THE STAR FORMATION NEWSLETTER

An electronic publication dedicated to early stellar evolution and molecular clouds

No. 160 — 28 February 2006 Editor: Bo Reipurth (reipurth@ifa.hawaii.edu)

Protostars and Planets V Special Issue

This issue of the Star Formation Newsletter is devoted to the 58 chapters that form the Protostars and Planets V book, edited by Bo Reipurth, David Jewitt, and Klaus Keil, and to be published in the Lunar and Planetary Institute's Space Science Series by the University of Arizona Press, Tucson.

These chapters are available at the following URL: http://www.ifa.hawaii.edu/UHNAI/ppv.htm

Under an agreement with the University of Arizona Press, the web-site will be open as a preprint-resource until the book becomes available later this year.

Unlike the usual issues of the Star Formation Newsletter, where abstracts are ordered alphabetically after the first author, the abstracts in this issue follow the order in which they will appear in the Protostars and Planets V book.

The Protostars and Planets V conference took place October 24-28, 2005 in Hawaii, and the editors are thankful to all the author teams, as well as their referees, for the dedication and hard work that enabled this book to become available only 4 months after the conference.

1. Molecular Clouds

Near-Infrared Extinction and Molecular Cloud Structure

Charles J. Lada, Joao F. Alves, and Marco Lombardi

E-mail contact: clada@cfa.harvard.edu

A little more than a decade has passed since the advent of large format infrared array cameras opened a new window on molecular cloud research. This powerful observational tool has enabled dust extinction and column density maps of molecular clouds to be constructed with unprecedented precision, depth and angular resolution. Near-infrared extinction studies can achieve column density dynamic ranges of $0.3 < A_V < 40$ magnitudes ($6 \times 10^{20} < N < 10^{23}$ cm^{-2}), allowing with one simple tracer a nearly complete description of the density structure of a cloud free from the uncertainties that typically plague measurements derived from radio spectroscopy and dust emission. This has led in recent years to an empirical characterization of the evolutionary status of dense cores based on the shapes of their radial column density profiles and revealed the best examples in nature of Bonnor-Ebert spheres. Wide-field infrared extinction mapping of large cloud complexes provides the most complete inventory of cloudy material that can be derived from observations. Such studies enable the measurement of the mass function of dense cores within a cloud, a critical piece of information for developing an understanding of the origin of the stellar IMF. Comparison with radio spectroscopic data has allowed detailed chemical structure studies of starless cores and provided some of the clearest evidence for differential depletion of molecular species in cold gaseous configurations. Recent studies have demonstrated the feasibility of infrared extinction mapping of GMCs in external galaxies, enabling the fundamental measurement of the GMC mass function in these systems. In this contribution we review recent results arising from this powerful technique, ranging from studies of Bok globules to local GMCs, to GMCs in external galaxies.

An Observational Perspective of Low-Mass Dense Cores I: Internal Physical and Chemical Properties

James Di Francesco, Neal J. Evans II, Paola Caselli, Philip C. Myers, Yancy Shirley, Yuri Aikawa, and Mario Tafalla

E-mail contact: james.difrancesco@nrc-cnrc.gc.ca

Low-mass dense cores represent the state of molecular gas associated with the earliest phases of low-mass star formation. Such cores are called “protostellar” or “starless,” depending on whether they do or do not contain compact sources of luminosity. In this chapter, the first half of the review of low-mass dense cores, we describe the numerous inferences made about the nature of starless cores as a result of recent observations, since these reveal the initial conditions of star formation. We focus on the identification of isolated starless cores and their internal physical and chemical properties, including morphologies, densities, temperatures, kinematics, and molecular abundances. These objects display a wide range of properties since they are each at different points on evolutionary paths from ambient molecular cloud material to cold, contracting, and centrally concentrated configurations with significant molecular depletions and, in rare cases, enhancements.

An Observational Perspective of Low Mass Dense Cores II: Evolution towards the Initial Mass Function

Derek Ward-Thompson, Philippe Andre, Richard Crutcher, Doug Johnstone, Toshikazu Onishi, and Christine Wilson

E-mail contact: Derek.Ward-Thompson@astro.cf.ac.uk

We review the properties of low mass dense molecular cloud cores, including starless, prestellar, and Class 0 protostellar cores, as derived from observations. In particular we discuss them in the context of the current debate surrounding the formation and evolution of cores. There exist several families of model scenarios to explain this evolution (with many variations of each) that can be thought of as a continuum of models lying between two extreme paradigms for the star and core formation process. At one extreme there is the dynamic, turbulent picture, while at the other extreme there is a slow, quasi-static vision of core evolution. In the latter view the magnetic field plays a dominant role, and it may also play some role in the former picture. Polarization and Zeeman measurements indicate that some, if not all, cores contain a significant magnetic field. Wide-field surveys constrain the timescales of the core formation and evolution processes, as well as the statistical distribution of core masses. The former indicates that prestellar cores typically live for 2–5 free-fall times, while the latter seems to determine the stellar initial mass function. In addition, multiple surveys allow one to compare core properties in different regions. From this it appears that aspects of different models may be relevant to different star-forming regions, depending on the environment. Prestellar cores in cluster-forming regions are smaller in radius and have higher column densities, by up to an order of magnitude, than isolated prestellar cores. This is probably due to the fact that in cluster-forming regions the prestellar cores are formed by fragmentation of larger, more turbulent cluster-forming cores, which in turn form as a result of strong external compression. It is then the fragmentation of the cluster-forming core (or cores) that forms a stellar cluster. In more isolated, more quiescent, star-forming regions the lower ambient pressure can only support lower density cores, which go on to form only a single star or a binary/multiple star system. Hence the evolution of cluster-forming cores appears to differ from the evolution of more isolated cores. Furthermore, for the isolated prestellar cores studied in detail, the magnetic field and turbulence appear to be playing a roughly equal role.

Extreme Deuteration and Hot Corinos: the Earliest Chemical Signatures of Low-Mass Star Formation

Cecilia Ceccarelli, Paola Caselli, Eric Herbst, Alexander G.G.M. Tielens, and Emmanuel Caux

E-mail contact: Cecilia.Ceccarelli@obs.ujf-grenoble.fr

Low-mass protostars form from condensations inside molecular clouds when gravity overwhelms thermal and magnetic supporting forces. The first phases of the formation of a solar-type star are characterized by dramatic changes not only in the physical structure but also in the chemical composition. Since PPIV (e.g., *Langer et al.*), exciting new developments have occurred in our understanding of the processes driving this chemical evolution. These developments include two new discoveries : 1) extremely enhanced molecular deuteration, which is caused by the freeze-out of heavy-element-bearing molecules onto grain mantles during the Prestellar Core and Class 0 source phases; and 2) hot corinos, which are warm and dense regions at the center of Class 0 source envelopes and which are characterized by a multitude of complex organic molecules. In this chapter we will review these two new topics, and will show how they contribute to our understanding of the first phases of solar-type stars.

Molecular Cloud Turbulence and Star Formation

Javier Ballesteros-Paredes, Ralf S. Klessen, Mordecai-Mark Mac Low, and Enrique Vazquez-Semadeni

E-mail contact: j.ballesteros@astrosmo.unam.mx

We review the properties of turbulent molecular clouds (MCs), focusing on the physical processes that influence star formation (SF). MC formation appears to occur during large-scale compression of the diffuse ISM driven by supernovae, magnetorotational instability, or gravitational instability in galactic disks of stars and gas. The compressions generate turbulence that can accelerate molecule production and produce the observed morphology. We then review the properties of MC turbulence, including density enhancements observed as clumps and cores, magnetic field structure, driving scales, the relation to observed scaling relations, and the interaction with gas thermodynamics. We argue that MC cores are dynamical, not quasistatic, objects with relatively short lifetimes not exceeding a few megayears. We review their morphology, magnetic fields, density and velocity profiles, and virial budget. Next, we discuss how MC turbulence controls SF. On global scales turbulence prevents monolithic collapse of the clouds; on small scales it promotes local collapse. We discuss its effects on the SF efficiency, and critically examine the possible relation between the clump mass distribution and the initial mass function, and then turn to the redistribution of angular momentum during collapse and how it determines the multiplicity of stellar systems. Finally, we discuss the importance of dynamical interactions between protostars in dense clusters, and the effect of the ionization and winds from those protostars on the surrounding cloud. We conclude that the interaction of self-gravity and turbulence controls MC formation and behavior, as well as the core and star formation processes within them.

Giant Molecular Clouds in Local Group Galaxies

Leo Blitz, Yasuo Fukui, Akiko Kawamura, Adam Leroy, Norikazu Mizuno, and Erik Rosolowsky

E-mail contact: blitz@astron.berkeley.edu

We present the first comparative study of extragalactic GMCs using complete data sets for entire galaxies and a uniform set of reduction and analysis techniques. We present results based on CO observations for the LMC, SMC, M33, M31, IC10 and the nucleus of M64, and make comparisons with archival Milky Way observations. Our sample includes large spirals and dwarf irregulars with metallicities that vary by an order of magnitude. GMCs in HI rich galaxies are seen to be well-correlated with HI filaments that pervade the galactic disks, suggesting that they form from pre-existing HI structures. Virial estimates of the ratio of CO line strength to H_2 column density, $X_{\rm CO}$, suggests that a value of 4 $\times 10^{20}$ cm^{-2}(K km s^{-1})$^{-1}$ is a good value to use in most galaxies (except the SMC) if the GMCs are virialized. However, if the clouds are only marginally self-gravitating, as appears to be the case judging from their appearance, half the virial value may be more appropriate. There is no clear trend of $X_{\rm CO}$ with metallicity. The clouds within a galaxy are shown to have the about the same H_2 surface density and differences between galaxies seem to be no more than a factor of ~ 2. We show that hydrostatic pressure appears to be the main factor in determining what fraction of atomic gas is turned into molecules. In the high-pressure regions often found in galactic centers, the observed properties of GMCs appear to be different from those in the found in the Local Group. From the association of tracers of star formation with GMCs in the LMC, we find that about 1/4 of the GMCs exhibit no evidence of star formation and we estimate that the lifetime of a typical GMC in these galaxies is 20–30 Myr.

