Origins of Solar Systems
Abstracts of selected proposals.
(NNH09ZDA001N-SSO)

Below are the abstracts of proposals selected for funding for the Origins of Solar Systems program. Principal Investigator (PI) name, institution, and proposal title are also included. 132 proposals were received in response to this opportunity, and 38 were selected for funding.

Charles Alcock/Harvard-Smithsonian Center for Astrophysics
Revealing the outer solar system using occultations of stars.

The solar system extends far beyond the orbits of the major planets. It extends far beyond the known Kuiper Belt and the exciting, recently discovered Sedna. Most of what we know or believe about the outer solar system is inferred from observations of new, long period comets, or derived from computational simulations. These models suggest that there are vast reservoirs of small bodies in orbits with semi-major axes as large as 50,000 AU. These reservoirs are, for the most part, invisible to currently available detection techniques.

Objects in the outer solar system may be detected indirectly by searching for events in which an object briefly occults a bright star. We infer the number of objects from the rate of events, their sizes from the depths and durations of the events, and their distance from the diffraction fringes. These surveys are very challenging because of the low expected event rates, the brevity and shallowness of the events, and the rapid sampling needed.

Recent results indicate that the technologies needed for this work are becoming available. This team led the development of the most extensive survey to date: the Taiwanese American Occultation Survey, which has recently published its first results. We have also pioneered the use of a large telescope (the 6.5 meter MMT) for this purpose, and are developing a program to use the Pan-STARRS system for a new survey. This proposal seeks support for these ongoing efforts, for related theoretical work, and for some technology development for a major new survey system.

Phil Arras/University of Virginia
Magnetospheres of Hot Jupiters

Gas giant exoplanets in short-period orbits around their parent star -- the ``hot Jupiters'' -- are exposed to ionizing radiation orders of magnitude more intense than for solar system gas giants. Energetic photons absorbed at high altitude heat and ionize gas in the upper atmosphere. The upper atmosphere of one planet, HD 209458b, has already been observed by the Hubble Space Telescope. A new era of comparative studies of exoplanet upper atmospheres is about to commence with the renovated Space Telescope Imaging Spectrograph and the newly installed Cosmic Origins Spectrograph.

The density and pressure of ionized gas in the upper atmosphere is so low that magnetic field effects become important in determining the atmospheric structure. The PI and Co-PI propose to develop magnetohydrodynamic simulations of the upper atmosphere to determine the density and velocity profiles for the gas, and to assess the relative importance of open and closed magnetic field line regions. A microphysical model for the ionization state and level populations of important atomic species will be implemented in the simulations.

The models for upper atmosphere structure will be used as input for radiation transfer calculations to determine the orbital phase-dependent Lyman “alpha” flux. Our preliminary estimates find that Lyman “alpha” reflected off the planet, and Doppler shifted by its orbital motion, may explain the observed line profile for HD 209458b. Detailed Monte Carlo calculations of resonant scattering including redistribution in angle and frequency will be carried out to to better understand the line profile as a function of orbital phase.

Taken together, these two projects will develop a new interpretation of the Hubble observations of extrasolar planet upper atmospheres.

Travis Barman/Lowell Observatory
Understanding the Atmospheres of Hot Exoplanets

The objective of our proposed research is to better understand the atmospheric properties of hot, short period, exoplanets. In particular, we will study the nature of atmospheric temperature inversions along with the thermal and chemical properties of the day-night boundary. We will also explore the conditions under which photochemistry, vertical/horizontal mixing and clouds become important. The primary tool we will use is the PHOENIX model atmosphere code with which a variety of one-dimensional and three-dimensional (3D) radiative transfer models will be calculated. These models will allow us to understand the interplay between atmospheric phenomena by experimenting with a broad parameter space. The models will also be compared to existing and future observations of exoplanet atmospheres, providing the critical feedback of real data. We will use 3D temperature structures produced by general circulation models as input to our spectrum models. The incident stellar flux transmitted through planetary limbs of hot-Jupiters will also be used to compute the variation in planet radius viewed during transiting events (for those planets with edge-on orbits). These new models will provide an important bridge between dynamical models and current and future observations of hot-Jupiters, leading to valuable inferences on extrasolar planet metallicities and atmospheric dynamics. This research is directly related to one of Origins of Solar Systems key goals, ``to detect and characterize extra-solar planets".

Robin Canup/Southwest Research Insitute
Formation of planets and satellites

This proposal contains four tasks concerning the origin of planets and large satellites. In Tasks 1 and 2, we propose to model planetary accretion in a circumsolar disk produced

by infalling gas and solids during the collapse of the Sun's precursor cloud core. Nearly all prior models assume that disk formation was complete before planet accretion begins. However, we argue that accretion processes during disk formation can create conditions very different from those of the typically invoked minimum mass solar nebula (MMSN), which will be more conducive to planet formation and survival against Type I migration. We will self-consistently model the circumsolar disk's formation and the concurrent accretion of planets, without adopting an ad hoc MMSN initial disk. In Task 1, we model the accretion of solid protoplanets and cores, while in Task 2 we consider the subsequent gas accretion phase and the formation of gas giants. Task 3 addresses the origin of the Uranian satellites. A large impact is thought to have caused Uranus' 98° obliquity, and it has been proposed that the same event produced its protosatellite disk. We will simulate a Uranus-tilting impact and the evolution of a resulting circumplanetary disk subject to magnetohydrodynamic turbulence to determine if this mode of origin is consistent with the properties of the Uranian satellites. In Task 4, we will estimate the amount of water retained during impacts between terrestrial protoplanets and ice-rich embryos originating in the outer asteroid belt, which are believed to be a major source of water to the Earth and Earth-like planets. Existing accretion models assume 100% of the water delivered by such collisions is retained; however at relevant impact speeds, substantial vaporization and loss is expected.

Steven Charnley/NASA Goddard Space Flight Center
Isotopic Fractionation in Primitive Materials: Quantifying the Contribution of Interstellar Chemistry

We propose to continue studies of the contribution of interstellar astrochemical processes to the isotopic fractionation of nitrogen, carbon and deuterium measured in carbonaceous meteoritic material, interplanetary dust particles (IDPs), and cometary dust samples returned by the Stardust mission.We shall undertake a definitive and comprehensive theoretical treatment of the fractionation processes for each of these elements, eventually developing a chemical reaction network that includes all three. This will allow us to quantify the maximum degree of stable-isotope enhancement or depletion present in the interstellar progenitors, in specific molecular functional groups, which were subsequently processed into cometary and asteroidal material. We will evaluate the role of state-to-state chemical reactions in low-temperature ion-molecule chemistry as a source of fractionation. In the case of D and heavy nitrogen, we will investigate whether the molecular hydrogen ortho/para ratio is responsible for the pronounced correlations and anti-correlations between the their isotopic `hotspots' , as found in primitive materials. We will model in detail the spatial structure of the presolar core, where the most extreme isotopic enrichments can occur, thereby making predictions that will testable by astronomical observation. These models will include, for the first time, multi-isotope chemistry, both in static and collapse scenarios, and so will allow us to investigate the expected correlations between the fractionation of different elements in abundant interstellar molecules which are likely to play an important role in the subsequent chemistry of the young solar nebula.

These studies will uniquely delineate the available parameter space for astronomical contributions to isotopic fractionation in primitive Solar System materials. In this way, we should also be able to exclude various astrochemical contributions and hence identify where nebular chemistry may provide the best explanation. We will seek to provide explanations of the meteoritic and IDP data and identify possible correlations that can be sought in subsequent laboratory analyses. The proposed work is therefore complementary to much previous work where the formation environments of meteoritic material have been elucidated through nucleosynthetic signatures. When completed, and the results disseminated, the results from this project should aid interpretation of the expected scientific returns from Stardust.

