Protostars and Planets V

Oral Program

Speakers are listed in italics

I. CLOUDS AND CORES

Giant Molecular Clouds in Galaxies
Yasuo Fukui, *Leo Blitz*, Akiko Kawamura, Adam Leroy, Norikazu Mizuno, Erik Rosolowsky

We review the properties of GMCs in a number of different nearby galaxies based largely on observations made with the Nagoya NANTEN telescope in Chile and the BIMA Array. Observations made with these telescopes resolve the molecular gas into individual GMCs in the LMC, SMC, M33, M31, IC10, and M64. In five galaxies, the LMC, SMC, M33, M31 and IC10, the CO has been surveyed in its entirety. The mean metallicity in these galaxies ranges over an order of magnitude and the morphologies include spirals and irregulars; most of the galaxies presently forming stars are represented in our sample. We apply a uniform method of analysis to all clouds and characterize their large scale properties. These and supplementary IR data make it possible to obtain new information on cloud lifetimes, star formation properties, latency times prior to the onset of star formation, the relationship between cloud mass and star formation, star formation efficiency from galaxy-to-galaxy, and changes in the X-factor: the CO/H2 conversion factor, among others. Comparisons that include Milky Way GMCs demonstrate that the slope of the GMC mass spectrum varies significantly among the galaxies. Most of the disk GMCs show only small variations in mean surface density, implying little change in the internal pressure from cloud-to-cloud.

Near-Infrared Extinction and the Structure and Nature of Molecular Clouds
Charles J. Lada, *Joao F. Alves*, Marco Lombardi, and Elizabeth A. Lada

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 easily achieve column density dynamic ranges of $0.3 < A_V < 50$ magnitudes ($6\times10^{20} < N < 10^{23}$ cm^{-2}), allowing with one simple tracer a complete description of the density structure of a cloud free from the uncertainties that typically plague extinction measurements derived from radio spectroscopy and dust emission. This has led in recent years to the characterization of the poorly studied diffuse halos surrounding molecular clouds and revealed the best examples in nature of Bonnor-Ebert spheres as well as previously unknown dense material configurations. Comparison with radio spectroscopy data has allowed detailed chemical structure studies of prestellar cores and the identification of vibrational modes within them, while comparison with dust emission data has generated a wealth of new data on the physical properties of dust grains. Here we review recent results arising from this novel technique, ranging from studies of Bok globules to local GMCs, to GMCs in external galaxies. In this review we emphasize what has been learned about the structure of molecular clouds and, in particular, about the origin and physical nature of the dense cores within them and the evolution of these cores to form stars.

Molecular Cloud Turbulence and Star Formation

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

Recent work supports the picture that molecular clouds form by convergent motions in the warm, magnetically subcritical, atomic gas, driven by self-gravity and interstellar turbulence. As the gas is dynamically compressed, it cools and becomes overpressured, molecular, self-gravitating, and roughly magnetically critical. The dynamical processes associated with molecular cloud formation give rise to strong internal turbulence, supersonic with respect to the cooled compressed gas. Turbulent density fluctuations substantially speed up molecule formation. Dynamically, this turbulence plays a dual role. On global scales it provides support against collapse; on small scales it promotes local collapse. The mass scale for the smallest gravitationally collapsing clumps may be determined by the length scale at which the velocity dispersion becomes subsonic. Molecular clouds as well as their internal structures appear to be transient, with lifetimes comparable to their local dynamical timescales. Numerical simulations suggest that the star formation efficiency depends nonlinearly on the mean field strength and decreases with the ratio of turbulent to gravitational energy in the clouds. Radiation and winds from the newly formed stars dissociate and disrupt nearby molecular gas, but also accelerate collapse by sweeping up dense shells of gas. Comparisons between observations and numerical simulations of gravoturbulent fragmentation in molecular clouds, focusing on their mass and angular momentum distributions, column density profiles, and velocity dispersions show good agreement. Whether or not the core mass distribution is universal remains a controversial topic. The origin of the stellar IMF is unclear, with many different, but not mutually exclusive, processes being plausible candidates.