2. Star Formation

Current Advances in the Methodology and Computational Simulation of the Formation of Low-Mass Stars

Richard I. Klein, Shu-ichiro Inutsuka, Paolo Padoan, and Kohji Tomisaka

E-mail contact: klein@astron.berkeley.edu

Developing a theory of low-mass star formation (~ 0.1 to 3 $M_\odot$) remains one of the most elusive and important goals of theoretical astrophysics. The star-formation process is the outcome of the complex dynamics of interstellar gas involving non-linear interactions of turbulence, gravity, magnetic field and radiation. The evolution of protostellar condensations, from the moment they are assembled by turbulent flows to the time they reach stellar densities, spans an enormous range of scales, resulting in a major computational challenge for simulations. Since the previous Protostars and Planets conference, dramatic advances in the development of new numerical algorithmic techniques have been successfully implemented on large scale parallel supercomputers. Among such techniques, Adaptive Mesh Refinement and Smooth Particle Hydrodynamics have provided frameworks to simulate the process of low-mass star formation with a very large dynamic range. It is now feasible to explore the turbulent fragmentation of molecular clouds and the gravitational collapse of cores into stars self-consistently within the same calculation. The increased sophistication of these powerful methods comes with substantial caveats associated with the use of the techniques and the interpretation of the numerical results. In this review, we examine what has been accomplished in the field and present a critique of both numerical methods and scientific results. We stress that computational simulations should obey the available observational constraints and demonstrate numerical convergence. Failing this, results of numerical simulations do not advance our understanding of low-mass star formation.

Stellar Properties of Embedded Protostars

R. J. White, T. P. Greene, G. W. Doppmann, K. R. Covey, and L. A. Hillenbrand

E-mail contact: rjw@astro.caltech.edu

Protostars are precursors to the nearly fully assembled T-Tauri and Herbig Ae/Be type stars undergoing quasi-static contraction towards the zero-age main sequence; they are in the process of acquiring the majority of their stellar mass. Although numerous young stars with spatially extended envelope-like structures appear to fit this description, their high extinction has inhibited observers from directly measuring their stellar and accretion properties and confirming that they are in fact in the main phase of mass accretion (i.e., true protostars). Recently, however, high dispersion spectrographs on large aperture telescopes have allowed observers to begin studying the stellar and accretion properties of a subset of these stars, commonly referred to as Class I stars. In this Chapter, we summarize the newly determined properties of Class I stars and compare them with observations of Class II stars, which are the more optically revealed T Tauri stars, to better understand the relative evolutionary state of the two classes. Class I stars have distributions of spectral types and stellar luminosities that are similar to those of Class II stars, suggesting similar masses and ages. The stellar luminosity and resulting age estimates, however, are especially uncertain given the difficulty in accounting for the large extinctions, scattered light emission and continuum excesses typical of Class I stars. Several candidate Class I brown dwarfs are identified. Class I stars appear to rotate somewhat more rapidly than T Tauri stars, by roughly a factor of 2 in the mean. Likewise, the disk accretion rates inferred from optical excesses and Brγ luminosities are similar to, but larger in the mean by a factor of a few than, the disk accretion rates of T Tauri stars. There is some evidence that the disk accretion rates of Class I stars are more distinct from T Tauri stars within the ρ Ophiuchi star forming region than in others (e.g., Taurus-Auriga), suggesting a possible environmental influence. The determined disk accretion rates are nevertheless 1-2 orders of magnitude less than the mass infall rates predicted by envelope models. In at least a few cases the discrepancy appears to be caused by T Tauri stars being misclassified as Class I stars because of their edge-on disk orientation. In cases where the envelope density and infall velocity have been determined directly and unambiguously, the discrepancy suggests that the stellar mass is not acquired in a steady-state fashion, but instead through brief outbursts of enhanced accretion. If the ages of some Class I stars are in fact as old as T Tauri stars, replenishment may be necessary to sustain the long-lived envelopes, possibly via continued dynamical interactions with cloud material.

The Fragmentation of Cores and the Initial Binary Population

Simon Goodwin, Pavel Kroupa, Alyssa Goodman, and Andreas Burkert

E-mail contact: S.Goodwin@sheffield.ac.uk

Almost all young stars are found in multiple systems. This suggests that protostellar cores almost always fragment into multiple objects. The observed properties of multiple systems such as their separation distribution and mass ratios provide strong constraints on star formation theories. We review the observed properties of young and old multiple systems and find that the multiplicity of stars changes. Such an evolution is probably due to (a) the dynamical decay of small-N systems and/or (b) the destruction of multiple systems within dense clusters. We review simulations of the fragmentation of rotating and turbulent molecular cores. Such models almost always produce multiple systems, however the properties of those systems do not match observations at all well. Magnetic fields appear to supress fragmentation, prehaps suggesting that they are not dynamically important in the formation of multiple systems. We finish by discussing possible reasons why theory fails to match observation, and the future prospects for this field.

The Origin of the Initial Mass Function

Ian A. Bonnell, Richard B. Larson, Hans Zinnecker

E-mail contact: iab1@st-andrews.ac.uk

We review recent advances in our understanding of the origin of the initial mass function (IMF). We emphasize the use of numerical simulations to investigate how each physical process involved in star formation affects the resulting IMF. We stress that it is insufficient to just reproduce the IMF, but that any successful model needs to account for the many observed properties of star forming regions including clustering, mass segregation and binarity. Fragmentation involving the interplay of gravity, turbulence, and thermal effects is probably responsible for setting the characteristic stellar mass. Low-mass stars and brown dwarfs can form through the fragmentation of dense filaments and disks, possibly followed by early ejection from these dense environments which truncates their growth in mass. Higher-mass stars and the Salpeter-like slope of the IMF are most likely formed through continued accretion in a clustered environment. The effects of feedback and magnetic fields on the origin of the IMF are still largely unclear. Lastly, we discuss a number of outstanding problems that need to be addressed in order to develop a complete theory for the origin of the IMF.

The Formation of Massive Stars

Henrik Beuther, Edward B.Churchwell, Christopher F. McKee, and Jonathan C. Tan

E-mail contact: hbeuther@cfa.harvard.edu

Massive stars have a profound influence on the Universe, but their formation remains poorly understood. We review the current status of observational and theoretical research in this field, describing the various stages of an evolutionary sequence that begins with cold, massive gas cores and ends with the dispersal and ionization of gas by the newly-formed star. The physical processes in massive star formation are described and related to their observational manifestations. Feedback processes and the relation of massive stars to star cluster formation are also discussed. We identify key observational and theoretical questions that future studies should address.

Ultra-Compact H II Regions and the Early Lives of Massive Stars

M.G. Hoare, S.E. Kurtz, S. Lizano, E. Keto, and P. Hofner

E-mail contact: mgh@ast.leeds.ac.uk

We review the phenomenon of ultra-compact H II regions (UCHIIs) as a key phase in the early lives of massive stars. This most visible manifestation of massive star formation begins when the Lyman continuum output from the massive young stellar object becomes sufficient to ionize the surroundings from which it was born. Knowledge of this environment is gained through an understanding of the morphologies of UCHII regions and we examine the latest developments in deep radio and mid-IR imaging. SPITZER data from the GLIMPSE survey are an important new resource in which PAH emission and the ionizing stars can be seen. These data provide good indications as to whether extended radio continuum emission around UCHII regions is part of the same structure or due to separate sources in close proximity. We review the role played by strong stellar winds from the central stars in sweeping out central cavities and causing the limb-brightened appearance. New clues to the wind properties from stellar spectroscopy and hard X-ray emission are discussed. A range of evidence from velocity structure, proper motions, the molecular environment and recent hydrodynamical modeling indicates that cometary UCHII regions require a combination of champagne flow and bow shock motion. The frequent appearance of hot cores, maser activity and massive young stellar objects (YSOs) ahead of cometary regions is noted. Finally, we discuss the class of hyper-compact H II regions or broad recombination line objects. They are likely to mark the transition soon after the breakout of the Lyman continuum radiation from the young star. Models for these objects are presented, including photo-evaporating disks and ionized accretion flows that are gravitationally trapped. Evolutionary scenarios tracing young massive stars passage through these ionized phases are discussed.

Disks around Young O-B (Proto)Stars: Observations and Theory

R. Cesaroni, D. Galli, G. Lodato, C.M. Walmsley, and Q. Zhang

E-mail contact: cesa@arcetri.astro.it

Disks are a natural outcome of the star formation process in which they play a crucial role. Luminous, massive stars of spectral type earlier than B4 are likely to be those that benefit most from the existence of accretion disks, which may significantly reduce the effect of radiation pressure on the accreting material. The scope of the present contribution is to review the current knowledge about disks in young high-mass (proto)stars and discuss their implications. The issues of disk stability and lifetime are also discussed. We conclude that for protostars of less than $\sim 20\ M_\odot$, disks with mass comparable to that of the central star are common. Above this limit the situation is unclear and there are no good examples of proto O4–O8 stars surrounded by accretion disks: in these objects only huge, massive, toroidal, non-equilibrium rotating structures are seen. It is clear on the other hand that the observed disks in stars of 10–20 $M_\odot$ are likely to be unstable and with short lifetimes.

3. Outflows

Observations of Jets and Outflows from Young Stars

John Bally, Bo Reipurth, and Christopher J.Davis

E-mail contact: bally@casa.colorado.edu

This review concentrates on observations of outflows from young stars during the last 6 years. Recent developments include detections of an increasing number of Herbig-Haro flows at X-rays and UV wavelengths, high resolution studies of irradiated jets with HST, wide-field imaging of parsec-scale outflows with ground-based CCDs and near-IR imagers, complete surveys of visual and near-IR emission from shocks in the vicinity of entire molecular clouds with wide-field imagers, far infrared studies with ISO and the Spitzer Space Telescope, and high angular sub-mm, mm, and cm wavelength aperture synthesis array data-cubes showing both the spatial and velocity structure of jets and outflows.