Theoretical interstellar chemistry can provide fundamental information on the isotopic composition of the material initially available to the forming protosolar nebula. Realization of the project goals will provide a comprehensive and detailed summary of the range of fractionation patterns amongst the major volatile elements in specific functional groups within interstellar molecules. This will provide a point of reference for the comparison of laboratory sample analysis of extraterrestrial materials with the expected products of interstellar chemistry. The issues to be addressed in this proposal have been raised by the large and growing body of data obtained from laboratory analyses of extraterrestrial materials. The theoretical studies proposed here are also timely and relevant for the ongoing interpretation of the data obtained from samples returned by NASA's Stardust mission, future sample return from asteroids and comets, and for astronomical observations to be made by the recently-launched Herschel Space Telescope.

Ara Chutjian/Jet Propulsion Laboratory
Origins of Life's Building Blocks: Polyatomic Molecule Formation on Dust Grain Analogs at Superthermal Atom Energies

This proposal focuses on the chemical processes in protostellar regions that are catalyzed by dust grains and can lead to the formation of building blocks of bio-forming molecules through a new, experimental reaction channel involving fast, ground-state H and O atoms. Molecular formation with well-characterized beams of ground-state H and O atoms at surface impact energies tunable in the range 0.2-100 eV will be studied in the laboratory using dust grain analogs. Conditions in the presolar nebula will be simulated, from shock-heated regions; to cold, dark, UV-shielded molecular clouds such as Taurus, Perseus, Ophiuchus, and Lupus. JPL results in the previous proposal cycle have shown synthesis of CO_2 [by the reactions O+CO(s) and H+CO(s)], H_2CO [H+CO(s)], CH_3OH [O+CH4(s)], HCOOH [O+CH_4(s)], and CH_3CH_2OH [O+CH_4(s)]. The proposed work will focus on the formation of species including formic acid (HCOOH), ketene (CH_2CO), hydrogen cyanide (HCN), glycine (NH_2CH_2COOH), amines, aminoalcohols, and the development of sulfur chemistry (e.g., CS, SO, OCS, SO_2). Use of the Metropolis random-walk algorithm will continue to be made to unfold the temperature-programmed desorption (TPD) results in terms of mass-spectral fractionation ratios. The JPL group is

the first to apply this compelling algorithm to TPD analyses. In addition to identifying open reaction channels at superthermal collision energies, absolute reaction yields will be measured for reaction channels to form CO_2, H_2CO, and CH_3OH. The yields will be measured by H- and O-beam diagnostics using the photodetachment current as well as optical emission characteristics of each atomic beam. The open channels and their yields are important input parameters in cloud modeling codes. They allow one to assess the important of this new superthermal chemistry. In addition, laboratory results will make possible close comparisons to space observations (e.g., from Spitzer and Herschel Space Telescope data), ground-based observations, and to laboratory studies that use UV light, ions, and thermal-energy atoms to initiate a polyatomic chain of events.

This work is proposed to be conducted as Fundamental Research."

Jeff Cuzzi/Ames Research Center, NASA
Global redistribution of condensibles in the protoplanetary nebula

Primitive chondrite parent bodies apparently accreted over several Myr, in which time models and observations tell us the nebula gas itself evolved significantly. The extended range of radioisotope ages for primitive body formation can be explained if the nebula were weakly turbulent; in this environment decimeter-to-meter-size particles can grow fairly easily, and undergo substantial inward radial migration, before being destroyed by mutual collisions or evaporating in a warmer environment and escaping capture into any surviving solar system objects. This leads to a significant redistribution of the nebula condensibles relative to the evolving gas, and questions the validity of the popular concepts of "minimum mass nebula" and "local cosmic abundance". An important obstacle to understanding this evolutionary stage has been the unwieldy calculations required to model particle coagulation.

During this cycle, we completed and published our "moments method" by which particle coagulation modeling can be enormously accelerated by tracking only certain general properties of the particle size distribution. For instance, the first moment of the radius distribution provides the cross section for charge scavenging, of importance to magnetorotational instability (MRI) modeling; the second moment provides the effective area or opacity for radiative transfer; the third moment provides the typical particle mass, critical for transport by gas-drag-driven radial drift. This method can incorporate realistic particle porosities and variable sticking coefficients as functions of size and relative velocity, and can handle either turbulent or nonturbulent nebulae. We then developed and implemented a model for the next evolutionary stage, which more carefully tracks growth and drift of the small fraction of large (decimeter to meter) size objects that statistically escape collisional disruption to grow into "migrators" that can range long distances radially while potentially growing into stable, nondrifting "planetesimals".

We will merge these newly completed particle growth and evolution codes with existing global nebula evolution models to produce a realistic, but efficient, first-principles growth and transport model constrained only by particle strength and nebula properties. We will then focus on a few important, diverse, and timely applications: (a) the increase

of the surface mass density of solids available for primary accretion of planetesimals and ultimately planets, due to inward radial drift of solids from much larger mass reservoirs at large distances; (b) the growth and redistribution of solid particles in circumplanetary disks under a variety of initial conditions, based on existing models, as the precursor to satellite formation; (c) the production and global redistribution of isotopically homogenized silicates by cycling large amounts of drifting rubble through a silicate evaporation front when the nebula was young and hot; (d) the transport by drifting rubble of heavy isotopes of oxygen from outer solar system (or pre-nebular) ices, into the terrestrial planet region where they affect the isotopic composition of meteorites and even entire planets; and (e) the enhancement of C, N, S, and the noble gases Ar, Kr, and Xe in the atmospheres of Jupiter and (probably) Saturn by enrichment of the local nebula gas prior to its accretion onto the cores of the giant planets.

Steven Desch/Arizona State University
Chondrule formation in solar nebula shocks: Probing the conditions during chondrule formation and the sources of shocks.

Numerous petrologic, cosmochemical and isotopic measurements of chondrules, the igneous spherules found in abundance in chondrites, potentially can constrain physical conditions and processes in the forming solar system, but only if chondrule formation is well understood. Previous work by the PI (Desch & Connolly 2002) and his team, including studies funded a previous Origins of Solar Systems grant (Morris et al 2009a,b), have helped establish the viability of passage through shock waves in the solar nebula gas as the model for chondrule formation.

We now turn our attention to using models of chondrule formation to constrain the physical conditions in the solar nebula, especially chondrule densities and clumpiness and the sizes and sources of the shocks. Doing so will require a refinement of current shock codes, expanding them to 2 dimensions (cylindrical geometry), to account for variations in chondrule density parallel to the shock front, and to model parabolic bow shocks associated with eccentric planetesimals. We propose to take the Perseus code written by the PI and his research team (Ouellette et al. 2007) to study supernova-driven bow shocks around protoplanetary disks and adapt it to the problem of chondrule formation. The critical modification will be the addition of modules to calculate the radiation field in cylindrical geometry. We describe details of how this and other changes will be achieved.

We will apply this modified code to test 3 ideas about chondrule formation by shocks. 1.) Desch & Connolly (2002) hypothesized a correlation between compound chondrules and barred olivine textures because chondrules in clumps experience higher peak temperatures and faster cooling rates. But shock models assume uniform densities on scales of 10^5 km larger than the likely sizes of clumps, < 10^3 km, and this idea is not fully tested. 2.) Recent measurements of primary Na in olivine phenocrysts by Alexander et al. (2008) led them to conclude chondrule melts were in equilibrium with high partial pressures of Na, due to partial evaporation of chondrules in exceptionally dense clumps. We instead hypothesize that high vapor pressures result from total evaporation of

chondrules in dense clumps, with chondrules melted normally, in nearby regions of lower chondrule density being focused by shocks into the dense, vapor-rich regions. Our code will quantify and test this effect. 3.) Gravitational instabilities are one proposed source of shocks, but bow shocks driven by eccentric planetesimals are a very likely alternative. Proponents of the bow shock model hypothesize that chondrule cooling rates would match observational constraints, but this is untested.

Our modified code, which will test the above hypotheses, is highly relevant to NASA's Strategic Goals and Research Objectives, especially subgoals 3C and 3D, and to the goals of the Origins of Solar Systems program. The key to understanding the origin of our solar system is to put chondrule formation in its proper context.