Structure and Evolution of Low Mass Dense Cores: An Observational Perspective

James Di Francesco, *Philippe Andre*, Derek Ward-Thompson, Paola Caselli, Mario Tafalla, Philip C. Myers, Neal J. Evans, Yancy L. Shirley, Yuri Aikawa, Doug Johnstone, Richard M. Crutcher, Christine D. Wilson, and Toshikazu Onishi

We will review the properties of low-mass dense cores, including starless, prestellar, and Class 0 protostellar cores as derived from observations. We will discuss them in the context of the current debate between two extreme paradigms for the star/core formation process: the dynamic, turbulent picture vs. the quasi-static, magnetic picture. Since PPIV, the characterization of low-mass dense cores prior to, or immediately after, protostar formation has improved with new, sensitive, infrared and radio data. The physical structure of isolated starless cores, obtained from submillimeter continuum or infrared extinction studies, include ”flat” inner density profiles and very cold inner temperatures. The chemical structure of low-mass dense cores, obtained from multiline molecular emission studies, is characterized by low levels of ionization and inner zones of significant molecular depletion and deuterium fractionation, sharply affecting line probes of the coldest and densest inner regions. Molecular line data have also probed the internal dynamics of isolated low-mass dense cores, revealing extended regions of infall and rotational motion as well as inner regions of subsonic turbulence. Polarization and Zeeman measurements indicate that some, if not all, cores contain a significant magnetic field. Wide-field surveys of nearby molecular clouds constrain the timescales of the core formation and evolution processes, as well as the statistical distribution of core masses. The latter provides clues to the origin of the stellar initial mass function. Finally, preliminary conclusions regarding possible core formation mechanisms, as well as future prospects, will be briefly summarized.

Extreme Deuteration and Hot Corinos:
The Earliest Signatures of Low-Mass Star Formation
Cecilia Ceccarelli, Paola Caselli, Xander Tielens, Eric Herbst, and Emmanuel Caux

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) the extreme deuteration, caused by the extreme molecular depletion, in pre-stellar cores and Class 0 sources; and 2) the hot corinos of Class 0 sources, warm and dense regions characterized by a multitude of complex molecules. In this presentation we will review these two new topics, and show how they contribute to our understanding of the first phases of solar-type stars.

II. STAR FORMATION AND PROTOSTARS

Current Advances in the Computational Simulation of the Formation of Low-Mass Stars
Richard I. Klein, *Shu-ichiro Inutsuka*, Paolo Padoan, Kohji Tomisaka

The formation of Giant Molecular Clouds (GMCs) sets the stage for the formation of protostellar systems by the gravitational collapse of dense regions within the GMC that fragment into smaller core components that in turn condense into stars. Developing a theory for low mass star formation ($\sim$0.2 to 3 solar masses) with the goal of understanding the nature and physical properties of the formation of binary and multiple stellar systems remains one of the most elusive and important goals of theoretical astrophysics. Inherent in the difficulty in attaining this goal is that the gravitational collapse and ensuing fragmentation depend critically upon initial conditions in the cores as well as maintenance of accuracy in the simulations over many orders of magnitude in dynamic range in spatial scale and density as the cores collapse. The physics of low mass star formation brings into play the non-linear interaction of hydrodynamics with self-gravity, turbulence, radiation transport and magnetic fields resulting in a major computational challenge for simulations . Over the last 6 years, dramatic advances in the development of new numerical algorithmic techniques including adaptive mesh refinement (AMR) coupled with radiation transport and MHD in three dimensions and Smooth Particle Hydrodynamics (SPH) have been successfully implemented on large scale parallel supercomputers to allow significant increases in the dynamic range possible for problem of low mass star formation. It is now feasible to explore the collapse and fragmentation of turbulent molecular clouds down to the formation of turbulent cores and finally to the formation of stars. Along with the increased sophistication of these powerful methods, comes the 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 what we can believe of the numerical results. This critical review of the field will examine both the positive aspects of the new approaches as well as discuss the pitfalls and difficulties associated with these approaches to enable both observers as well as theorists an objective view of assessing the recent results of large scale numerical simulation as they confront the observational data. The review will examine the initial conditions that can now be inferred from observations as well as the necessary physics required to attack the problem of low mass star formation. The essential physics and implementation including turbulence, magnetic fields, radiation transport and their role in low mass star formation will be discussed as will a critical examination of the interpretation of numerical results from the diverse methods. The future of where we must go with numerical simulation will be addressed.

