquity comparable to Jupiter's current obliquity, we obtain $O(10^5)$ years. But since the change in α_S would be due primarily to dissipation of the protosatellite disk, we conclude that a disk life much longer than this is not consistent with Jupiter's low obliquity spin state. Alternatively, the pre-satellite disk may have been of insufficient mass to cause passage through the Jupiter-Saturn resonance (*e.g.,* Canup & Ward 2002).

P51F-07 1150h

Accretion of the Galilean Satellites

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We consider a scenario in which the Galilean satellites form within a circumplanetary accretion disk produced during the end stages of gas accretion onto Jupiter. In Canup and Ward (2002), we identified disk conditions compatible with three main constraints on satellite formation: 1) disk temperatures low enough for ices in the general region of Ganymede and Callisto, 2) satellite accretion times of 10^5 years or more for consistency with an incompletely differentiated Callisto, and 3) satellite survival against inward orbital decay due to disk density wave torques. We found that such conditions can be simultaneously satisfied in a disk produced by a very slow inflow of gas and solids to Jupiter, with an implied rate of inflow during the satellite formation era of less than a Jovian mass per five million years. A similarly slow inflow rate is implied by the requirement that Jupiter had contracted to a radius smaller than the orbits of the Galilean satellites by the time of their formation (Magni and Coradini 2003). A slow inflow rate yields a much lower steady-state gas surface density than is implied by augmenting the mass of the current satellites to solar composition as has been done previously, and instead yields a "gas-starved" protosatellite disk. This implies that satellite accretion occurred in a relatively gas-free environment, and at a rate regulated by the inflow rather than by the local orbital period. Here we consider the ramifications of this gas-starved disk model for the accretional histories of the Galilean satellites, including implications for their individual growth times, and impact and migration histories.

P51F-08 1205h

ESTIMATING THE EFFECTIVENESS OF COSMIC RECYCLING IN THE HISTORY OF PLANETARY RINGS AND RING MOONS

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Strong evidence implies that small moons near the giant planets, like the asteroids they resemble, are best described as piles of rubble. These re-constituted small bodies are the source of material for planetary rings. Previous calculations by Colwell and Esposito show the short lifetimes for such moons imply that we are nearly at the end of the age of rings. Does this philosophically unappealing result truly describe our solar system and the rings that may surround giant extra-solar planets? Calculations from a Markov chain model explicate how inclusion of recycling can lengthen the lifetime of rings and moons. Non-linear effects not previously considered are also important. We apply our results to Saturn's F ring and to Neptune's ring arcs.

P52A MCC: Level 1 Friday 1330h

Impact Cratering Posters

Presiding: **D H Abbott,** Lamont-Doherty Earth Observatory; **B A Karlow,** Lawrence Livermore National Laboratory

P52A-0471 1330h POSTER

MARID Suite Minerals in Ejecta Layer from Ewing Crater (Core PLDS-111P) in the Central Equatorial Pacific

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The Ewing crater is a 150 km diameter impact crater located between the Clarion and Clipperton fracture zones in the central equatorial Pacific about 10 degrees east of the longitude of Hawaii. The crater is early part of the late Miocene in age (7-11 Ma). The typical excavation depth of impact craters is about 1/10th of their diameter. Thus, the Ewing crater should have excavated down to 15 km, well below the oceanic Moho at 6 to 7 km depth. We test the impact origin of the Ewing crater by looking at the composition, morphology, and X-ray diffraction characteristics of minerals in the top part of core PLDS-111P. These minerals appear with abundant impact spherules and microtektites, at least 40 total in a 6-gram sample. We found high Ti amphibole with etching on the ends of the crystals. Etching of crystal terminations is characteristic of placer deposits and impact deposits. High Ti amphibole is characteristic of the MARID suite (Mica (Phlogopite)-Amphibole-Rutile - Ilmenite-Diopside). We have also found phologopitic mica, ilmenite and diopside in our sample. We did not find rutile, but rutile can be absent in the MARID suite. We have also found zircon and apatite, both of which are accessory minerals of the MARID suite. The MARID suite is confined to areas where the mantle has been heavily metasomatized. Previously documented occurrences of the MARID suite are from kimberlites and veins in metasomatized periodotites. Because the oceanic crust beneath the Ewing crater is Eocene (34-55 Ma) in age, kimberlites are unlikely to form. The most likely alternative is that the MARID suite minerals are from mantle that was metasomatized by normal processes of hydrothermal alteration within the oceanic plate. This metasomatized material was brought to the surface by excavation of the suboceanic mantle during the impact of the bolide that formed the Ewing crater. The impact hypothesis is supported by microcraters (10 to15 microns in diameter) found in phlgopite and ilmenite, similar to ones on surfaces of associated microtektites.