Sarah Dodson-Robinson/California Institute of Technology
Modeling the Observational Signatures of Ice Lines in Protostellar Disks

Our project goal is to compute synthetic molecular line maps and velocity profiles of high-quality model T-Tauri disks. Our models will allow Herschel, ALMA and JWST observers to locate ice condensation fronts in protostellar disk midplanes and surface layers. Not only do ice lines demarcate the giant planet nurseries of today's young stars, their locations illuminate the underlying physics of protostellar disk evolution. Simply by finding and resolving two or more ice lines in a single disk, astronomers can directly measure four quantities that have heretofore been poorly (or not at all) constrained by observations: disk midplane temperature profile, turbulent viscosity, viscous diffusion timescale, and total disk mass. The HCN, CO and H_2S ice lines are particularly suited for direct detection because the molecules' low condensation temperatures place their ice lines at ~10 AU from 1 Myr T-Tauri stars. However, these ice lines must be detected through rare isotopologues since the isotopically normal ALMA transitions are optically thick.

ALMA, JWST and Herschel observers aiming to spatially or kinematically resolve protostellar disk composition will all require detailed models of gas and ice abundances as a function of radial and vertical location in the disk. For the isotopically normal molecules that will be targeted by JWST and Herschel (CO, H_2O, CH4), the chemical model is already in place. Our ALMA precursor science goal is to compute synthetic molecular line maps of model T-Tauri disks, (1) confirming that the CO, H_2S and HCN transitions we wish to observe have midplane optical depths less than unity and (2) calculating the abundance ratios between these trace isotopologues and H_2. We will expand our chemically evolving protostellar disk model (Dodson-Robinson et al. 2009) to cover C, H and O isotope chemistry in a range of star and disk masses.

This proposal clearly falls within two of the Origins of Solar Systems program categories, as stated within the NRA: Theoretical investigations related to the formation and evolution of planetary systems and Studies of chemical and atomic processes related to the formation and evolution of planetary systems. Our proposed theoretical research will enable future research in a third category, Observations related to the formation and evolution of planetary systems.

Greg Doppmann/NOAO
New Window on Disk Chemistry: Infrared Spectroscopy of Water and Organic Molecules in the Planet Formation Region of Disks

We propose to analyze high resolution infrared spectra of a sample of young stars expected to show strong emission in water, OH, CO, and organic molecules. We will model the emission features observed in the K and L-bands using software developed by us. By comparing the observed spectra with synthetic disk models we will be able to: (a) measure the intrinsic line broadening in disks; (b) characterize the mechanical heating in the inner disk; (c) examine the role of photochemistry in setting inner disk surface abundances, and (d) detect or set detection limits on organic molecules in inner disks. These results will provide major insights into the nature of the accretion mechanism in disks. They will also open a new window onto the nature of disk chemistry and the ability of disks to synthesize molecules of biological interest.

Debra Fischer/San Francisco State University
The Lick Observatory Planet Search

We propose a work plan that will dramatically improve the productivity of the Lick Planet Search program by reaching a Doppler precision of at least 1 m s-1 on the 3-m Shane telescope. In order to achieve this goal, we will adopt key attributes of HARPS: installing a fiber feed to scramble light entering the Hamilton spectrometer and controlling the temperature in the Coude room that houses the spectrometer. In addition, we are implementing an innovative new Doppler code to analyze the spectra.

1. With higher Doppler precision we will launch a new program: a high cadence search for low mass planets around bright, nearby stars. We are partnering in this effort with our Keck eta_EARTH program and expect to make the Lick and Keck programs more efficient and more powerful than just the sum of the two programs.

2. Because our new Doppler code allows us to solve for the PSF from sequential observations, we will be able to achieve higher precision on stars that have broader spectral lines and we will also begin a search for planets orbiting mid-to-late type F dwarfs. Like the search for planets around subgiants and the search for planets orbiting M dwarfs, the F dwarf search will help us to understand planet formation as a function of stellar mass.

3. Our improved Doppler precision will also help us to model complex, multi-planet exoplanet architectures. The Lick program has discovered 20% of the known multi-planet systems and will continue to detect additional planets around known exoplanet hosts.

4. The Lick program provides a legacy database for long-period systems that will be precious for NASA space missions: direct imaging of jovian planets (JWST) and key for resolving long-period planets in high precision spaceborn astrometric measurements (SIM, Planet Hunter)

5. The extensive set of precision radial velocities will also help us to understand astrophysical noise sources. The spectral format at Lick contains both Ca II H and K lines and the Ca II IRT lines and we actively working on understanding correlations between stellar activity and velocity jitter.

Christine Floss/Washington University
Characterization of Silicate Stardust Grains in Primitive Meteorites

Silicates are commonly observed in the outflows of oxygen-rich stars, and presolar silicate grains have been found in primitive meteorites, interplanetary dust particles and Antarctic micrometeorites. The small sizes of most silicate stardust grains and the fact that they are embedded in matrices of abundant silicates of solar system origin, make their mineralogical identification a non-trivial task. We are carrying out detailed characterizations of presolar silicate grains in primitive meteorites using a combination of NanoSIMS, Auger spectroscopy and FIB/TEM. The resulting data allow us to compare presolar silicate populations in meteorites with observational data from the dust around oxygen-rich stars. In addition, abundances and physical characteristics of presolar silicates in extraterrestrial materials provide crucial information about the effects of parent body processing on the survival of circumstellar silicate grains in these reservoirs.

Andrea Ghez/ University of California, Los Angeles
Precision Dynamical Masses for Substellar Objects

We propose to test and calibrate the theoretical substellar evolutionary models by obtaining precision (<10%) dynamical mass estimates of brown dwarf binaries. This work capitalizes on the advent of Laser Guide Star Adaptive Optics on the W. M. Keck 10-m telescope. Initial work on this project has already yielded some tantalizing new results, based on total dynamical mass measurements for 5 binary systems. We find that instead of one model being more consistent with the empirical mass than another, extant theoretical models are systematically discrepant. Specifically, it appears that the late M/early L spectral type systems have higher dynamical massesthan the models predict, the mid-L system is consistent with model predictions, and the one T dwarf system has a lower dynamical mass than predicted. If true, this result has important implications for masses inferred for directly imaged planets, which may currently be over-predicted. However, much further work is necessary to confirm these putative trends.

We therefore intend to (1) increase the number of (by a factor of 3) and spectral range of precision total mass estimates, with a particular focus on the lowest mass objects that approach or overlap with the planetary mass regime, (2) obtain individual, as opposed to total, mass measurements through a concerted observational and analysis efforts to extract precision absolute radial velocities, and (3) improve our method of effective temperature derivation to include other atmospheric models and a combination of photometry and spectroscopy. Our proposed measurements will comprehensively test theoretical substellar evolutionary models, by systematically covering a wide range of

spectral types across the substellar regime, and thereby will take a crucial step in the characterization of gas giant planets.

Jeremy Goodman/Princeton University
Predicting signatures of accretion and turbulence in protoplanetary disks

In response to new and upcoming direct observations of gas in the planet-forming zones of protostellar disks, we will construct global models that represent both the dynamics of the gas and its observable emissions. To do this, we will improve the microphysics in our existing MHD codes with modules to represent heating and cooling, nonthermal ionization balance, tensorial conductivities, chemistry, and limited radiative transfer including interaction with the protostellar radiation field. With this tool, we will predict molecular line and dust-continuum emissions for various hypothesized dynamical states: passive disks, accretion driven by magnetorotational turbulence, and accretion driven by winds. The goal is to allow these states to be constrained by observations, since it is not possible to model all aspects of disk evolution from first principles. The importance of this work, in addition to the desire to make use of rapidly improving observational data, is that the dynamical state of the disk influences the efficiency of planetary formation and migration.