Stellar Properties of Embedded Protostars

T. Greene, *R. White*, G. Doppmann, and L. Hillenbrand

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). Moreover, how and how quickly this process proceeds has been difficult to assess. Recently, however, high dispersion spectrographs on large aperture telescopes have allowed observers to begin studying the stellar and accretion properties of dozens of embedded low mass protostars. These high dispersion spectra allow, for the first time, direct measurements of stellar effective temperatures, surface gravities, rotation velocities, radial velocities (and spectroscopic binarity), mass accretion rates, and mass outflow rates at an unprecedentedly early age. Additionally, comparisons of the stellar properties with evolutionary models provide direct tests of predicted masses, radii, and ages. The inferred properties indicate that current protostellar identification criteria, which are based on infrared energy distributions, are often unreliable as evolutionary diagnostics; orientation and other effects can bias this assessment. More generally, these new results provide strict observational constraints on the timescale and means by which stars acquire the majority of their mass.

The Origin of the IMF

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

We will discuss the physical processes involved in star formation and assess how they contribute to the resultant IMF. The initial stages are dominated by turbulent motions and thermal effects which together must determine the onset of gravitational collapse and the median or characteristic stellar mass of the IMF. Turbulent motions may also play a role in setting the distribution of stellar masses at the prestellar molecular core phase. The fragmentation of collapsing cores into multiple systems and stellar clusters then sets the initial stellar masses, and potentially the lower-mass end of the IMF. Subsequent gas accretion increases these masses and likely determines the upper-mass end of the IMF, with either non-uniform accretion rates due to internal competition or non-uniform accretion timescales due to dynamical interactions or stellar feedback. Lastly, dynamical triggering, and its ability to affect the onset of star formation, may potentially play a role in setting the distribution of stellar masses. We stress the need for secondary indicators, and predictions, of the various theoretical models. These should include such diverse observable features such as the mass segregation in stellar clusters as well as the kinematics and spatial distribution of young stars in star forming regions. Finally, we discuss the implications for the IMF with regard to the metallicity dependence and environmental pressure of the star forming molecular gas.

Fragmentation of Cores and the Origin of the Primordial Binary Population
Simon Goodwin, Andi Burkert, Alyssa Goodman, and Pavel Kroupa

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 will review the relevant properties of multiple systems and the cores from which they are assumed to form. We will then examine the various mechanisms for core fragmentation and focus in particular on the fragmentation of rotating, turbulent, condensed cores and disc fragmentation. Currently, no theoretical model appears able to quantitatively reproduce all of the observed binary properties and we explore the reasons why this might be the case.

III. BINARIES AND MULTIPLES

New Observational Frontiers in the Multiplicity of Young Stars
Gaspard Duchene, Andrea M. Ghez, *Karl E. Haisch Jr*, Laurent Loinard, Luis F. Rodriguez, and Eduardo Delgado-Donate

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, at least as frequently as Main Sequence stars are in the Solar neighborhood. This high rate of multiple systems 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 evolve into stable multiple systems and possibly a few ejecta. Studying the statistical properties of young multiple systems in a variety of environments has therefore become a powerful approach for constraining the details of core fragmentation as well as of the subsequent few-body dynamics. Both mechanisms may depend on the environment, although little evidence exists to support this so far. In recent years, we have conducted a number of systematic surveys to improve our knowledge of the multiplicity of young stars, in an attempt to provide more stringent constraints on the core fragmentation models. In particular, we will review here new results that have been obtained in relation to two main topics. First, we focus on the multiplicity of very low-mass young stellar objects in several star-forming regions, much closer to the brown dwarf limit than previous surveys had done. Most models predict significant mass-dependency for the properties of multiple systems and comparing these new results to previous surveys provides important clues on the fragmentation process. Second, we present a number of studies, conducted in the near-, mid-infrared and in the radio domain, concerning the multiplicity and properties of optically-undetected, heavily embedded protostars. These objects are much younger than the previously-studied, optically-bright, young stars, and they therefore offer a closer look at the primordial population of multiple systems, i.e., they represent a population that has not yet suffered much few-body dynamical interactions. In addition to these two 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*, C. McCabe, and A. Ghez

We will review observations of a range of disk diagnostics in multiple systems, including hydrogen emission lines (indicative of ongoing accretion), K-L and K-N colour excesses (evidence of warm inner disks), millimeter emission (tracing cooler circumstellar and circumbinary material), and polarization and V sin i (indicative of the relative orientations of the disks around each component). In each case we will 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 circumbinary reservoir, the observational evidence for which we will also critically review. Our conclusions - in terms of the relative lifetimes of disks around single stars, binary primaries and binary secondaries - will be discussed in terms of the planet forming potential of multiple star systems.