Toward Resolving the Outflow Engine: An Observational Perspective

Tom Ray, Catherine Dougados, Francesca Bacciotti, Jochen Eisloeffel, and Antonio Chrysostomou

E-mail contact: tr@cp.dias.ie

Jets from young stars represent one of the most striking signposts of star formation. The phenomenon has been researched for over two decades and there is now general agreement that such jets are generated as a by-product of accretion; most likely by the accretion disk itself. Thus they mimic what occurs in more exotic objects such as active galactic nuclei and micro-quasars. The precise mechanism for their production however remains a mystery. To a large degree, progress is hampered observationally by the embedded nature of many jet sources as well as a lack of spatial resolution: Crude estimates, as well as more sophisticated models, nevertheless suggest that jets are accelerated and focused on scales of a few AU at most. It is only in the past few years however that we have begun to probe such scales in detail using classical T Tauri stars as touchstones. Application of adaptive optics, data provided by the HST, use of specialised techniques such as spectro-astrometry, and the development of spectral diagnostic tools, are beginning to reveal conditions in the jet launch zone. This has helped enormously to constrain models. Further improvements in the quality of the observational data are expected when the new generation of interferometers come on-line. Here we review some of the most dramatic findings in this area since Protostars and Planets IV including indications for jet rotation, i.e. that they transport angular momentum. We will also show how measurements, such as those of width and the velocity field close to the source, suggest jets are initially launched as warm magneto-centrifugal disk winds. Finally the power of the spectro-astrometric technique, as a probe of the central engine in very low mass stars and brown dwarfs, is shown by revealing the presence of a collimated outflow from a brown dwarf for the first time, copying what occurs on a larger scale in T Tauri stars.

Molecular Outflows in Low- and High-Mass Star Forming Regions

Hector G. Arce, Debra Shepherd, Frdric Gueth, Chin-Fei Lee, Rafael Bachiller, Alex Rosen, and Henrik Beuther

E-mail contact: harce@amnh.org

We review the known properties of molecular outflows from low- and high-mass young stars. General trends among outflows are identified, and the most recent studies on the morphology, kinematics, energetics, and evolution of molecular outflows are discussed, focusing on results from high-resolution millimeter observations. We review the existing four broad classes of outflow models and compare numerical simulations with the observational data. A single class of models cannot explain the range of morphological and kinematic properties that are observed, and we propose a possible solution. The impact of outflows on their cloud is examined, and we review how outflows can disrupt their surrounding environment, through the clearing of gas and the injection of momentum and energy onto the gas at distances from their powering sources from about 0.01 to a few pc. We also discuss the effects of shock-induced chemical processes on the ambient medium, and how these processes may act as a chemical clock to date outflows. Lastly, future outflow research with existing and planned millimeter and submillimeter instruments is presented.

Jets and Bipolar Outflows from Young Stars: Theory and Observational Tests

Hsien Shang, Zhi-Yun Li, and Naomi Hirano

E-mail contact: shang@asiaa.sinica.edu.tw

Jets and outflows from young stars are an integral part of the star formation process. A particular framework for explaining these phenomena is the X-wind theory. Since PPIV, we have made good progress in modeling the jet phenomena and their associated fundamental physical processes, in both deeply embedded Class I objects and more revealed classical T Tauri stars. In particular, we have improved the treatment of the atomic physics and chemistry for modeling jet emission, including reaction rates and interaction cross-sections, as well as ambipolar diffusion between ions and neutrals. We have broadened the original X-wind picture to include the winds driven magnetocentrifugally from the innermost disk regions. We have carried numerical simulations that follow the wind evolution from the launching surface to large, observable distances. The interaction between the magnetocentrifugal wind and a realistic ambient medium was also investigated. It allows us to generalize the shell model of *Shu et al.* (1991) to unify the the jet-driven and wind-driven scenarios for molecular outflow production. In addition, we review related theoretical works on jets and outflows from young stars, and make connection between theory and recent observations, particularly those from HST/STIS, VLA and SMA.

Disk Winds, Jets, and Outflows: Theoretical and Computational Foundations

Ralph E. Pudritz, Rachid Ouyed, Christian Fendt, and Axel Brandenburg

E-mail contact: pudritz@thyme.physics.mcmaster.ca

We review advances in the theoretical and computational studies of disk winds, jets and outflows including: the connection between accretion and jets, the launch of jets from magnetized disks, the coupled evolution of jets and disks, the interaction of magnetized young stellar objects with their surrounding disks and the relevance to outflows, and finally, the link between jet formation and gravitational collapse. We also address the important predictions of the theory on jet kinematics, collimation, and rotation, that have recently been confirmed by high spatial and spectral resolution HST observations. Finally, we show that disk winds have a universal character that can account for jets and outflows during the formation of massive stars as well as brown dwarfs.

4. Young Stars and Clusters

The Rotation of Young Low-Mass Stars and Brown Dwarfs

William Herbst, Jochen Eislöffel, Reinhard Mundt, and Alexander Scholz

E-mail contact: wherbst@wesleyan.edu

We review the current state of our knowledge concerning the rotation and angular momentum evolution of young stellar objects and brown dwarfs from a primarily observational view point. There has been a tremendous growth in the number of young, low-mass objects with measured rotation periods over the last five years, due to the application of wide field imagers on 1-2 m class telescopes. Periods are typically accurate to 1% and available for about 1700 stars and 30 brown dwarfs in young clusters. Discussion of angular momentum evolution also requires knowledge of stellar radii, which are poorly known for pre-main sequence stars. It is clear that rotation rates at a given age depend strongly on mass; higher mass stars (0.4-1.2 $M_\odot$) have longer periods than lower mass stars and brown dwarfs. On the other hand, specific angular momentum is approximately independent of mass for low mass pre-main sequence stars and young brown dwarfs. A spread of about a factor of 30 is seen at any given mass and age. The evolution of rotation of solar-like stars during the first 100 Myr is discussed. A broad, bimodal distribution exists at the earliest observable phases ($\sim$1 Myr) for stars more massive than 0.4 $M_\odot$. The rapid rotators (50-60% of the sample) evolve to the ZAMS with little or no angular momentum loss. The slow rotators continue to lose substantial amounts of angular momentum for up to 5 Myr, creating the even broader bimodal distribution characteristic of 30-120 Myr old clusters. Accretion disk signatures are more prevalent among slowly rotating PMS stars, indicating a connection between accretion and rotation. Disks appear to influence rotation for, at most, $\sim$5 Myr, and considerably less than that for the majority of stars. This time interval is comparable to the *maximum* life time of accretion disks derived from near-infrared studies, and may be a useful upper limit to the time available for forming giant planets. If the dense clusters studied so far are an accurate guide, then the typical solar-like star may have only $\sim$1 Myr for this task. There is less data available for very low mass stars and brown dwarfs but the indication is that the same mechanisms are influencing their rotation as for the solar-like stars. However, it appears that both disk interactions and stellar winds are less efficient at braking these objects. We also review our knowledge of the various types of variability of these objects over as broad as possible a mass range with particular attention to magnetically induced cool spots and magnetically channeled variable mass accretion.

X-ray Properties of Young Stars and Stellar Clusters

Eric Feigelson, Leisa Townsley, Manuel Guedel, and Keivan Stassun

E-mail contact: edf@astro.psu.edu

Although the environments of star and planet formation are thermodynamically cold, substantial X-ray emission from $10 - 100$ MK plasmas is present. In low mass pre-main sequence stars, X-rays are produced by violent magnetic reconnection flares. In high mass O stars, they are produced by wind shocks on both stellar and parsec scales. The recent *Chandra* Orion Ultradeep Project, *XMM-Newton* Extended Survey of Taurus, and *Chandra* studies of more distant high-mass star forming regions reveal a wealth of X-ray phenomenology and astrophysics. X-ray flares mostly resemble solar-like magnetic activity from multipolar surface fields, although extreme flares may arise in field lines extending to the protoplanetary disk. Accretion plays a secondary role. Fluorescent iron line emission and absorption in inclined disks demonstrate that X-rays can efficiently illuminate disk material. The consequent ionization of disk gas and irradiation of disk solids addresses a variety of important astrophysical issues of disk dynamics, planet formation, and meteoritics. New observations of massive star forming environments such as M 17, the Carina Nebula and 30 Doradus show remarkably complex X-ray morphologies including the low-mass stellar population, diffuse X-ray flows from blister HII regions, and inhomogeneous superbubbles. X-ray astronomy is thus providing qualitatively new

insights into star and planet formation.

The Taurus Molecular Cloud: Multi-Wavelength Surveys with XMM-Newton, the Spitzer Space Telescope, and CFHT

Manuel Güdel, Deborah L. Padgett, and Catherine Dougados

E-mail contact: guedel@astro.phys.ethz.ch

The Taurus Molecular Cloud (TMC) ranks among the nearest and best-studied low-mass star formation regions. It contains numerous prototypical examples of deeply embedded protostars with massive disks and outflows, classical and weak-lined T Tauri stars, jets and Herbig-Haro objects, and a growing number of confirmed brown dwarfs. Star formation is ongoing, and the cloud covers all stages of pre-main sequence stellar evolution. We have initiated comprehensive surveys of the TMC, in particular including: (i) a deep X-ray survey of about 5 sq. degrees with *XMM-Newton*; (ii) a near-to-mid-infrared photometric survey of ≈30 sq. degrees with the Spitzer Space Telescope, mapping the entire cloud in all available photometric bands; and (iii) a deep optical survey using the Canada-France-Hawaii Telescope. Each wavelength regime contributes to the understanding of different aspects of young stellar systems. *XMM-Newton* and Spitzer mapping of the central TMC is a real breakthrough in disk characterization, offering the most detailed studies of correlations between disk properties and high-energy magnetic processes in any low-mass star-forming region, extending also to brown dwarfs in which disk physics is largely unexplored. The optical data critically complements the other two surveys by allowing clear source identification with $0.8''$ resolution, identifying substellar candidates, and, when combined with NIR data, providing the wavelength baseline to probe NIR excess emission. We report results and correlation studies from these surveys. In particular, we address the physical interpretation of our new X-ray data, discuss the entire young stellar population from embedded protostars to weak-lined T Tau stars and their environment, and present new results on the low-mass population of the TMC, including young brown dwarfs.