Uma Gorti/SETI Institute
Disks in Transition: Planet Formation, Gaps and Photoevaporation

The origins of planetary systems is intimately connected with the late stages of protoplanetary disk evolution. Gas-rich disks transition to dust-rich and gas-poor within a few to several Myrs. This transition involves disk gas dispersal and sets the time for the final accretion epoch of gas giant planets. While most of the gas is removed from a disk by energetic photons emitted by the central star, affecting planet formation, the presence of a tidally-induced gap in the disk's surface density produced by a giant planet may in turn facilitate disk gas dispersal. We propose to study the synergetic relation existing between late phases of disk evolution and planet formation by constructing unified models of protoplanetary disks that incorporate (i) photoevaporation by EUV, FUV and X-ray photons emitted by the star, (ii) gap formation through gravitational torques exerted by an embedded massive planet (iii) dust evolution and radiative transfer and (iv) radial and vertical transport driven by turbulent viscous diffusion in order to account for the temporal and spatial distribution of gas density, temperature and chemistry in the disk. Through extensive parameter studies, we will investigate how the combined effects of photoevaporation and disk-planet interactions can impact disk morphologies and lifetimes, how the final masses and orbital properties of giant planets are affected by gas removal from the disk and whether this is consistent with gas giants in the solar system and beyond, and how these processes are dependent on stellar mass.

Ian Hutcheon/Lawrence Livermore National Lab
Isotopic studies of chondrite precursor materials in the solar nebula

The primary goal of the proposed research is to investigate the sources and distribution of isotopes in the solar nebula, with a particular emphasis on the initial isotopic ompositions recorded by primitive nebular materials. To accomplish this goal we will carry out new observations of isotope and trace element abundances, coupled to complete petrographic characterization, in a diverse array of pristine solar system materials including chondrules, refractory inclusions and Wark-Lovering rims around CAIs in carbonaceous chondrites and interplanetary dust particles derived from comets. The 26Al-26Mg and 36Cl-36S chronometers will be applied in CAIs and chondrules to evaluate potential nucleosynthetic or irradiation origins of 36Cl and determine a "best" value for the initial abundance of 36Cl. We will expand the characterization of cometary IDPs, using O-isotopes to better understand isotopic reservoirs, gas-dust fractionation and mixing processes in the protoplanetary disk. We will assess the magnitude of Sm-Nd isotopic heterogeneity in the early solar system based on new measurements of CAIs to constrain nucleosynthetic contributions from disparate stellar sources to the nebula over the timescale of CAI formation. The proposed work presents an integrated analytical strategy of coordinated petrographic, mineralogical and isotopic measurements using multiple, high resolution instruments to examine individual specimens. This full scope of activities will contribute to a better understanding of the earliest history of the solar system and of the sequence of events extending from production of short-lived radionuclides in disparate stellar atmospheres to condensation in a hot, gaseous nebula to alteration in cool nebular and asteroidal environments.

David Jewitt/University of California, Los Angeles
Properties of Jovian Trojans

This proposal is to determine selected physical properties of the Jovian Trojan asteroids. These objects share Jupiter's orbit but remain separated from the planet by about +/-60 degrees of orbital longitude. The origin of the Trojans is unknown. Possible source regions range from the proto-Jupiter feeding zone near 5 AU to the Kuiper belt (now) beyond 30 AU. If the former, they can be considered as surviving samples representative of Jupiter's heavy-element core. If the latter, they are primitive bodies (comets) from the outer regions of the protoplanetary disk. Either way, the Trojans carry potentially invaluable information about the origin and evolution of the Solar system, especially about the way in which disks and planets interact to redistribute matter.

Although comparable in number to the main-belt asteroids, the Trojans have received comparatively little observational attention, perhaps because of their greater mean heliocentric distance and resulting faintness. We here seek to obtain physical data using large telescopes to better address the physical natures of the Trojans. Observations to be obtained include a) near infrared spectra for compositionally diagnostic absorption bands b) deep optical imaging for comet-like comae c) albedos from combined optical and thermal infrared photometry, and more. The objective is to understand to what degree the Trojans can be meaningfully compared with other small body populations, particularly those in the Kuiper belt and the comets derived therefrom. We will exploit the world's largest telescope for the majority of these measurements. Ground-based characterization

of the Trojans is an important first step towards NASA's eventual exploration of these bodies by spacecraft.

Christopher Johns-Krull/Rice University
Exploring the Magnetic Field Geometry of Pre-Main Sequence Stars

Magnetic fields on newly formed stars appear to play a critical role in determining the dynamics of the inner regions of the planet forming accretion disks around such stars. They regulate the accretion of disk material onto the stellar surface and likely play a key role in the launching of strong outflows which are critical in shedding the excess angular momentum of the disk material. Stellar magnetic fields may even determine where inward migrating giant planets halt their inward journey, thus determining the final architecture of extra-solar planetary systems. While strong fields are known to exist on virtually all low mass pre-main sequence stars, there is little observational data to date on the geometry of these surface magnetic fields, which is a key component of the puzzle. If the geometry of the fields is small scale as it is on the Sun, then stellar magnetic fields can not produce the phenomena attributed to them. If, on the other hand, the magnetic fields on these stars have substantial large scale components, the current models of these phenomena are on a secure foundation.

The goal of this proposed work is to primarily study the magnetic field geometry on low mass pre-main sequence stars. We will use time resolved optical spectropolarimetry to study this field geometry and thereby test current models of magnetospheric accretion and disk locking in young stars.

The work proposed here directly relates to NASA's Strategic Goals in astrophysics. In particular, Research Objectives 3 and 4, put forward the ambitious goal of understanding star and planet formation. A key aspect is to understand how the star interacts with and disperses its circumstellar accretion disk. It is understanding this interaction that is the central goal of this research proposal.

Paul Kalas/University of California, Berkeley
Direct Detection & Characterization of Extra-Solar Planets

We propose a three-year project to study exoplanets and dusty debris disks around nearby stars using a combination of high angular resolution and dynamic range imaging. We focus on three areas:

(1) Direct imaging observations of exoplanets and their associated debris disks from 0.4 µm to 1 mm to study the formation and evolution of planetary systems using HST, Keck, Gemini, VLT, and CARMA/SMA. A key priority is to determine the properties of Fomalhaut b, a recently imaged exoplanet orbiting the 200 Myr-old A star Fomalhaut. Moreover, there is a pressing need to study the now significant number of resolved debris disks (>16) that have yet to be observed at multiple wavelengths. This campaign will yield comprehensive mapping of their structure (which is linked to planetary perturbations) and the composition, size spectrum, and porosity of the grain populations that comprise them.

(2) An optical survey of Doppler exoplanets using a new, high precision polarimeter. We have demonstrated part-per-million precision on bright stars and the first detection of stellar limb polarization for the transiting exoplanet system HD 189733. We will extend this work to over a dozen stars with exoplanets. This survey will detect scattered light from exoplanet atmospheres, constraining key properties such as albedo and orbital inclination (thereby eliminating the sin i ambiguity in masses).

(3) Preparation for direct exoplanet imaging surveys, e.g., with the Gemini Planet Imager (GPI). GPI is an "extreme" adaptive optics coronagraph that will image self-luminous exoplanets orbiting stars in the solar neighborhood. Although the youngest stars (<100 Myr) are the best targets, GPI has good sensitivity to exoplanets with ages up to 2 Gyr. These "adolescent" host stars are more numerous than their youthful cousins and therefore they are important because they offer the statistical riches necessary to characterize planet populations. Although the majority of young stars within 100 pc have been located, a much smaller fraction of < 2 Gyr stars have been identified. We propose a spectroscopic survey at Lick to identify young stars and constrain their ages. The proposed echelle survey of about 1500 stars will measure Ca II H&K and Li I 6707 Å line strengths, as well as stellar v sin i and radial velocities.

Scott Kenyon/Smithsonian Astrophysical Observatory
Understanding the Diversity of Debris Disks

Using a hybrid multi-annulus planetesimal/N-body code, we propose to construct detailed numerical models of icy planet formation around stars of various masses. In addition to following the growth of km-sized planetesimals into Earth-mass or larger planets, our approach yields predicted fluxes from debris disks produced as planets grow larger than roughly 1000 km. Our proposed simulations of icy planet growtharound 0.1-0.5 solar mass stars will yield the first theoretical results for the masses of icy planets around the most common stars in the Galaxy. In addition to providing initial exploration of planet

formation models in these environments, our calculations will yield the first direct predictions for debris disk evolution for comparison with observations from Spitzer and Herschel.Our proposed calculations of icy planet formation around 1-3 solar mass stars will yield the first estimates for the relative frequency of gas giants and super-Earths in AFG-type stars with debris disks. In addition to deriving estimates for the frequency of planetary systems around stars of various masses, these calculations will inform observing programs and instrument development for JWST and other planned NASA missions.