The Masses of Pre-Main-Sequence Stars: Fundamental Tests of the Physics of Young Stars
R. Mathieu, *K. Stassun*, I. Baraffe, M. Simon, and R. White

Knowledge of the masses and ages of young stars is fundamental for most star- and planet-formation research. Typically these quantities are derived from theoretical pre-main-sequence (PMS) stellar evolution models. Today, the rapidly increasing number (19 as of July 2005) of accurate mass measurements for PMS stars is placing critical constraints on PMS stellar astrophysics. Our chapter will summarize the existing mass measurements, with a critical review of their uncertainties. We will also focus on a few recent exemplars of particular importance, including a PMS brown dwarf eclipsing binary and prospects for an astrometric-spectroscopic orbit solution for Haro 1-14c from the new generation of near-infrared interferometers. With the growing sample of accurate masses, a primary observational uncertainty is becoming the measurement of other stellar parameters, in particular effective temperature and luminosity. Systematic errors in temperature are the present limitation on the critical tests of sub-solar convective tracks. Our chapter will highlight the current successes and limitations of this new era of high precision stellar astrophysics for young stars. Even given the uncertainties in stellar parameters, the newly measured stellar masses have greatly advanced our knowledge of PMS stellar physics. Our chapter will discuss present constraints on: treatments of convection, uncertainties in atmosphere models, effect of magnetic activity and fields on structure/surface properties, and initial conditions. We will also discuss surface lithium abundances as probes into young stellar interiors, especially with respect to convection.

IV. NEWBORN MASSIVE STARS

Ultracompact HII Regions and the Early Lives of Massive Stars
Melvin Hoare, Peter Hofner, Eric Keto, Stan Kurtz, and Susana Lizano

We review the phenomenon of ultra-compact H II regions (UCHIIs) as a key phase in the early lives of massive stars. These objects are the most visible manifestation of massive star formation that begins when the Lyman continuum output from the massive young stellar object is no longer quenched. We first summarise the properties of these objects as determined from high resolution observations in the infrared through radio regimes. New evidence of the dominance of cometary morphologies is presented. Evidence from velocity structure, proper motions, the molecular environment and hydrodynamical modeling indicates that these are indeed champagne flows. Strong stellar winds from the central stars do play a role in sweeping out central cavities and causing the limb-brightened appearance; new clues to the wind properties from stellar spectroscopy are discussed. As the cometary regions expand they appear to trigger further episodes of massive star formation as demonstrated by the frequent appearance of hot cores, maser activity and massive YSOs near the cometary region. We discuss recent observational results of these UCHII precursors, and the presence of X-ray emission in massive star-forming regions. Finally, we discuss a new class of very compact source: broad recombination line objects. These appear to be intermediate between the ionised stellar winds which have similar velocities of order 100 km/s, but are much weaker in their radio emission, and UCHIIs, which are brighter but have much narrower line-widths. Possible explanations for these transition objects are presented, and we evaluate them in the context of the co-existence of accreting hot molecular cores and embedded, hypercompact HII regions.

The Formation of Massive Stars
Henrik Beuther, Ed Churchwell, Christopher McKee, *Jonathan Tan*

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 relation of massive stars to star cluster formation is also discussed. We identify key observational and theoretical open questions that future studies should address.

Disks around Young O-B (Proto)Stars: Observations and Modeling
R. Cesaroni, D. Galli, G. Lodato, C.M. Walmsley, and Q. Zhang