The Low-mass Populations in OB Associations

Cesar Briceno, Thomas Preibisch, William H. Sherry, Eric E. Mamajek, Robert D. Mathieu, Frederick M. Walter, and Hans Zinnecker

E-mail contact: briceno@cida.ve

Low-mass stars ($0.1 \leq \mathrm{M} \leq 1\ M_{\odot}$) in OB associations are key to addressing some of the most fundamental problems in star formation. The low-mass stellar populations of OB associations provide a snapshot of the fossil star-formation record of giant molecular cloud complexes. Large scale surveys have identified hundreds of members of nearby OB associations, and revealed that low-mass stars exist wherever high-mass stars have recently formed. The spatial distribution of low-mass members of OB associations demonstrate the existence of significant substructure (”subgroups”). This ”discretized” sequence of stellar groups is consistent with an origin in short-lived parent molecular clouds within a Giant Molecular Cloud Complex. The low-mass population in each subgroup within an OB association exhibits little evidence for significant age spreads on time scales of ∼ 10 Myr or greater, in agreement with a scenario of rapid star formation and cloud dissipation. The Initial Mass Function (IMF) of the stellar populations in OB associations in the mass range $0.1 \leq \mathrm{M} \leq 1\ M_{\odot}$ is largely consistent with the field IMF, and most low-mass pre-main sequence stars in the solar vicinity are in OB associations. These findings agree with early suggestions that *the majority of stars in the Galaxy were born in OB associations.* The most recent work further suggests that a significant fraction of the stellar population may have their origin in the more spread out regions of OB associations, instead of all being born in dense clusters. Ground-based and space-based (Spitzer Space Telescope) infrared studies have provided robust evidence that primordial accretion disks around low-mass stars dissipate on timescales of a few Myr. However, on close inspection there appears to be great variance in the disk dissipation timescales for stars of a given mass in OB associations. While some stars appear to lack disks at ∼1 Myr, a few appear to retain accretion disks up to ages of ∼10-20 Myr.

The Structure and Evolution of Young Stellar Clusters

Lori Allen, S. Thomas Megeath, Robert Gutermuth, Philip C. Myers, Scott Wolk, Fred Adams, James Muzerolle, Erick Young, and Judith L. Pipher

E-mail contact: leallen@cfa.harvard.edu

We examine the properties of embedded clusters within 1 kiloparsec using new data from the *Spitzer Space Telescope*, as well as recent results from 2MASS and other ground-based near-infrared surveys. We use surveys of entire molecular clouds to understand the range and distribution of cluster membership, size and surface density. The *Spitzer* data demonstrate clearly that there is a continuum of star-forming environments, from relative isolation to dense clusters. The number of members of a cluster is correlated with the cluster radius, such that the average surface density of clusters having a few to a thousand members varies by a factor of only a few. The spatial distributions of *Spitzer*-identified young stellar objects frequently show elongation, low density halos, and sub-clustering. The spatial distributions of protostars resemble the distribution of dense molecular gas, suggesting that their morphologies result directly from fragmentation of the natal gas. We also examine the effects of the cluster environments on star and planet formation. Although Far-UV and Extreme-UV radiation from massive stars can truncate disks in a few million years, fewer than half of the young stars in our sample (embedded clusters within 1 kpc) are found in regions of strong FUV and EUV fields. Typical volume densities and lifetimes of the observed clusters suggest that dynamical interactions are not an important mechanism for truncating disks on solar system size scales.

5. Young Binaries – Brown Dwarfs

New Observational Frontiers in the Multiplicity of Young Stars

Gaspard Duchêne, Eduardo Delgado-Donate, Karl E. Haisch Jr, Laurent Loinard, and Luis F. Rodríguez

E-mail contact: Gaspard.Duchene@obs.ujf-grenoble.fr

It has now been known for over a decade that low-mass stars located in star-forming regions are very frequently members of binary and multiple systems, even more so than main sequence stars in the solar neighborhood. This high multiplicity rate has been interpreted as the consequence of the fragmentation of small molecular cores into a few seed objects that accrete to their final mass from the remaining material and dynamically evolve into stable multiple systems, possibly producing a few ejecta in the process. Analyzing the statistical properties of young multiple systems in a variety of environments therefore represents a powerful approach to place stringent constraints on star formation theories. In this contribution, we first review a number of recent results related to the multiplicity of T Tauri stars. We then present a series of studies focusing on the multiplicity and properties of optically-undetected, heavily embedded protostars. These objects are much younger than the previously studied pre-main sequence stars, and they therefore offer a closer look at the primordial population of multiple systems. In addition to these observational avenues, we present new results of a series of numerical simulations that attempt to reproduce the fragmentation of small molecular cores into multiple systems, and compare these results to the observations.

Disk Evolution in Young Binaries: from Observations to Theory

J.-L. Monin, C. Clarke, L. Prato, and C. McCabe

E-mail contact: jean-louis.monin@obs.ujf-grenoble.fr

The formation of a binary system surrounded by disks is the most common outcome of stellar formation. Hence studying and understanding the formation and the evolution of binary systems and associated disks is a cornerstone of star formation science. Moreover, since the components within binary systems are coeval and the sizes of their disks are fixed by the tidal truncation of their companion, binary systems provide an ideal ”laboratory” in which to study disk evolution under well defined boundary conditions. Since the previous edition of Protostars and Planets, large diameter (8−10m) telescopes have been optimized and equipped with adaptive optics systems, providing diffraction-limited observations in the near-infrared where most of the emission of the disks can be traced. These cutting edge facilities provide observations of the inner parts of circumstellar and circumbinary disks in binary systems with unprecedented detail. It is therefore a timely exercise to review the observational results of the last five years and to attempt to interpret them in a theoretical framework. In this paper, we review observations of several inner disk diagnostics in multiple systems, including hydrogen emission lines (indicative of ongoing accretion), $K-L$ and $K-N$ color excesses (evidence of warm inner disks), and polarization (indicative of the relative orientations of the disks around each component). We examine to what degree these properties are correlated within binary systems and how this degree of correlation depends on parameters such as separation and binary mass ratio. These findings will be interpreted both in terms of models that treat each disk as an isolated reservoir and those in which the disks are subject to re-supply from some form of circumbinary reservoir, the observational evidence for which we will also critically review. The planet forming potential of multiple star systems is discussed in terms of the relative lifetimes of disks around single stars, binary primaries and binary secondaries. Finally, we summarize several potentially revealing observational problems and future projects that could provide further insight into disk evolution in the coming decade.

Dynamical Mass Measurements of Pre-Main-Sequence Stars: Fundamental Tests of the Physics of Young Stars

R. D. Mathieu, I. Baraffe, M. Simon, K. G. Stassun, and R. White

E-mail contact: mathieu@astro.wisc.edu

There are now 23 dynamical mass measurements for PMS stars of less than 2 $M_\odot$, with most of the measured stars having masses greater than 0.5 $M_\odot$. The masses of two PMS brown dwarfs have also been precisely measured. The most important application of these dynamical mass measurements has been to provide tests of theoretical masses derived from PMS stellar evolution models. On average most models in use today predict stellar masses to within 20%; however, the predictions for individual stars can be in error by 50% or more. Now that dynamical mass measurements are relatively abundant, and will become more so with the application of ground-based optical/infrared interferometers, the primary limitations to such tests have become systematic errors in the determination of the stellar properties necessary for the comparison with evolutionary models, such as effective temperature, luminosity, and radii. Additional dynamical mass determinations between 0.5 $M_\odot$ and 2 $M_\odot$ will not likely improve the constraints on evolutionary models until these systematic uncertainties in measurements of stellar properties are reduced. The nature and origin of these uncertainties, as well as the dominant physical issues in theoretical PMS stellar evolution models, are discussed. There are immediately realizable possibilities for improving the characterizations of those stars with dynamical mass measurements. Additional dynamical mass measurements for stars below 0.5 $M_\odot$ are also very much needed.

Not Alone: Tracing the Origins of Very Low Mass Stars and Brown Dwarfs Through Multiplicity Studies

Adam J. Burgasser, I. Neill Reid, Nick Siegler, Laird Close, Peter Allen, Patrick Lowrance, and John Gizis

E-mail contact: ajb@space.mit.edu

The properties of multiple stellar systems have long provided important empirical constraints for star formation theories, enabling (along with several other lines of evidence) a concrete, qualitative picture of the birth and early evolution of normal stars. At very low masses (VLM; $M \leq 0.1\ M_\odot$), down to and below the hydrogen burning minimum mass, our understanding of formation processes is not as clear, with several competing theories now under consideration. One means of testing these theories is through the empirical characterization of VLM multiple systems. Here, we review the results of various VLM multiplicity studies to date. These systems can be generally characterized as closely separated (93% have projected separations $\Delta < 20$ AU), near equal-mass (77% have $M_2/M_1 \geq 0.8$) and occurring infrequently (perhaps 10–30% of systems are binary). Both the frequency and maximum separation of stellar and brown dwarf binaries steadily decrease for lower system masses, suggesting that VLM binary formation and/or evolution may be a mass-dependent process. There is evidence for a fairly rapid decline in the number of loosely-bound systems below $\sim$0.3 $M_\odot$, corresponding to a factor of 10–20 increase in the minimum binding energy of VLM binaries as compared to more massive stellar binaries. This wide-separation "desert" is present among both field ($\sim$1–5 Gyr) and older ($>$ 100 Myr) cluster systems, while the youngest ($\leq$10 Myr) VLM binaries, particularly those in nearby, low-density star forming regions, appear to have somewhat different systemic properties. We compare these empirical trends to predictions laid out by current formation theories, and outline future observational studies needed to probe the full parameter space of the lowest mass multiple systems.

The Formation of Brown Dwarfs: Observations

Kevin L. Luhman, Viki Joergens, Charles Lada, James Muzerolle, Ilaria Pascucci, and Russel White

E-mail contact: kluhman@astro.psu.edu

We review the current state of observational work on the formation of brown dwarfs, focusing on their initial mass function, velocity and spatial distributions at birth, multiplicity, accretion, and circumstellar disks. The available measurements of these various properties are consistent with a common formation mechanism for brown dwarfs and stars. In particular, the existence of widely separated binary brown dwarfs and a probable isolated proto-brown dwarf indicate that some substellar objects are able to form in the same manner as stars through unperturbed cloud fragmentation. Additional mechanisms such as ejection and photoevaporation may play a role in the birth of some brown dwarfs, but there is no observational evidence to date to suggest that they are the key elements that make it possible for substellar bodies to form.