Harold Levison/SwRI
The Early Dynamical Evolution of the Solar System

We propose a 3-year continuation of a study of the formation and long-term dynamical behavior of the Solar System and its constituent bodies. The proposed research in this cycle has a unifying theme: to understand the role that small bodies played in determining the current anatomy of the outer Solar System. Within the context of this new grant, we plan to address: 1) the origin and evolution of the scattered disk and Oort cloud, 2) to extend and further develop the so-called 'Nice Model' of the early dynamical evolution of the outer Solar System as a whole, and 3) to study a new idea for the formation of Iapetus which could explain its ridge and equatorial bulge.

Zhi-Yun Li/University of Virginia
Magnetic Braking and The Origin of Protostellar Disks

Disks play a central role in both star and planet formation. They are the conduit through which material from dense cores of molecular clouds flows onto protostars, and they are also the birthplaces of planets. Disks are generally expected to form automatically out of rotating, collapsing cores, because of angular momentum conservation. This expectation changes in the presence of a magnetic field, which removes angular momentum from the collapsing material through magnetic braking. If the magnetic field and matter are well coupled (i.e., in the ideal MHD limit), even a field much weaker than that observed in star-forming dense cores can suppress disk formation completely. The non-ideal MHD effect most widely studied in star formation, ambipolar diffusion, does not weaken the braking enough to enable disk formation for realistic levels of core magnetization and ionization. And yet, disks are observed around many young stellar objects, at least at relatively late stages of formation. When and how disks form remains a mystery. We aim to resolve this conundrum by determining (1) whether the remaining two non-ideal MHD effects, Ohmic dissipation and the Hall effect, can weaken the magnetic braking enough to enable disk formation, and (2) whether the disk can be saved by the oft-observed wind stripping of the slowly rotating protostellar envelope, which is largely responsible for disk braking; the envelope is linked by magnetic field lines to the fast rotating material that would form a disk in the absence of such a magnetic coupling. Our proposed work will delineate the conditions under which protostellar disks can form during the collapse of rotating, magnetized cores. Such disks provide the initial conditions for the subsequent disk evolution and planet formation. Understanding the formation of planetary systems is a major goal of NASA's Origins of Solar Systems program.

James Lyons/University of California, Los Angeles
Photochemical Self-shielding and the Isotopic Evolution of Primitive Materials in the Solar System

We propose to quantitatively investigate and evaluate CO self-shielding as the mechanism responsible for the much of the oxygen isotope composition of the inner solar system, including the CAI mixing line. To achieve this goal we will model transport of water produced by CO self-shielding in the outer solar nebula and parent molecular cloud. Photochemical models of CO self-shielding will be coupled, to varying degrees, to the radial diffusive and advective transport on the nebula. Initially, we will run the photochemical and dynamical models separately, and determine the capability of self-shielding to account for the oxygen isotope signatures of meteorite silicates and CAIs. We will perform similar calculations for CO self-shielding products derived from the parent molecular cloud. Then, we will run truly coupled photochemical-dynamical models to determine whether a self-consistent self-shielding solution is possible. Similar calculations will be made of N_2 self-shielding, which we will relate to the nitrogen-15 hotspots observed in CR and CB meteorites. We will also consider incorporation of self-shielding isotope signatures into meteorite insoluble organic matter (IOM). Finally, we will compare the timescales of photolysis and transport to the timescales of oxygen exchange and diffusion between nebular gas and meteorite CAIs and silicates minerals. This latter test is essential for evaluating whether or not CO self-shielding can actually account for meteorite oxygen isotope observations.

Bruce Macintosh/Lawrence Livermore National Lab
Characterization of the HR8799 planetary system

The recent adaptive optics imaging of 3 self-luminous extrasolar planets orbiting the young (60 Myr) A5V star HR8799 is a major step forward in the study of other solar systems. The three co-eval massive planets in co-planar wide orbits represent a new window onto planetary system formation, particularly as the planets are bright enough for high-SNR follow-up observations. We propose to characterize the system using adaptive optics observations on the Keck II telescope, with a parallel program of advanced modeling. First, we will use the NIRC2 infrared imaging camera to carry out a campaign of precise relative astrometry (1-2 mas accuracy) for the three planets in the system over a 3-year period. These should constrain key orbital parameters such as period and inclination to ~15% accuracy. Recent simulations show that if the planets are in simple circular orbits the system is rapidly unstable and that either the planetary masses must be lower than predicted and/or the planets must be in resonance. With our additional astrometry, we will carry out orbital stability integrations using LLNL computing facilities to determine the most likely planetary masses and orbital properties.

Second, we will use integral field spectroscopy on the Keck telescope to obtain high-SNR moderate-resolution (R~1000) spectra of the outer two planets. Spectra will provide information about planetary temperature and perhaps gravity, and also on the physics of the cloud structures that dominate atmospheric opacity for these objects. We will develop new planetary atmosphere models to match these observations.

Third, we will participate in an international campaign to measure the mass and age of the host star using the MOST satellite and high-resolution spectroscopy.

The HR8799bcd may represent a new class of extrasolar planetary systems, formed through new mechanisms, or may represent a high-mass equivalent of our own solar system. Integrated studies of the planets, their orbits, and the parent star are necessary to understanding the origin and nature of the system. Such direct spectroscopic and imaging characterization with high-contrast coronagraphy and adaptive optics also lays the groundwork for future space missions to discover and characterize mature planets, including ultimately Earth analogs.

Geoffrey Marcy/Regents of the University of California
Properties of Super Earths: Putting Rocky Planets on Solid Ground

Our Doppler work on exoplanets continues its renowned leadership role in a wide variety of exoplanet programs. From hot super-earths to cold gas giants at 5 AU, the 157 exoplanets discovered and characterized by our team continue to offer the precious fundamental data on which the exoplanet community depends. With longstanding support from NASA Origins, we discovered the first multi-planet system, the first saturn-mass planet, the first neptune mass planet, and many of the brightest transiting planets amenable to Spitzer followup.

Here we propose to carry out precise RV measurements into two crucial exoplanet domains, the super-earths and the normal gas giants beyond 3 AU. Prominent claims about the frequency of planets having 5-30 Earth-masses disagree wildly, ranging from 30% to a "desert", from both observational and theoretical groups. We propose to carry out a major, precise RV program on two telescopes, Keck 1 and the new Lick Observatory 2.4-m Automated Planet Finder, to detect and characterize super-earths and neptune-mass planets. This program builds on our successful Keck Doppler survey for super Earths that has already provided remarkable results.

As a second program, we will extend our legacy long-term Doppler survey for normal giant planets orbiting beyond 3 AU and the multiple-planet systems associated with them. The vast majority of giant planets orbit beyond 1 AU, and our RV survey leads the world at exploring the properties of these jovian planets. Moreover, gas giant exoplanets beyond 3 AU offer direct comparisons to the properties of jovian planets in our Solar System. We collaborate with numerous observers and theorists to optimize the study of exoplanets by the community. For both super-Earths and long-period planets, the target stars will include the 300 nearest FGKM-type stars, namely those stars on the SIM and TPF/Darwin target lists within 25 pc. We will integrate our results with (and indeed contribute to) the results from the NASA-Kepler mission, thereby yielding robust statistical properties of planetary systems from terrestrial-sized to jovian planets.

Peter McCullough/Space Telescope Science Institute
XO Project: Discovery and Characterization of Transiting Extrasolar Planets

We describe a four year plan to continue discovering and characterizing planets that transit bright stars. To date, astronomers have reported more than 30 such transiting planets orbiting bright stars, and their numbers are increasing rapidly (both the number of planets and the number of astronomers studying them). The brightest typically are discovered by oscillating radial velocities, and somewhat fainter ones in much larger numbers are discovered by transits.