Theory of stellar evolution predicts that O-B type stars should reach the zero-age main sequence while still accreting material from the parental cloud. The radiation pressure from the star can reverse infall of circumstellar material and inhibit further growth of stellar mass beyond the limit of about 8 $M_\odot$. To solve this problem and hence explain the formation of stars in excess of 8 $M_\odot$, various models have been proposed including non-spherical accretion with sufficiently large accretion rates. Thus, the direct detection of disks around newly formed massive (proto)stars would lend strong support to this type of models. Indeed, in recent years there is growing evidence for flattened structures rotating about luminous young stellar objects (YSOs). However, massive disks seem to be absent around the youngest optically visible B stars, which suggests rapid disk dissipation. In this review we wish to summarize and analyze the observational results obtained so far in the search for disks in O-B (proto)stars and discuss the findings in the context of the theoretical predictions of different models. Since most of the detections concern disks with masses comparable or exceeding those of the associated YSOs, we will also discuss the stability of massive disks and their lifetimes. This is a critical issue which must take into account not only the dynamics of the molecular gas, but also the effect of the powerful Lyman continuum of the star and of the associated outflows. The relationship between disk lifetime and spectral type of the star will be investigated.

V. JETS AND OUTFLOWS

Observations of Jets and Outflows from Young Stars

John Bally, Bo Reipurth, and Chris Davis

We will review the status of observational work on Herbig-Haro jets and infrared outflows, including observations of irradiated outflows in HII regions, X-ray emission from fast shocks, high-resolution imaging studies, and large-scale imaging surveys of entire GMCs. The bending of irradiated jet by side-winds, radiation pressure, and the rocket effect provide new insights into YSO behavior, jet formation, propagation, and HII region physics. S-shaped outflow symmetries may indicate dynamic interactions with companion stars. Million Kelvin plasmas behind fast shocks have been detected in X-rays. 0.1" - 1" resolution images and spectra obtained with interferometers, HST, and adaptive-optics have clarified how jets move, fragment, and entrain surrounding media. Surveys of entire GMCs with CCD and NIR cameras have led to new estimates of the momentum and kinetic energy injected into parent clouds by outflows. There has been growing interest in studies of massive stars and their optical/infrared outflows. The relationships between masers, shocks, jets, and wide-angle outflows, and the dependence of outflow properties on stellar mass and luminosity are being clarified.

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

Hsien Shang, Zhi-Yun Li, Frank H. Shu, and Naomi Hirano

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 revealed CTTS. In particular, we have improved the atomic physics, chemistry, rates and interaction cross-sections, as well as the treatment of ambipolar diffusion between ions and neutrals. We also have broadened the original X-wind picture to include the winds driven magnetocentrifugally from the inner disk regions. We have carried numerical simulations that follow the wind evolution from the launching surface to large, observable distances. The interaction between the self-consistently determined wind and a realistic ambient medium was also investigated. The investigation enabled us to generalize the wind-shell model of Shu et al. (1991) for classical molecular outflows into one that could explain ones with extremely high velocity jet components. Through detailed calculations using self-consistently determined structures for the wind and ambient medium, we are able to unify the jet-driven and wind-driven scenarios for molecular outflow production from Class 0 to Class I and II sources. We will also discuss and review works on jets and outflows from young stellar objects, and make connection to recent observations by STIS, VLA and SMA for critical comparisons. Finally, we will also discuss broader implications of protostellar jets and outflows from the framework of a generalized picture of star formation from magnetic collapse.

Resolving the Central Engine: An Observational Perspective

Tom Ray, Catherine Dougados, Francesca Bacciotti, *Jochen Eislöffel*, and Antonio Chrysostomou

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; almost certainly 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, suggest that jets are accelerated and focused on scales of a few AU 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 specialized 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 PP IV, including jet rotation, i.e. evidence of angular momentum transport, measurements of transverse velocity profiles and jet widths. All of these data are consistent with magneto-centrifugal disk wind ejection operating at moderately high ejection efficiencies. 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.

Disk Winds, Jets, and Outflows: Theoretical and Computational Foundations
R.E. Pudritz, R. Ouyed, Ch. Fendt, and A. Brandenburg

The physics of jets and outflows and their role in star formation has become one of the most interesting and rigorous aspects of research in the field. We examine the theoretical foundations 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 underlying magnetized accretion disks, the interaction of magnetized young stellar objects with their surrounding disks - and relevance to outflows, and finally, the link between jet formation and gravitational collapse. We will connect our study with observational reviews of jets and outflows such as the recent high spatial and spectral resolution HST observations of protostellar jets which confirm predictions that jets rotate and carry off angular momentum from their underlying accretion disks. Finally, we attempt to synthesize work on jets from disks, jet-driven outflows, funnel flows, and magnetized winds from accreting stars - into a complete picture of the role of outflows in low and high mass star formation.