The Formation of Brown Dwarfs: Theory

Anthony Whitworth, Matthew R. Bate, Åke Nordlund, Bo Reipurth, and Hans Zinnecker

E-mail contact: ant@astro.cf.ac.uk

We review five mechanisms for forming brown dwarfs: *(i)* turbulent fragmentation of molecular clouds, producing very low-mass prestellar cores by shock compression; *(ii)* collapse and fragmentation of more massive prestellar cores; *(iii)* disc fragmentation; *(iv)* premature ejection of protostellar embryos from their natal cores; and *(v)* photo-erosion of pre-existing cores overrun by HII regions. These mechanisms are not mutually exclusive. Their relative importance probably depends on environment, and should be judged by their ability to reproduce the brown-dwarf IMF, the distribution and kinematics of newly formed brown dwarfs, the binary statistics of brown dwarfs, the ability of brown dwarfs to retain discs, and hence their ability to sustain accretion and outflows. This will require more sophisticated numerical modelling than is presently possible, in particular more realistic initial conditions and more realistic treatments of radiation transport, angular momentum transport and magnetic fields. We discuss the minimum mass for brown dwarfs, and how brown dwarfs should be distinguished from planets.

6. Circumstellar Disks

Magnetospheric Accretion in Classical T Tauri Stars

J. Bouvier, S. H. P. Alencar, T. J. Harries, C.M. Johns-Krull, and M.M. Romanova

E-mail contact: Jerome.Bouvier@obs.ujf-grenoble.fr

The inner 0.1 AU around accreting T Tauri stars hold clues to many physical processes that characterize the early evolution of solar-type stars. The accretion-ejection connection takes place at least in part in this compact magnetized region around the central star, with the inner disk edge interacting with the star's magnetosphere thus leading simultaneously to magnetically channeled accretion flows and to high velocity winds and outflows. The magnetic star-disk interaction is thought to have strong implications for the angular momentum evolution of the central system, the inner structure of the disk, and possibly for halting the migration of young planets close to the stellar surface. We review here the current status of magnetic field measurements in T Tauri stars, the recent modeling efforts of the magnetospheric accretion process, including both radiative transfer and multi-D numerical simulations, and summarize current evidence supporting the concept of magnetically-channeled accretion in young stars. We also discuss the limits of the models and highlight observational results which suggest that the star-disk interaction is a highly dynamical and time variable process in young stars.

Interferometric Spectro-imaging of Molecular Gas in Proto-Planetary Disks

Anne Dutrey, Stephane Guilloteau, and Paul Ho

E-mail contact: anne.dutrey@obs.u-bordeaux1.fr

Proto-planetary disks are found to orbit around low and intermediate mass stars. Current theories predict that these disks are the likely sites for planet formation. In this review, we summarize the improvement in our knowledge of their observed molecular properties since PPIV. This is timely since a new facility, the Submillimeter-Array (SMA), has recently begun operation and has opened the submillimeter atmospheric windows to interferometry, allowing studies of warmer gas and dust in disks at subarcsecond resolution. Using results from the IRAM array and the SMA, we focus on two complementary main topics: 1) the determination of the physical structure of the disks from multi-transition CO isotopic analysis of high angular resolution millimeter interferometric data and 2) the observations of molecules other than CO (and isotopes), which enable investigations of the chemistry in proto-planetary disks. In particular, we emphasize how to handle the available data to provide relevant constraints on the thermal, physical and chemical structure of the disks as a function of radius, within the current limitations in sensitivity and angular resolution of the existing arrays. These results suggest the importance of photo-dissociation effects and X-ray heating. They also reveal unexpected results, such as the discovery of non-Keplerian rotation in the AB Aur disk. We also discuss how to extrapolate these results in the context of the tremendous capabilities of the ALMA project currently under construction in Chile.

Gaseous Inner Disks

Joan R. Najita, John S, Carr, Alfred E. Glassgold, and Jeff A.Valenti

E-mail contact: najita@noao.edu

As the likely birthplaces of planets and an essential conduit for the buildup of stellar masses, inner disks are of fundamental interest in star and planet formation. Studies of the gaseous component of inner disks are of interest because of their ability to probe the dynamics, physical and chemical structure, and gas content of this region. We review the observational and theoretical developments in this field, highlighting the potential of such studies to, e.g., measure inner disk truncation radii, probe the nature of the disk accretion process, and chart the evolution in the gas content of disks. Measurements of this kind have the potential to provide unique insights on the physical processes governing star and planet formation.

Multi-Wavelength Imaging of Young Stellar Object Disks: Toward an Understanding of Disk Structure and Dust Evolution

Alan M. Watson, Karl R. Stapelfeldt, Kenneth Wood, and Francois Menard

E-mail contact: a.watson@astrosmo.unam.mx

We review recent progress in high-resolution imaging of scattered light from disks around young stellar objects. Many new disks have been discovered or imaged in scattered light, and improved instrumentation and observing techniques have led to better disk images at optical, near-infrared, and thermal-infrared wavelengths. Multi-wavelength datasets are particularly valuable, as dust particle properties have wavelength dependencies. Modeling the changes in scattered-light images with wavelength gives direct information on the dust properties. This has now been done for several different disks. The results indicate that modest grain growth has taken place in some of these systems. Scattered-light images also provide useful constraints on the disk structure, especially when combined with long-wavelength SEDs. There are tentative suggestions in some disks that the dust may have begun to settle. The next few years should see this work extended to many more disks; this will clarify our understanding of the evolution of protoplanetary dust and disks.

The Circumstellar Environments of Young Stars at AU Scales

Rafael Millan-Gabet, Fabien Malbet, Rachel Akeson, Christoph Leinert, John Monnier, and Rens Waters

E-mail contact: rafael@ipac.caltech.edu

We review recent advances in our understanding of the inner-most regions of the circumstellar environment around young stars made possible by the technique of long baseline interferometry at infrared wavelengths. Near-infrared observations directly probe the location of the hottest dust. The characteristic sizes found are much larger than previously thought, and strongly correlate with the luminosity of the central young stars. This relation has motivated in part a new class of models of the inner disk structure. The first mid-infrared observations have probed disk emission over a larger range of scales, and spectrally resolved interferometry has for the first time revealed mineralogy gradients in the disk. These new measurements provide crucial information on the structure and physical properties of young circumstellar disks, as initial conditions for planet formation. In addition to summarizing these pioneering observations, we expose the many open questions that accompany the impressive progress made, and anticipate the experimental and modelling efforts that promise to help elucidate the diverse phenomena associated with the close circumstellar environment of young stars.

Models of the Structure and Evolution of Protoplanetary Disks

C.P. Dullemond, D. Hollenbach, I. Kamp, and P. D'Alessio

E-mail contact: dullemon@mpia.de

We review advances in the modeling of protoplanetary disks. This review will focus on the regions of the disk beyond the dust sublimation radius, i.e. beyond 0.1 - 1 AU, depending on the stellar luminosity. We will be mostly concerned with models that aim to fit spectra of the dust continuum or gas lines, and derive physical parameters from these fits. For optically thick disks, these parameters include the accretion rate through the disk onto the star, the geometry of the disk, the dust properties, the surface chemistry and the thermal balance of the gas. For the latter we are mostly concerned with the upper layers of the disk, where the gas and dust temperature decouple and a photoevaporative flow may originate. We also briefly discuss optically thin disks, focusing mainly on the gas, not the dust. The evolution of these disks is dominated by accretion, viscous spreading, photoevaporation, and dust settling and coagulation. The density and temperature structure arising from the surface layer models provide input to models of photoevaporation, which occurs largely in the outer disk. We discuss the consequences of photoevaporation on disk evolution and planet formation.

Evolution of Circumstellar Disks Around Normal Stars: Placing Our Solar System in Context

Michael R. Meyer, Dana E. Backman, Alycia Weinberger, and Mark C. Wyatt

E-mail contact: mmeyer@as.arizona.edu

Over the past 10 years abundant evidence has emerged that many (if not all) stars are born with circumstellar disks. Understanding the evolution of post–accretion disks can provide strong constraints on theories of planet formation and evolution. In this review, we focus on developments in understanding: a) the evolution of the gas and dust content of circumstellar disks based on observational surveys, highlighting new results from the Spitzer Space Telescope; b) the physical properties of specific systems as a means to interpret the survey results; c) theoretical models used to explain the observations; d) an evolutionary model of our own solar system for comparison to the observations of debris disks around other stars; and e) how these new results impact our assessment of whether systems like our own are common or rare compared to the ensemble of normal stars in the disk of the Milky Way.

7. Planet Formation and Extrasolar Planets

Formation of Giant Planets

Jack J. Lissauer and David J. Stevenson

E-mail contact: jlissauer@mail.arc.nasa.gov

The observed properties of giant planets, models of their evolution and observations of protoplanetary disks provide constraints on the formation of gas giant planets. The four largest planets in our Solar System contain considerable quantities of hydrogen and helium; these gasses could not have condensed into solid planetesimals within the protoplanetary disk. Jupiter and Saturn are mostly hydrogen and helium, but have larger abundances of heavier elements than does the Sun. Neptune and Uranus are primarily composed of heavier elements. The transiting extrasolar planet HD 149026 b, which is slightly more massive than is Saturn, appears to have comparable amounts of light gases and heavy elements. The other observed transiting exoplanets are primarily hydrogen and helium, but may contain supersolar abundances of heavy elements. Spacecraft flybys and observations of satellite orbits provide estimates of the gravitational moments of the giant planets in our Solar System, which in turn provide information on the internal distribution of matter within Jupiter, Saturn, Uranus and Neptune. Atmospheric thermal structure and heat flow measurements constrain the interior temperatures of these planets. Internal processes may cause giant planets to become more compositionally differentiated or alternatively more homogeneous; high-pressure laboratory experiments provide data useful for modeling these processes. The preponderance of evidence supports the core nucleated gas accretion model. According to this model, giant planets begin their growth by the accumulation of small solid bodies, as do terrestrial planets. However, unlike terrestrial planets, the giant planet cores grow massive enough to accumulate substantial amounts of gas before the protoplanetary disk dissipates. The primary question regarding the core nucleated growth model is under what conditions can planets develop cores sufficiently massive to accrete gas envelopes within the lifetimes of gaseous protoplanetary disks.