The XO observatory has recently been expanded to six 0.1-meter diameter cameras, two of which have been operating robotically since Sep 2003 and with which we have discovered five transiting planets. By Dec 31, 2013 XO will have observed 90% of the northern sky with two lenses for two seasons, permitting its team and others to discover and characterize transiting extrasolar planets (TEPs). We evaluate transiting-planet candidates produced by the XO survey cameras with precise photometric observations, which significantly reduces the number of candidates we observe spectroscopically. For the follow-up photometry, we have recruited a global network of amateur astronomers, in addition to our team's institutional access to observatories in Texas and Arizona. Dozens of candidates per year will be scrutinized with moderate-precision (1 km/s) radial velocity observations and a few of those will be confirmed to be planets with (5 m/s) precision.

We will pursue precise photometric and spectroscopic follow up observations of transiting planets. Our team has prior experience with scintillation-limited ground-based photometry, time-series photometry with SST IRAC, spectrophotometry with HST instruments NICMOS, STIS, FGS, ACS, and WFC3 (in ground-tests), and is developing spectroscopic analysis techniques to improve the precision of radial velocities from the HET and Keck. Using radial velocities and photometry we will search for additional companions around stars known to host a transiting planet.

For the period 2003-2009, the XO team has been supported by two NASA Origins awards. Follow-up observations with HST and SST have been supported by those NASA programs. The tripling of XO's cameras and associated electronics has been supported by peer-reviewed competition for institutional funds of the STScI Director.

Larry Nittler/Carnegie Institution of Washington
Coordinated Microanalytical Study of the Origin and Evolution of Extraterrestrial Organic Matter

Carbon plays crucial roles in the origin and evolution of stars, planets, and life. Primitive extraterrestrial materials contain abundant C, mostly in organic form, and in fact were probably extremely important in delivering organic compounds to the early Earth. H and N isotopic anomalies (generally enrichments in D and/or 15N) in this organic matter indicate an origin either in presolar molecular clouds or the in cold outer reaches of the Sun¿s protoplanetary disk. We propose to continue our successful research program to

investigate the origin and evolution of organic matter in the Solar System, based on a multi-technique microanalytical approach. Our main scientific goals are: 1) Determine the microscale distribution of H, C and N isotopic ratios in organics from a range of meteorite classes, both in situ and in well-characterized insoluble organic (IOM) residues. Samples with a range of isotopic compositions will be targeted for subsequent correlated analyses. 2) Investigate the structure and composition of meteoritic organic matter on sub-micron scales with the goal of better understanding its origins and processing histories in the early solar system. For example, we will search for distinct chemical bonding signatures in the most isotopically anomalous materials to provide constraints on the interstellar chemical processes that produced them. 3) Investigate the nature and origin of so-called "nanoglobules" that are now known to be a common constituent of primitive extraterrestrial organic matter. 4) Investigate the relationship between organic matter and surrounding inorganic materials in situ in matrices of different classes of primitive meteorites to better understand how parent-body processes affect organic matter on microscopic scales and how some microscale isotopically primitive material survives in some meteorites, even when the bulk of the organic matter has been modified. 5) Compare the range of chemical, isotopic and microstructural properties of IOM to those of organics found in situ in the same meteorites to accurately assess any possible effects of the demineralizing acids used to purify IOM. These goals will be accomplished by performing highly coordinated analyses of the same materials using secondary ion mass spectrometry, micro-Raman spectroscopy, focused ion beam microscopy, scanning and transmission electron microscopy, and synchrotron x-ray transmission microscopy. The research proposed here is aligned with the goals of the Origins program in that it will increase "understanding [of] the formation and early evolution of planetary systems" by providing information as to how a key component of the solar system - organic matter - formed and evolved on the path from molecular cloud to the solar system we know today.

Steven Pravdo/JPL/Caltech
Finding Planets Around Low-Mass Stars

We propose to search for planets around low-mass stars with ground-based astrometric instruments. First we will continue our observations with the STEPS CCD camera system that has already been successful with the first astrometrically-discovered planet as well as other companions to low-mass stars. Second we will initiate a parallel program with our new HyViSI camera system that will test the relative astrometric precision of the two technologies, evaluate a high-dynamic range mode enabled by the new system, and expand the planet search. Finding planets around low-mass stars that are difficult to detect with other planet-finding techniques is a strength of astrometry and is crucial to NASA's goal to inventory planets, since low-mass stars are >70% of all stars. This work is proposed to be conducted as Fundamental Research.

Aki Roberge/Goddard Space Flight Center
Finding the Needle in the Haystack: Realistic Simulations of ExoEarth Observations in the Presence of Exozodiacal Dust

In recent years, the rapid pace of exoplanet discoveries has brought the exciting goal of finding habitable planets (or "exoEarths") and probing them for signs of extraterrestrial life within reach. Achieving this goal is still difficult and will require very high contrast to image the planets and obtain direct spectra of their atmospheres. Several designs for large space telescopes with these capabilities are in development. However, these efforts are hampered by unknowns about the target systems, including the fraction of stars with terrestrial planets in their habitable zones (eta_Earth) and the characteristics of the exozodiacal dust in the system. Mission performance is typically evaluated using a single model for the target system (i.e. the Solar System at 10 parsecs). To properly prepare for future exoEarth observations, we must better define the challenge, using the knowledge gained through two decades of extrasolar planetary studies.

We propose the first truly realistic simulations of exoEarth images and direct spectra, in order to rigorously investigate the complex sources of noise and confusion that will inevitably be present. The first step will be producing a diverse suite of detailed planetary system models. They will include several different planet types, as well as a broad range of stellar types that encompasses all the most likely target stars for future exoEarth observations (F, G, K, & M stars). Exozodiacal dust (or "exozodi"), expected to be the largest source of noise in direct observations of terrestrial planets, will be carefully handled. The models will incorporate a range of plausible exozodi structures, brightness levels, and colors. We will evaluate the expected frequencies of all potential sources of confusion (e.g. background galaxies and stars, exozodi clumps, non-habitable planets, comets) and realistically seed them into the models. The second step will be using the models to create simulated exoEarth observations, then testing data analysis techniques and characterizing possible systematic errors. Finally, we will examine the severity of the various sources of confusion and develop observing strategies to remove them.

Alex Ruzicka/Portland State University
Shock histories of chondrites as revealed by combined microstructural (TEM), petrographic, and X-ray microtomographic (µCT) analysis

The picture that emerges from recent research on planet formation is that of an active early solar system characterized by bodies undergoing collisions, early melting and differentiation, and delayed accretion for chondrite parent bodies. It appears that some partly melted planetesimals or planetary embryos could have experienced major disruptive collisions. Unlike other rocky bodies, chondrites escaped whole-scale melting, so their micro- and macrostructures potentially provide a record of collisional processes in the early solar system not otherwise available from studies of other meteorites.

We propose to use three independent techniques to better understand the deformation and thermal histories of chondrites and their parent bodies, especially the collisions that could

have been important in the early formation and metamorphism of the H-group parent body. The techniques include: (1) transmission electron microscopy (TEM), to determine microstructures in olivine and plagioclase, (2) optical petrography, to determine shock stages, and (3) x-ray microtomography (microCT), to determine the 3-dimensional shapes and orientations of metal grains. Fourteen type 6 H, L, and LL chondrites will be studied as part of three separate tasks that involve different goals. Task 1 will involve cross-correlation of microstructures in olivine and feldspar observed with TEM and the 3-dimensional characteristics of metal for six L chondrites that span the range of shock stages, to provide the basis for understanding shock-induced deformation, compaction, and annealing. A single late shock event could have affected all these meteorites to a variable extent. Task 2 will involve the study of three H-chondrites and two LL-chondrites that have been proposed to have been extensively annealed following shock, with annealing occurring as a result of thermal metamorphism, either related or unrelated to shock. For these samples we will evaluate the extent to which such post-deformation annealing occurred and whether deformation could have occurred at high temperature during metamorphism. Task 3 involves the study of three additional H-chondrites with low shock stages that together with Task 2 will help constrain the role of collisions in onion-shell cooling models for the H-group parent body.