Molecular Outflows from Newborn Stars
Hector G. Arce, Chin-Fei Lee, Frederic Gueth, *Debra Shepherd*, Rafael Bachiller, Alex Rosen, and Henrik G. Beuther

As a star forms by gravitational infall, it energetically expels mass in a bipolar jet. There is strong evidence for a physical link between inflow and outflow and that magnetic stresses in the disk initially lauch the outflowing material. The ejected matter can accelerate entrained gas to velocities greater than those of the cloud, thereby creating a molecular outflow. Outflows can induce changes in the chemical composition of their host cloud and may even contribute to the decline of the infall process by clearing out dense gas surrounding the protostar. In addition, outflows can be useful tools to help understand the underlying formation processes of young stars, as outflows provide a record of the mass-loss history of the system. We review the known properties of molecular outflows from young stars and discuss implications for possible differences between low-mass and massive star formation. We discuss the most recent results from high-resolution observational studies of the evolution of the physical (i.e., morphology, kinematics, and energetics) and chemical properties of molecular outflows, as well as the evolution of the outflow's impact on its surroundings. We also examine the most recent outflow models and compare them with the observational data. In addition, future outflow research with existing and planned millimeter and submillimeter instruments will also be presented.

VI. CLUSTERS AND ASSOCIATIONS

The Structure and Evolution of Young Stellar Clusters

Lori Allen, *Tom Megeath*, Phil Myers, Scott Wolk, Judy Pipher, Rob Gutermuth, James Muzerolle, Erick Young, and Fred Adams

At the time of PPIV, it was well accepted that star formation typically occurs in groups and clusters. Since PPIV, there have been enormous advances in observations of young clusters from infrared to X-ray wavelengths. The goal of our contribution is to offer a new look at young clusters by combining three surveys being conducted by the authors: ANCHORS - an archival database of Chandra observations of young clusters, The Spitzer Young Stellar Cluster Survey - a Spitzer, near-IR, and millimeter-wave survey of 30 clusters and The Spitzer Orion Molecular Cloud Survey - which covers 6 square degrees of the Orion clouds. These surveys have an unprecedented combination of spectral range, wide field coverage, and sensitivity, with the capability to detect objects below the hydrogen-burning limit. Using elevated X-ray emission, mid-infrared excesses from dusty disks and envelopes, and near-IR variability as signatures of youth, as well as using maps of the surface density of stars, we present an analysis of the structure of known young clusters within 1 kpc, and address the following questions: (A) What is the spatial distribution of stars and protostars in young stellar clusters? We will review observational evidence that: 1.) stars form in elongated clusters that are aligned with filamentary molecular clouds, 2.) protostars are more densely clustered than more evolved pre-main sequence stars, and 3.) clusters expand as the natal gas is dispersed, as predicted by theory. (B) What is the relative frequency of isolated vs. clustered star formation? Using mid-IR emission from disks and envelopes and elevated X-ray emission as signatures of youth, we can reliably identify populations of isolated young stars and protostars. We show that a significant fraction of stars form in relatively isolated environments, either in low density halos surrounding young clusters or in distributed populations extending throughout molecular clouds. (C) How does the cluster environment affect planet formation? We see evidence for significant disk evolution in clusters with ages < 3 Myr, Combining our new knowledge of the cluster environment with theoretical work on the evaporation of disks and dynamical interactions between solar systems, we will assess the role environment plays in the formation of planets.

X-ray Properties of Young Stars and Stellar Clusters

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

Recent studies with the Chandra and XMM-Newton space observatories have revolutionized our knowledge of high energy processes during the earliest phases of stellar evolution. From the brown dwarf limit to the most massive O stars, from embedded protostellar phases to the zero-age main sequence, stars produce X-ray plasmas with temperatures T ∼10-200 MK. In lower mass stars, these arise in violent magnetic reconnection flares, while in rich clusters the X-rays arise from both small-scale and large-scale shocks of O star winds. Our review concentrates on recent findings of three large surveys: the Chandra Orion Ultradeep Project, an XMM-Newton survey of the Taurus-Auriga clouds, and a Chandra survey of high mass star formation regions across the Galactic disk. We discuss a variety of astrophysical implications including: the nature of magnetic fields in young stellar systems; the effects of X-ray irradiation of protoplanetary disks and molecular clouds; the role of accretion in X-ray emission; and the discovery of X-ray flows in HII regions.