Gravitational Instabilities in Gaseous Protoplanetary Disks and Implications for Giant Planet Formation

Richard H. Durisen, Alan P. Boss, Lucio Mayer, Andrew F. Nelson, Thomas Quinn, and W.K.M. Rice

E-mail contact: durisen@astro.indiana.edu

Protoplanetary gas disks are likely to experience gravitational instabilites (GI's) during some phase of their evolution. Density perturbations in an unstable disk grow on a dynamic time scale into spiral arms that produce efficient outward transfer of angular momentum and inward transfer of mass through gravitational torques. In a cool disk with rapid enough cooling, the spiral arms in an unstable disk form self-gravitating clumps. Whether gas giant protoplanets can form by such a disk instability process is the primary question addressed by this review. We discuss the wide range of calculations undertaken by ourselves and others using various numerical techniques, and we report preliminary results from a large multi-code collaboration. Additional topics include – triggering mechanisms for GI's, disk heating and cooling, orbital survival of dense clumps, interactions of solids with GI-driven waves and shocks, and hybrid scenarios where GI's facilitate core accretion. The review ends with a discussion of how well disk instability and core accretion fare in meeting observational constraints.

Gaseous Planets, Protostars and Young Brown Dwarfs: Birth and Fate

G. Chabrier, I. Baraffe, F. Selsis, T. Barman, P. Hennebelle, and Y. Alibert

E-mail contact: chabrier@ens-lyon.fr

We review recent theoretical progress aimed at understanding the formation and the early stages of evolution of giant planets, low-mass stars and brown dwarfs. Calculations coupling giant planet formation, within a modern version of the core accretion model that includes planet migration and disk evolution, and subsequent evolution yield consistent determinations of the planet structure and evolution. Uncertainties in the initial conditions, however, translate into large uncertainties in the luminosity at early ages. It is thus not possible to say whether young planets are faint or bright compared with low-mass young brown dwarfs. We review the effects of irradiation and evaporation on the evolution of short period planets and argue that substantial mass loss may have occurred for these objects. Concerning star formation, geometrical effects in protostar core collapse are examined by comparing 1D and 3D calculations. Spherical collapse is shown to significantly overestimate the core inner density and temperature and thus to yield incorrect initial conditions for pre-main sequence or young brown dwarf evolution. Accretion affects the evolution of young brown dwarfs and yields more compact structures for a given mass and age, thus fainter luminosities, confirming previous studies for pre-main sequence stars. This can lead to severe misinterpretations of the mass and/or age of young accreting objects from their location in the HR diagram. Since accretion covers only a limited fraction of the protostar surface, we argue that newborn stars and brown dwarfs should appear rapidly over an extended area in the HR diagram, depending on their accretion history, rather than on a well defined birth line. Finally, we suggest that the distinction between planets and brown dwarfs be based on an observational diagnostic, reflecting the different formation mechanisms between these two distinct populations, rather than on an arbitrary, confusing definition.

The Diverse Origins of Terrestrial-Planet Systems

Makiko Nagasawa, Edward W. Thommes, Scott J. Kenyon, Benjamin C. Bromley, and Doug Lin

E-mail contact: nagaswmk@cc.nao.ac.jp

We review the theory of terrestrial planet formation as it currently stands. In anticipation of forthcoming observational capabilities, the central theoretical issues to be addressed are: 1) what is the frequency of terrestrial planets around nearby stars, 2) what mechanisms determine the mass distribution, dynamical structure and the stability of terrestrial-planet systems, and 3) what processes regulated the chronological sequence of gas and terrestrial planet formation in the Solar System? In the context of Solar System formation, the last stage of terrestrial planet formation will be discussed along with cosmochemical constraints and different dynamical architectures together with important processes such as runaway and oligarchic growth. Observations of dust around other stars, combined with models of dust production during accretion, give us a window on exo-terrestrial planet formation. We discuss the latest results from such models, including predictions which will be tested by next-generation instruments such as GMT and ALMA.

Disk-Planet Interactions During Planet Formation

J.C.B. Papaloizou, R.P. Nelson, W. Kley, F.S. Masset, and P. Artymowicz

E-mail contact: J.C.B.Papaloizou@damtp.cam.ac.uk

The discovery of close orbiting extrasolar giant planets led to extensive studies of disk planet interactions and the forms of migration that can result as a means of accounting for their location. Early work established the type I and type II migration regimes for low mass embedded planets and high mass gap forming planets respectively. While providing an attractive means of accounting for close orbiting planets intially formed at several *AU*, inward migration times for objects in the earth mass range were found to be disturbingly short, making the survival of giant planet cores an issue. Recent progress in this area has come from the application of modern numerical techniques wich make use of up to date supercomputer resources. These have enabled higher resolution studies of the regions close to the planet and the initiation of studies of planets interacting with disks undergoing MHD turbulence. This work has led to indications of how the inward migration of low to intermediate mass planets could be slowed down or reversed. In addition, the possibility of a new very fast type III migration regime, that can be directed inwards or outwards, that is relevant to partial gap forming planets in massive disks has been investigated.

Planet Migration in Planetesimal Disks

Harold E. Levison, Alessandro Morbidelli, Rodney Gomes, and Dana Backman

E-mail contact: hal@boulder.swri.edu

Planets embedded in a planetesimal disk will migrate as a result of angular momentum and energy conservation as the planets scatter the planetesimals that they encounter. A surprising variety of interesting and complex dynamics can arise from this apparently simple process. In this Chapter, we review the basic characteristics of planetesimal-driven migration. We discuss how the structure of a planetary system controls migration. We describe how this type of migration can cause planetary systems to become dynamically unstable and how a massive planetesimal disk can save planets from being ejected from the planetary system during this instability. We examine how the Solar System's small body reservoirs, particularly the Kuiper belt and Jupiter's Trojan asteroids, constrain what happened here. We also review a new model for the early dynamical evolution of the outer Solar System that quantitatively reproduces much of what we see. And finally, we briefly discuss how planetesimal driven migration could have affected some of the extra-solar systems that have recently been discovered.

A Decade of Radial-Velocity Discoveries in the Exoplanet Domain

Stephane Udry, Debra Fischer and Didier Queloz

E-mail contact: Stephane.Udry@obs.unige.ch

Since the detection of planetary companion orbiting 51 Peg one decade ago, more than 165 extra-solar planets have been unveiled by radial-velocity measurements. They exhibit a wide variety of characteristics, including large masses with small orbital separations, high eccentricities, multi-planet architectures and orbital period resonances. Here, we discuss the statistical distributions of orbital parameters and host star properties in the context of constraints they provide for planet-formation models. We expect that radial-velocity surveys will continue to provide important discoveries. Thanks to ongoing instrumental developments and improved observing strategies, Neptune-mass planets in short-period orbits have recently been detected. We foresee continued improvement in radial-velocity precision that will reveal Neptune-mass planets in longer-period orbits and planets down to a few Earth masses in short-period orbits. The next decade of Doppler observations should expand the mass distribution function of exoplanets to lower masses. Finally, the role of radial-velocity follow-up measurements of transit candidates is emphasized.

When Extrasolar Planets Transit their Parent Stars

David Charbonneau, Timothy M. Brown, Adam Burrows, and Gregory Laughlin

E-mail contact: dcharbon@cfa.harvard.edu

When extrasolar planets are observed to transit their parent stars, we are granted unprecedented access to their physical properties. It is only for transiting planets that we are permitted direct estimates of the planetary masses and radii, which provide the fundamental constraints on models of their physical structure. In particular, precise determination of the radius may indicate the presence (or absence) of a core of solid material, which in turn would speak to the canonical formation model of gas accretion onto a core of ice and rock embedded in a protoplanetary disk. Furthermore, the radii of planets in close proximity to their stars are affected by tidal effects and the intense stellar radiation; as a result, some of these "hot Jupiters" are significantly larger than Jupiter in radius. Precision follow-up studies of such objects (notably with the space-based platforms of the *Hubble* and *Spitzer Space Telescopes*) have enabled direct observation of their transmission spectra and emitted radiation. These data provide the first observational constraints on atmospheric models of these extrasolar gas giants, and permit a direct comparison with the gas giants of the Solar system. Despite significant observational challenges, numerous transit surveys and quick-look radial velocity surveys are active, and promise to deliver an ever-increasing number of these precious objects. The detection of transits of short-period Neptune-sized objects, whose existence was recently uncovered by the radial-velocity surveys, is eagerly anticipated. Ultra-precise photometry enabled by upcoming space missions offers the prospect of the first detection of an extrasolar Earth-like planet in the habitable zone of its parent star, just in time for Protostars and Planets VI.

Direct Detection of Exoplanets

J.-L. Beuzit, D. Mouillet, B. Oppenheimer, and J. Monnier

E-mail contact: Jean-Luc.Beuzit@obs.ujf-grenoble.fr

Direct detection of exoplanets from the ground is now within reach of existing astronomical instruments. Indeed, a few planet candidates have already been imaged and analyzed and the capability to detect (through imaging or interferometry) young, hot, Jupiter-mass planets exists. We present here an overview of what such detection methods can be expected to do in the near and far term. These methods will provide qualitatively new information about exoplanets, including spectroscopic data that will mature the study of exoplanets into a new field of comparative exoplanetary science. Spectroscopic study of exoplanet atmospheres promises to reveal aspects of atmospheric physics and chemistry as well as internal structure. Astrometric measurements will complete orbital element determinations partially known from the radial velocity surveys. We discuss the impact of these techniques, on three different timescales, corresponding to the currently available instruments, the new "Planet Finder" systems under development for 8 to 10-m telescopes, foreseen to be in operation in 5 to 10 years, and the more ambitious but more distant projects at the horizon of 2020.