Altogether, the results of our proposed study will provide the data needed to test models that invoke shock heating as an important contributor to the thermal metamorphism of chondrites, whether annealing can obliterate optical evidence for deformation in olivine, whether a record of early shock deformation can be preserved in chondrites, and the mechanisms involved in shock compaction. Finally, our results will provide constraints for understanding the accretion, lithification, collisional response, and collisional evolution of solar system bodies. The proposed work is highly relevant for NASA's Origins of Solar Systems program as it focuses on the analysis of primitive materials and relates to the formation and evolution of planetary systems; more broadly it is relevant for NASA's goal of advancing scientific knowledge of the origin and history of the solar system.

Mark Thiemens/University of California, San Diego
Determination of Photochemical Isotopic Fractionation Factors in Oxygen and Nitrogen in the VUV Photodissociation of Carbon Monoxide, N_2 and Other Nitrogen Bearing Species and Their Relevance to Meteoritic Observations

With the recent substantive increase in the amount of isotopic data from different meteorites, IDPs, Genesis and Stardust mission return samples, there is an enormous interest in the early solar system and understanding the linkage between different isotopic systematic and the origin and evolution of the solar system. This has become increasingly apparent as these isotopic measurements are made at levels where chemical speciation is known, and phases characterized. As such, measurement of chemical fractionation processes that may be operative in the production of these anomalies is highly desirable.

This proposal focuses on two isotopic systems, oxygen and nitrogen. The purpose of this proposal is to measure the isotopic fractionation associated with oxygen and nitrogen due to VUV photodissociation of carbon monoxide, nitrogen and UV

photodissociation of other relevant nitrogen bearing molecules (e.g., HCN and NH3) and to evaluate the potential applicability of proto-processes in the early evolutionary stages of the solar nebula.

Isotopic self-shielding of CO was invoked to explain the observed CCAM (e.g. Carbonaceous Chondrite Anhydrous Mineral) line of oxygen isotopes (Thiemens and Heidenreich, 1983; Clayton, 2002; Yurimoto and Kuramoto, 2004; Lyons and Young, 2005). With NASA support (Origins: NASA NNX07AJ81G), we tested this hypothesis and found an enormously large oxygen isotopic fractionation during CO dissociation and no apparent evidence of self-shielding and which was subsequently published in Science (Chakraborty et al., 2008; 2009). These experiments were the first to test the self shielding process and, to actually probe a photochemical dissociative process at the fundamental quantum level. These experiments lead to recognition of the need for a next generation of studies and, to accomplish this a research program to further experimental test of CO photo-dissociation at VUV wavelengths under a variety of relevant experimental conditions is proposed. These experimental observations and analysis will lead to a better understanding of the physical chemistry of CO photodissociation as well as, to determine the isotopic fraction associated with CO-photolysis across the VUV solar spectrum at relevant temperature conditions.

Enormous (~ 4500 permil) nitrogen isotopic compositions of a wide range (- 300 to 4500 permil relative to the terrestrial atmosphere) are reported from different solar system objects (i.e., meteorites, IDPs, Comets, Jovian planets and their satellites). Similar to CO self-shielding, self-shielding of N_2 during VUV photodissociation was proposed in solar nebula as a mechanism to generate large 15N-isotopic enrichment (Thiemens and Heidenreich, 1983). This proposition however has never been experimentally tested. Here we propose an experimental program to test this hypothesis using VUV photons from the Advanced Light Source (ALS) synchrotron. The observed association of 15N enrichments (in a hotspot) with large amounts of organic material may be an indication of other processes responsible of these isotope effects (Briani et al., 2009). Photolysis of N-containing molecules (such as, HCN, NH3), closely related to the organic compound chain may be relevant and have never been investigated for the associated isotope effects of dissociation at short photochemical wavelengths. In this 4-year program, along with N2 photolysis, we also propose to carry out UV photolysis experiments with HCN and NH3 to determine the associated fractionation factors in nitrogen isotope due to these photo-processes.

Neal Turner/Jet Propulsion Laboratory
Clearing The Dust From Protostellar Disks

Infrared observations of young stars have identified a population of circumstellar disks with a deficit of emission from the region within a few AU of the central star. These systems are in transition between an early stage where planetesimals form in an optically-thick disk of gas and dust, and a later stage where a diskless star contracts toward the main sequence. Consequently they are a key to understanding the gathering together of solids and the dispersal of gas that are fundamental to the growth of the planets. We propose to synthesize Spitzer Space Telescope and other observations of these disks into a picture of the processes responsible for clearing the dust. We will develop models

incorporating the best available information about grain transport and growth, including the rates of turbulent mixing and accretion derived from 3-D magnetohydrodynamical (MHD) calculations. The MHD calculations provide detailed insights into the processes at work in local patches of the disk over timescales of a few hundred orbits, yielding answers to questions such as how the strength of the turbulence varies with position and how the dust and gas flows are coupled. Integrating these findings into global models that span the disk radius and lifetime will enable us to identify the key steps in clearing the dust. We will also construct synthetic observations of the global models using radiative transfer techniques, enabling the separation of the signatures of the dust transport from those of ongoing planet formation and migration.

This work is proposed to be conducted as Fundamental Research.

Gautam Vasisht/Jet Propulsion Laboratory
Data Processing Methods for Direct Imaging of Exoplanets with the Palomar Project 1640

We propose to undertake a systematic study of speckles and research innovative methods to suppress them using hyperspectral data; our data are acquired with a state-of-the-art high contrast system called Project 1640. Effective speckle control will allow us to conduct truly transformative imaging-spectroscopy of exoplanets and debris disks orbiting young stars. Project 1640, now in operation on the Palomar Hale Telescope, is a collaboration between the American Museum of Natural History, the Jet Propulsion Laboratory and Caltech Optical Observatories. It is built as a Northern Hemisphere very-high-contrast imaging system (an optimized coronagraph and integral field unit), and now mated with Palomar AO, is undertaking a broadbrush early survey around a sample of a few hundred stars. In 2011, it will mate with PALM-3000 extreme adaptive optics and a specialized wavefront sensor (CAL) to image with exquisite potential (contrasts of 10^{-7} at 400 mas), thereby generating tremendous opportunities in direct detection and spectroscopy of self-luminous giant planets, sub-stellar objects and debris disks around a volume limited sample of stars. The instrument, i.e. the integral field unit and to be installed CAL wavefront sensor, provides diversity to discriminate between speckle activity from the light of a putative companion. However, the observed behavior of speckles in a real instrument fed by partially corrected wavefronts is non-trivial. The proposed work will study this currently ill-understood behavior, and provide the wherewithal to bring Project 1640 to its full potential. We request funds, via this "Origins of Solar Systems" call, to conduct algorithmic research and develop numerical schemes to model and suppress dynamic speckle-fields. While these algorithms will be tailored to maximize the scientific output of Project 1640, they will nevertheless be applicable to other upcoming high contrast imagers making the proposed work timely and crucial. In this pursuit, we hope to leverage considerable expertise at JPL that has gone into the study of speckle control for proposed NASA missions such as the Terrestrial Planet Finder or its successors.

This work is proposed to be conducted as Fundamental Research.

Frederick Walter/SUNY
All The Low Mass Objects - Where Do They All Come From?

Hidden within the depths of the fossil star forming regions lie myriads of very low mass objects - brown dwarfs and massive free-floating planets. Current instrumentation can detect this population down to a mass of about 2 Jovian masses at young ages. We are engaged in a deep optical/near-IR survey with the aim of characterizing this very low mass population in the young (2-10 Myr) Orion OB1a and b fossil star forming regions. We seek to understand whether the lowest mass free-floaters (including planetary mass objects) form in isolation from low mass cores, or whether they represent underdone stars perhaps prematurely ejected from their birthplaces. The spatial distribution of the stars, brown dwarfs, and free-floating planets will provide insights into how these low mass objects form.