The Taurus Molecular Cloud:
Multi-Wavelength Surveys with XMM-Newton, Spitzer Space Telescope, and CFHT
M. Guedel & the XMM-Newton-Taurus Team,
D. Padgett & the Spitzer-Taurus Team,
C. Dougados & the CFHT-Taurus Team

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 Tau 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 nearly 5 sq. degrees with XMM-Newton; (ii) a near-to-mid-infrared photometric survey of 29 sq. degrees with the Spitzer Space Telescope, mapping the entire cloud in all available photometric bands; and (iii) a deep optical and near-infrared survey using the Canada-France-Hawaii Telescope. Each wavelength regime will contribute 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 entirely 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 will 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 Briceño, *Thomas Preibisch*, Robert Mathieu, Bill Sherry, Fred Walter, and Hans Zinnecker

We review the current state of observational work on several nearby OB associations, with emphasis on the low-mass stars spread over wide spatial scales and with ages ∼3-10 Myr. These young populations are ideal laboratories to explore fundamental issues like protoplanetary disk evolution and the lifetimes of molecular clouds; in particular, samples of young, low-mass stars spread over large areas allow comparison with young dense clusters for investigating possible effects of the environment on disk survival and the IMF. We describe recent wide field (∼100 sqr.

deg.) photometric and spectroscopic surveys of regions like Orion OB1 and Sco OB2, that are providing a comprehensive census of the young population down to nearly the substellar limit. We present the latest results from ongoing work by team members, both from ground-based and Spitzer observations, on disk properties of these young low-mass stars, discussing implications for our understanding of disk evolution.

VII. T TAURI STARS AND DISKS

Star-Disk Interaction and Magnetospheric Accretion in Classical T Tauri Stars

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

The inner 0.1 AU around accreting T Tauri stars hold clues to many of the 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 channelled 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 disk structure, and possibly for the halting of planetary migration close to the stellar surface. Considerable evidence has built up in the last decade in support of the idea that magnetospheric accretion acts as a common regulation mechanism for YSOs. We will review observational evidence in support of magnetospheric accretion but we will also review those observational results which do not easily fit into the standard magnetospheric accretion picture, thus providing a critically balanced discussion of the current status of this paradigm. We will then provide a review of the recent progresses made on the observational characterization of the star disk interaction process in young stars, as well as on recent developments in the modelling of the magnetospheric accretion process, including analytical approaches, MHD numerical simulations, and radiative transfer models. We will in particular insist on the dynamical and time variable aspects which appear to be a major characteristic of the star disk interaction process.

Rotation: From Solar-Mass Stars to Brown Dwarfs

W. Herbst, J. Eislöffel, R. Mundt, and A. Scholz

We will discuss the rotation of young low mass stars and brown dwarfs based on photometric monitoring of their spotted surfaces. Distributions of specific angular momentum at selected ages between 1 and 100 My will be presented, based on cluster studies. The angular momentum evolution of solar-like stars will be particularly highlighted and the important roles of angular momentum conservation and disk-locking during the pre-main sequence phase emphasized. The dependence of rotation on mass will be exhibited. The data will be placed in the context of current theory of rotational evolution.

Molecular Disks: Mm/Submm Interferometric Observations and their Interpretations

A. Dutrey, *S.Guilloteau*, and P.Ho

Although dust is the easiest tracer of proto-planetary disks, molecules represent more than 80% of the total disk mass. Even if a few direct H_2 detections are now possible, the detectable lines trace the gas in the warm inner disks ($R <$ 10-20 AU), while disks are known to extend out to several 100 AU. These outer regions may even contain most of the mass, and can only be traced by large millimeter and sub-millimeter instruments such as interferometers which can resolve large disks with good spatial resolutions. Since the SMA has entered into operation, the submillimeter range is now available for imaging studies of proto-planetary disks, while the IRAM array routinely provides images of $0.6''$ resolution at 1.3mm. Since PPIV, observations of molecular disks have improved a lot and many new direct constraints on physical and chemical models are now provided by mm/submm arrays. In this review, we summarize the evolution of our knowledge since PPIV, focussing on two complementary aspects: 1) the determination of the physical structure of disks which can be retrieved from multi-transition CO isotopic analyses of high angular resolution images and 2) the observations of molecules other than CO (and isotopes), which now open to investigations the era of chemistry in proto-planetary disks. In particular, we emphazise how these two observational aspects are coupled together. We indicate how to handle the available data to provide relevant constraints on the thermal, physical and chemical structure of disks, within the current limitations in sensitivity and angular resolution of the existing arrays. Applications of these methods have provided direct insight on the thermal structure of disks, and start showing direct evidence for chemical differenciation as function of radius, pointing towards the importance of photo-dissociation effects. They also revealed unexpected results, such as the discovery of non-Keplerian rotation in the AB Auriga disk. We discuss how to extrapolate these results to the capabilities of the ALMA project currently under construction in Chile.