Atmospheres of Extrasolar Giant Planets

Mark S. Marley, Jonathan Fortney, Sara Seager, and Travis Barman

E-mail contact: Mark.S.Marley@nasa.gov

The key to understanding an extrasolar giant planet's spectrum–and hence its detectability and evolution–lies with its atmosphere. Now that direct observations of thermal emission from extrasolar giant planets are in hand, atmosphere models can be used to constrain atmospheric composition, thermal structure, and ultimately the formation and evolution of detected planets. We review the important physical processes that influence the atmospheric structure and evolution of extrasolar giant planets and consider what has already been learned from the first generation of observations and modeling. We pay particular attention to the roles of cloud structure, metallicity, and atmospheric chemistry in affecting detectable properties through *Spitzer Space Telescope* observations of the transiting giant planets. Our review stresses the uncertainties that ultimately limit our ability to interpret EGP observations. Finally we will conclude with a look to the future as characterization of multiple individual planets in a single stellar system leads to the study of comparative planetary architectures.

8. Dust, Meteorites, and the Early Solar System

The Chemical Evolution of Protoplanetary Disks

Edwin A. Bergin, Yuri Aikawa, Geoffrey A. Blake, and Ewine F. van Dishoeck

E-mail contact: ebergin@umich.edu

In this review we re-evaluate our observational and theoretical understanding of the chemical evolution of protoplanetary disks. We discuss how improved observational capabilities have enabled the detection of numerous molecules exposing an active disk chemistry that appears to be in disequilibrium. We outline the primary facets of static and dynamical theoretical chemical models. Such models have demonstrated that the observed disk chemistry arises from warm surface layers that are irradiated by X-ray and FUV emission from the central accreting star. Key emphasis is placed on reviewing areas where disk chemistry and physics are linked: including the deuterium chemistry, gas temperature structure, disk viscous evolution (mixing), ionization fraction, and the beginnings of planet formation.

Dust in Proto-Planetary Disks: Properties and Evolution

Antonella Natta, Leonardo Testi, Nuria Calvet, Thomas Henning, Rens Waters, and David Wilner

E-mail contact: natta@arcetri.astro.it

We review the properties of dust in protoplanetary disks around optically visible pre-main sequence stars obtained with a variety of observational techniques, from measurements of scattered light at visual and infrared wavelengths to mid-infrared spectroscopy and millimeter interferometry. A general result is that grains in disks are on average much larger than in the diffuse interstellar medium (ISM). In many disks, there is evidence that a large mass of dust is in grains with millimeter and centimeter sizes, more similar to "sand and pebbles" than to grains. Smaller grains (with micron-sizes) exist closer to the disk surface, which also contains much smaller particles, e.g., polycyclic aromatic hydrocarbons. There is some evidence of a vertical stratification, with smaller grains closer to the surface. Another difference with ISM is the higher fraction of crystalline relative to amorphous silicates found in disk surfaces. There is a large scatter in dust properties among different sources, but no evidence of correlation with the stellar properties, for samples that include objects from intermediate to solar mass stars and brown dwarfs. There is also no apparent correlation with the age of the central object, over a range roughly between 1 and 10 Myr. This suggests a scenario where significant grain processing may occur very early in the disk evolution, possibly when it is accreting matter from the parental molecular core. Further evolution may occur, but not necessarily rapidly, since we have evidence that large amounts of grains, from micron to centimeter size, can survive for periods as long as 10 Myr.

Growth of Dust as the Initial Step Toward Planet Formation

Carsten Dominik, Jürgen Blum, Jeffery Cuzzi, and Gerhard Wurm E-mail contact: dominik@science.uva.nl

We discuss the results of laboratory measurements and theoretical models concerning the aggregation of dust in protoplanetary disks, as the initial step toward planet formation. Small particles easily stick when they collide and form aggregates with an open, often fractal structure, depending on the growth process. Larger particles are still expected to grow at collision velocities of about 1m/s. Experiments also show that, after an intermezzo of destructive velocities, high collision velocities above 10m/s on porous materials again lead to net growth of the target. Considerations of dust-gas interactions show that collision velocities for particles not too different in surface-to-mass ratio remain limited up to sizes about 1m, and growth seems to be guaranteed to reach these sizes quickly and easily. For meter sizes, coupling to nebula turbulence makes destructive processes more likely. Global aggregation models show that in a turbulent nebula, small particles are swept up too fast to be consistent with observations of disks. An extended phase may therefore exist in the nebula during which the small particle component is kept alive through collisions driven by turbulence which frustrates growth to planetesimals until conditions are more favorable for one or more reasons.

Astronomical and Meteoritic Evidence for the Nature of Interstellar Dust and its Processing in Protoplanetary Disks

C.M.O'D. Alexander, A.P. Boss, L.P. Keller, J.A. Nuth, and A. Weinberger

E-mail contact: alexande@dtm.ciw.edu

Here we compare the astronomical and meteoritic evidence for the nature and origin of interstellar dust, and how it is processed in protoplanetary disks. The relative abundances of circumstellar grains in meteorites and interplanetary dust particles (IDPs) are broadly consistent with most astronomical estimates of Galactic dust production, although graphite/amorphous C is highly underabundant. The major carbonaceous component in meteorites and IDPs is an insoluble organic material (IOM) that probably formed in the interstellar medium, but a solar origin cannot be ruled out. GEMS (glass with embedded metal and sulfide) that are isotopically solar within error are the best candidates for interstellar silicates, but it is also possible that they are Solar System condensates. No dust from young stellar objects has been identified in IDPs, but it is difficult to differentiate them from Solar System material or indeed some circumstellar condensates. The crystalline silicates in IDPs are mostly solar condensates, with lesser amounts of annealed GEMS. The IOM abundances in IDPs are roughly consistent with the degree of processing indicated by their crystallinity if the processed material was ISM dust. The IOM contents of meteorites are much lower suggesting that there was a gradient in dust processing in the Solar System. The microstructure of much of the pyroxene in IDPs suggests that it formed at temperatures >1258 K and cooled relatively rapidly (∼1000 K/hr). This cooling rate favors shock heating rather than radial transport of material annealed in the hot inner disk as the mechanism for producing crystalline dust in comets and IDPs. Shock heating is also a likely mechanism for producing chondrules in meteorites, but the dust was probably heated at a different time and/or location to chondrules.

Comet Grains and Implications for Heating and Radial Mixing in the Protoplanetary Disk

Diane Wooden, Steve Desch, David Harker, Hans-Peter Gail, and Lindsay Keller

E-mail contact: dwooden@mac.com

Observations of comets and chondritic porous interplanetary dust particles (CP-IDPs, grains likely shed from comets), as well as of protoplanetary disks, show that a large fraction of the submicron silicate grains in these objects are Mg-rich crystalline silicates. Here we review observations of the mineralogy and crystallinity of cometary grains and anhydrous CP IDPs, including new spectroscopy of the dust liberated by the Deep Impact experiment on 9P/Tempel. Some key results of these observations are: that crystalline silicates are very Mg-rich; and that in most disks (including the Solar System's) a gradient in the silicate crystalline fraction exists. We discuss the mechanisms by which Mg-rich crystals can be produced in protoplanetary disks, including: complete evaporation followed by slow-recondensation; or reduction of Fe in Mg-Fe silicates (possibly facilitated by C combustion to CO or CO_2), combined with thermal annealing. Finally, we discuss how these processes might occur in protoplanetary disks. We conclude that there are three viable scenarios that may operate in protoplanetary disks to produce Mg-rich crystalline silicates with a crystallinity gradient. I) Steady-state conditions can maintain temperatures high enough in the inner disk ($<$ few AU) to evaporate dust and allow it to re-condense; this must be followed by moderately effective outward radial transport of the dust produced. II) Transient heating events, probably shocks, may evaporate dust in the outer disk ($<$ tens of AU) and allow it to recondense over timescales of hours to days, directly producing Mg-rich silicates; alternatively, it may recondense rapidly but be thermally annealed by a second event. III) Transient heating events (shocks) may heat amorphous Mg-Fe silicates only to $\approx$ 1200-1400 K, enough to anneal the dust without destroying it; excess Fe in the silicate must be simultaneously reduced to Fe metal. On the other hand, the presence and characteristics of volatile and refractory organics in cometary materials demonstrate that a significant fraction of the outer disk mass sustained low temperatures ($\sim$30–150 K), and so did not pass through the hottest, inner regions of the disk in the early collapse phase nor was shocked. All models are as yet too incomplete for us to favor any: outward radial transport by turbulent diffusion suffers from a lack of knowledge of the cause of the turbulence; and shock models have not been developed sufficiently to say where in disks shocks can heat or vaporize dust, and for how long. All processes might be simultaneously occurring in disks. What is clear is that cometary grains and anhydrous CP IDPs contain a component of dust – crystalline Mg-rich silicates – that necessarily saw very high temperatures, either by large-scale radial excursions through the solar nebula disk, or by very energetic transient heating events in the comet-forming zone.

From Dust to Planetesimals: Implications for the Solar Protoplanetary Disk from Short-lived Radionuclides

M. Wadhwa, Y. Amelin, A. M. Davis, G. W. Lugmair, B. Meyer, M. Gounelle, and S. Desch

E-mail contact: mwadhwa@fieldmuseum.org

Since the publication of the Protostars and Planets IV volume in 2000, there have been signifi-cant advances in our understanding of the potential sources and distributions of short-lived, now ex-tinct, radionuclides in the early Solar System. Based on recent data, there is definitive evidence for the presence of two new short-lived radionuclides (^{10}Be and ^{36}Cl) and a compelling case can be made for revising the estimates of the initial Solar System abundances of several others (e.g., ^{26}Al, ^{60}Fe and ^{182}Hf). The presence of ^{10}Be, which is produced only by spallation reactions, is either the result of irradiation within the solar nebula (a process that possibly also resulted in the production of some of the other short-lived radionuclides) or of trapping of Galactic Cosmic Rays in the protosolar molecular cloud. On the other hand, the latest estimates for the initial Solar System abundance of ^{60}Fe, which is produced only by stellar nucleosynthesis, indicate that this short-lived radionuclide (and possibly significant proportions of others with mean lives $\leq$10 My) was injected into the solar nebula from a nearby stellar source. As such, at least two distinct sources (e.g., irradiation and stellar nucleosynthesis) are required to account for the abundances of the short-lived radionuclides estimated to be present in the early Solar System. In addition to providing constraints on the sources of material in the Solar System, short-lived radionuclides also have the potential to provide fine-scale chronological information for events that occurred in the solar protoplanetary disk. An increasing number of studies are demonstrating the feasibility of applying at least some of these radionuclides as high-resolution chronometers. From these studies, it can be inferred that the mm to cm-sized refractory calcium-aluminum-rich inclusions in chondritic meteorites are among the earliest solids to form (at 4567.2 ± 0.6 Ma). Formation of chondrules (i.e., sub-mm-sized ferromagnesian silicate spherules in chondrites) is likely to have occurred over a time span of at least $\sim$3 My, with the earliest ones possibly forming contemporaneously with CAIs. Recent work also suggests that the earliest planetesimals began accreting and differentiating within a million years of CAI formation, i.e., essentially contemporaneous with chondrule formation. If so, it is likely that undifferentiated chondrite parent bodies accreted a few million years thereafter, when the short-lived radionuclides that served as the main heat sources for melting planetesimals (^{26}Al and ^{60}Fe) were nearly extinct.