The Orion OB1a and b associations are fossil star formation regions wherein star formation has ceased yet all the products of the processes remain behind. We have surveyed some 15 square degrees in the near-IR, complete down to about 10 Jovian masses. We estimate there are of order 10,000 substellar mass objects in the associations to this limit. We now have some deep optical and near-IR imaging which pushes the limits deeper. We request support to complete the photometric survey, to ingest longer wavelength Spitzer IRAC images, and to embark on a spectroscopic followup.

In addition to providing strong observational clues as to how the very low mass stars form, this study will yield a uniform and complete sample of a very young population of substellar mass objects. We will produce and disseminate a catalog of these objects. We request support for three years to complete this on-going study of the formation of very low mass stars and substellar (including planetary) mass objects.

Benjamin Weiss/MIT
Search for Records of Early Solar System Magnetic Fields

Observations of young stellar objects indicate that a key step in the formation of solar systems is the formation and evolution of a protoplanetary disk. Over several million years, somehow nearly all of the final mass of the solar system is transferred inwards to form the young star while nearly all of the final angular momentum is carried by the newly formed planets. How exactly this occurs in the disk remains a key unsolved problem.

Recent theoretical advances in astrophysical magnetohydrodynamics suggest that interplanetary magnetic fields may have played a critical role in this process. By providing a pathway via the magnetorotational instability (MRI) to trigger turbulence, magnetocentrifugally driven winds and/or magnetic braking, these fields may be the primary agent responsible for the transfer of mass and momentum in protoplanetary disks. Postulated interplanetary magnetic fields arising from the MRI, as well as from stellar x-winds and nebular lightning may have also even been responsible for the

formation of some of the first solar system solids. However, as yet there are no clear signatures of these early fields identified in meteorites.

Magnetization in meteorite also may have important implications for early planetary differentiation. Recent paleomagnetic analyses of meteorites indicate that parent bodies of some achondrites as well as even CV carbonaceous chondrites likely formed metallic cores and core dynamos within the first 3-10 million years of solar system formation. Although chondrites are traditionally thought to be samples of bodies that have never experienced melting or differentiation, these data would imply that the CV parent body had a molten interior overlain by a relict chondritic crust. Records of these magnetic fields therefore provide unique information on the timing and extent of global differentiation and core formation on planetesimals.

Here we propose a paleomagnetic investigation of meteorites with two major goals:

Task 1. Test the hypothesis that the CV carbonaceous chondrite parent body was partially differentiated by searching for postaccretional paleomagnetism in other CV chondrites.

Task 2. Test various hypothesized mechanisms responsible for (a) mass and momentum transfer in the disk and (b) formation of the first solids, by characterizing any preaccretional paleomagnetism in CV carbonaceous chondrites.

For Task 1, we will study several oxidized CV chondrites which are most likely to have recorded any core dynamo fields. For Task 2, we will study oriented refractory inclusions and chondrules extracted from Allende and from one of the most pristine CV chondrites, Vigarano. We will also conduct high-resolution magnetic and geochemical imaging of CV chondrite thin sections.

This proposal meets the NASA OSS goals to support laboratory research into "star formation and the relationship to planetary system formation, solar nebula processes, accumulation and dynamical evolution [and] analysis of primitive materials" The proposal falls into the categories of "Observations related to the formation and evolution of planetary systems" and "Studies of chemical and atomic processes related to the formation of planetary systems." This collaborative proposal involving paleomagnetists, meteoriticists, and theoretical astrophysicists also "realizes the existing potential for complementary interdisciplinary efforts to solve key scientific questions." We note that while both Tasks fit within the SSO program, Task 1 has overlap with the NASA Planetary Geology and Geophysics (PGG) program. As we have discussed with the SSO and PGG program officers, it is possible that funding for this proposal could be shared with PGG if the review panel feels this is warranted.

Karen Willacy/JPL
Accretion shocks and chemical processing in protostellar disks

This work is proposed to be conducted as Fundamental Research.

The chemical composition of the protosolar disk defined the composition of the planets and other bodies formed from it. Understanding what this composition was and how it came to be requires detailed modeling of all stages of the star formation process, from the collapse of the parent molecular cloud core, through the formation of the protostar and its attendant disk, the infall of material through the shock at the surface of the disk and finally the evolution of material inside the disk. All phases of this process are important but the accretion shock is the least studied. We propose the model the chemical changes that take place in this shock. Our models will allow us to establish what happens to the molecular cloud material as it is accreted into the disk, and whether it could pass into the protosolar nebula unchanged. If the latter is true, then interstellar material could be incorporated into preplanetary bodies, and ultimately into objects such as comets. An alternative possibility is that the high densities and temperatures in the post-shock region result in the destruction of interstellar molecules and the formation of new and possibly more complex molecules. Our main objectives are to

1. Obtain radial abundance profiles of molecules in the shock that will be used in conjunction with radiative transfer modeling to provide maps of emission intensity across the disk surface.

2. Determine what ices can reform after material has passed through the shock.

We will model shocks appropriate for the early stages of protostellar disk evolution. Using disk models we will be able to link our work to particular radii in the disk, thereby building up a picture of the radial abundance distribution of molecules in the shock across the disk. Our model will include a complex chemical network, including desorption and freezeout of molecules, grain surface reactions, and the deuterium chemistry. The latter will be used to trace the thermal history of the material and to enable us to distinguish between molecules that formed in the molecular cloud and were able to survive the shock, and those which formed in the hot-post shock region.

Jason Wright/The Pennsylvania State University
Multiple and long-period exoplanetary systems: the habitable zone, the ice line, and beyond.

This proposal has three, interrelated objectives:

1) To exploit upgrades to the Hobby-Eberly Telescope and its High Resolution Spectrograph, improving its radial velocity precision and throughput to levels competitive with Keck/HIRES, and integrate it into the California Planet Search.
2) To discover and characterize new multiple-exoplanet systems, especially systems with detectable interactions or apparently empty Habitable Zones, and those beyond 3--5 AU.
3) To discover and characterize new long-period exoplanets, at and beyond the 3--5 AU `ice-line', especially Jupiter analogs.

We will accopmylish the first goals by applying the proven methodology of the California Planet Search to improve its precision to 1-3 m/s, making it competitive with

Keck (and HARPS) and greatly increasing the overall volume of Doppler planet detection and characterization. The PI in a new Penn State faculty member with institutional access to HET.

We will accomplish the latter two goals by carefully analyzing shifts in the positions of absorption lines in the spectra of our target stars. At current levels of sensitivity, we are capable of detecting the reflex motions of the stars due to planets in orbit around them. To characterize the orbits, we require multiple observations over at least one orbit of the planet. We will use Keck Observatory and the RV history of stars on the CPS target list to discover new multiplanet and long-period systems through additional monitoring of stars showing promising signals.

This investigation falls under two of the categories identified in the Origins of Solar Systems call for proposals: "Investigations to detect and characterize extra-solar planets", and "Observations related to the formation and evolution of planetary systems". This investigation also supports NASA Strategic Goal 3.4.4: "Progress in creating a census of extra-solar planets and measuring their properties".

Edward Young/University of California Los Angeles
Measuring oxygen and carbon isotope ratios in young stellar objects: placing the solar system in a Galactic context

The capability to compare isotope ratios of meteorites with those in protoplanetary systems presents exciting new possibilities for learning about the early history of our solar system. Oxygen is of particular value in this regard because it occurs in great abundance; oxygen comprises ~ 50 % by mass of most rocky materials and ranks behind only hydrogen and helium in abundance in the gas phase. With the advent of improved instrumentation, astronomical observations of stable isotope ratios are becoming a powerful new tool for probing the chemistry of young stellar objects (YSOs), making comparisons with the solar system possible.
We plan to continue our survey of the abundances of oxygen and carbon isotopes in CO in YSOs. Our purpose is to provide a Galactic context for the oxygen and carbon isotope ratios that characterize our solar system. Our focus is on CO because, after H_2, it is the most abundant molecular species in circumstellar disks reminiscent of our solar system at the time of its birth. Results will help us identify analogs in the present-day Galaxy for the environment in which our solar system formed 4.6 billion years ago.