Origin and Evolution of Oxygen Isotopic Compositions of the Solar System

Hisayoshi Yurimoto, Kiyoshi Kuramoto, Alexander N. Krot, Edward R. D. Scott, Jeffrey N. Cuzzi, Mark H. Thiemens, and James R. Lyons

E-mail contact: yuri@ep.sci.hokudai.ac.jp

On a three-isotope diagram oxygen isotopic compositions of most primitive meteorites (chondrites), chondritic components (chondrules, refractory inclusions, and matrix), and differentiated meteorites from asteroids and Mars deviate from the line along which nearly all terrestrial samples plot. Three alternative mechanisms have been proposed to explain this oxygen isotope anomaly: nucleosynthetic effects, chemical mass-independent fractionation effects, and photochemical self-shielding effects. Presently, the latter two are the most likely candidates for production of the isotopic anomalies. Recent data on solar wind oxygen isotopes lends support to the photochemical self-shielding scenario, but additional solar isotope data are needed. Observations, experiments and modeling are described that will advance our understanding of the complex history of oxygen in the solar system.

Water in Small Bodies of the Solar System

David Jewitt, Lysa Chizmadia, Robert Grimm, and Dina Prialnik

E-mail contact: jewitt@ifa.hawaii.edu

Water is important for its obvious role as the enabler of life but more generally as the most abundant volatile molecule in the Solar system, containing about half of the condensible mass in solids. In its solid phase, water strongly influences the opacity of the protoplanetary disk and may determine how fast, and even whether, gas giant planets form. Water ice is found or suspected in a wide range of small-body populations, including the asteroids, the giant planet Trojan librators, Centaurs, comets and Kuiper belt objects. in addition to ice, there is mineralogical evidence for the past presence of liquid water in certain meteorites and, by inference, in their parent main-belt asteroids. The survival and evolution of liquid and solid water in small bodies is discussed.

Physical Properties of Trans-Neptunian Objects

D.P. Cruikshank, M.A. Barucci, J.P. Emery, Y.R. Fernández, W.M. Grundy, K.S. Noll, and J.A. Stansberry

E-mail contact: Dale.P.Cruikshank@nasa.gov

In 1992, the first body beyond Neptune since the discovery of Pluto in 1930 was found. Since then, nearly a thousand solid bodies, including some of planetary size, have been discovered in the outer Solar System, largely beyond Neptune. Observational studies of an expanding number of these objects with space- and ground-based telescopes are revealing an unexpected diversity in their physical characteristics. Their colors range from neutral to very red, revealing diversity in their intrinsic surface compositions and/or different degrees of processing that they have endured. While some show no diagnostic spectral bands, others have surface deposits of ices of H_2O, CH_4, and N_2, sharing these properties with Pluto and Triton. Thermal emission spectra of some suggest the presence of silicate minerals. Measurements of thermal emission allow determinations of the dimensions and surface albedos of the larger (diameter ¿ $\sim$75 km) members of the known population; geometric albedos range widely from 2.5% to >60%. Some 22 trans-Neptunian objects (including Pluto) are multiple systems. Pluto has three satellites, while 21 other bodies, representing about 11% of the sample investigated, are binary systems. In one binary system where both the mass and radius are reliably known, the mean density of the primary is $\sim$500 kg/m^3, comparable to some comets (e.g., Comet P1/Halley (Keller et al. 2004).

A Brief History of Trans-Neptunian Space

Eugene Chiang, Yoram Lithwick, Ruth Murray-Clay, Marc Buie, Will Grundy, and Matthew Holman

E-mail contact: chiang.eugene@gmail.com

The Edgeworth-Kuiper belt encodes the dynamical history of the outer solar system. Kuiper belt objects (KBOs) bear witnss to coagulation physics, the evolution of planetary orbits, and external perturbations from the solar neighborhood. We critically review the present-day belt's observed properties and the theories designed to explain them. Theories are organized according to a possible time-line of events. In chronological order, epochs described include (1) coagulation of KBO's in a dynamically cold disk, (2) formation of binary KBOs by fragmentary collisions and gravitational captures, (3) stirring of KBOs by Neptune-mass planets ("oligarchs"), (4) eviction of excess oligarchs, (5) continued stirring of KBOs by remaining planets whose orbits circularize by dynamical friction, (6) planetary migration and capture of Resonant KBOs, (7) creation of the inner Oort cloud by passing stars in an open stellar cluster, (8) *in situ* coagulation of Neptune Trojans, and (9) collisional comminution of the smallest KBOs. Recent work underscores how small, collisional, primordial planetesimals having low velocity dispersion permit the rapid assembly of $\sim$5 Neptune-mass oligarchs at distances of 20-40 AU. We explore the consequences of such a picture. We propose that Neptune-mass planets whose orbits cross into the Kuiper belt for up to $\sim$40 Myr help generate the high-perihelion members of the hot Classical disk and Scattered belt. By contrast, raising perihelia by sweeping secular resonances during Neptune's migration might fill these reservoirs too inefficiently when an account is made of how little primordial mass might reside in bodies large enough to be observable. These and other frontier issues in trans-Neptunian space are discussed quantitatively.

9. Life

Comparative Planetology and the Search for Life Beyond the Solar System

Charles A. Beichman, Malcolm Fridlund, Wesley A. Traub, Karl R. Stapelfeldt, Andreas Quirrenbach, and Sara Seager

E-mail contact: chas@ipac.caltech.edu

The study of planets beyond the solar system and the search for other habitable planets and life is just beginning. Ground-based (radial velocity and transits) and space-based surveys (transits and astrometry) will identify planets spanning a wide range of size and orbital location, from Earth-sized objects within 1 AU to giant planets beyond 5 AU, orbiting stars as near as a few parsec and as far as a kiloparsec. After this initial reconnaissance, the next generation of space observatories will directly detect photons from planets in the habitable zones of nearby stars. The synergistic combination of measurements of mass from astrometry and radial velocity, of radius and composition from transits, and the wealth of information from the direct detection of visible and mid-IR photons will create a rich field of comparative planetology. Information on proto-planetary and debris disks will complete our understanding of the evolution of habitable environments from the earliest stages of planet-formation through to the transport into the inner solar system of the volatiles necessary for life. The suite of missions necessary to carry out the search for nearby, habitable planets and life requires a "Great Observatories" program for planet finding (SIM PlanetQuest, Terrestrial Planet Finder-Coronagraph, and Terrestrial Planet Finder-Interferometer/Darwin), analogous to the highly successful "Great Observatories Program" for astrophysics. With these new Great Observatories, plus the James Webb Space Telescope, we will extend planetology far beyond the solar system, and possibly even begin the new field of comparative evolutionary biology with the discovery of life itself in different astronomical settings.

From Protoplanets to Protolife: The Emergence and Maintenance of Life

Eric Gaidos and Franck Selsis

E-mail contact: gaidos@hawaii.edu

Despite great advances in our understanding of the formation of the Solar System, the evolution of the Earth, and the chemical basis for life, we are not much closer than the ancient Greeks to an answer of whether life has arisen and persisted on any other planet. The origin of life as a planetary phenomenon will probably resist successful explanation as long as we lack an early record of its evolution and additional examples. Plausible but meagerly-investigated scenarios for the origin of important prebiotic molecules and their polymers on the Earth involving atmospheric chemistry, meteorites, deep-sea hot springs, and tidal flat sediments have been developed. Our view of the diversity of extant life, from which properties of a last universal common ancestor (LUCA) can be inferred, has also improved in scope and resolution. It is widely thought that the geologic record shows that life emerged quickly after the end of prolonged bombardment of the Earth. New data and simulations contradict that view and suggest that more than half a billion years of unrecorded Earth history may have elapsed between the origin of life and LUCA. The impact-driven exchange of material between the inner planets may have allowed earliest life to be more cosmopolitan. Indeed, terrestrial life may not have originated on the Earth, or even on any planet. Smaller bodies, e.g., the parent bodies of primitive meteorites, in which carbon molecules and catalytic transition metals were abundant, and in which hydrothermal circulation persisted for millions of years, offer alternative environments for the origin of life in our Solar System. However, only planet-sized bodies offer the stable physiochemical conditions necessary for the persistence of life. The search for past or present life on Mars is an obvious path to greater enlightenment. The absence of intense geologic activity on Mars, which contributes to its inhospitable state today, has also preserved its ancient history. If life did emerge on Mars or was transferred from Earth, the lack of sterilizing impacts (due to a low gravity and no oceans) means that a more diverse biota may have thrived than is represented by extant life on Earth. On the other hand, a habitable but still lifeless early Mars is strong evidence against efficient transfer of life between planets. The subsurface oceans of some icy satellites of the outer planets represent the best locales to search for an independent origin of life in the Solar System because of the high dynamical barriers for transfer, intense radiation at their surfaces, and thick ice crusts. These also present equally formidable barriers to our technology. The "ultimate" answer to the abundance of life in the Cosmos will remain the domain of speculation until we develop observatories capable of detecting habitable planets - and signs of life - around the nearest million or so stars.