Gas in Inner Disks
Joan Najita, Al Glassgold, *John Carr*, and Jeff Valenti

We will review recent developments in the study of gas in the inner planet-forming regions of circumstellar disks ($r < 10$ AU). The gaseous component of disks is important for understanding the processes at work in the formation of both stars and planets. Our review will focus on how the observations bear on our understanding of the dynamical, physical, and chemical processes that affect inner disks. The observational results to be discussed include those obtained at infrared (H2, CO and other molecular transitions) and UV wavelengths (H2 fluorescence and other atomic transitions) using space (ISO, FUSE, Spitzer) and ground-based facilities. In addition to comparing the observations with existing theories, we will identify major issues confronting both observations and theory. We will also connect these results with those of parallel studies of the dust component of the inner disk (e.g., recent results from infrared interferometry) and with studies of the gaseous component at larger disk radii (> 10 AU).

Multiwavelength Imaging of Young Stellar Object Disks:
Toward an Understanding of Disk Structure and Dust Grain Evolution
Francois Menard, *Karl Stapelfeldt*, Kenneth Wood, Alan Watson

We review the progress in high resolution imaging of young disks since the PP4 meeting. Many new disks have been discovered or imaged in scattered light; improved instrumentation and observing techniques have led to better disk images at all wavelengths; and observers have worked to build multifaceted imaging datasets for many disks spanning optical, near-infrared, thermal infrared, and millimeter wavelengths. These multiwavelength datasets are particularly valuable, as dust particle properties have wavelength dependencies that can be used to diagnose the particle size and composition. In disks where the density structure has been reasonably well-constrained by high resolution imaging, the changes in scattered light structure with wavelength can be directly related to the dust properties by fitting multiple scattering models to multiwavelength datasets. This has now been done in the case of several different disks; the results indicate that modest grain growth has taken place in some of these systems. The simultaneous modeling of multi-wavelength intensity and polarimetric images is a powerful tool, going well beyond previous studies that were limited to unresolved spectral energy distributions. Such models are quickly becoming mandatory in realistic studies of the disk structure and evolution, both being pivotal to understand the stellar and planetary formation processes and early evolution stages.

Spatially Resolved Observations of the Close Circumstellar Environment of Young Stars and Implications for Star, Disk and Planet Formation

Rafael Millan-Gabet, *F. Malbet*, R. Akeson, Ch. Leinert, J. Monnier, and L.B.F.M. Waters

In recent years, the close circumstellar environment of young stars has been spatially resolved at near and mid infrared wavelengths, using the technique of long baseline optical interferometry. For baseline lengths ranging from 20 to 130 meters, this technique achieves milli-arcsecond angular resolution, which at the distance of typical star forming regions corresponds to sub-AU to few-AU spatial scales. In the near-infrared, spatially resolved observations directly probe the innermost circumstellar regions. Observations at a variety of facilities have revealed for Herbig Ae and T Tauri objects characteristic sizes much larger than predicted by models of the putative pre-planetary disks that were tailored to reproduce the spectro-photometric information alone. These new results have forced a previously ignored rigorous treatment of how the disk inner edge is passively and actively heated. In a currently favored class of models, the inner dust disk forms an abrupt ”wall” at sublimation radii that are large compared to the co-rotation and magnetic truncation radii. The constraints on theories of star and planet formation that the new spatially resolved data provides have far reaching implications, ranging from tests of the magnetospheric accretion scenario, to understanding the initial conditions for inner planet formation. In the mid-infrared, cooler material located further out in the disk is probed, and the technique is ideally suited for tracing global structure and physical conditions. Recent measurements of Herbig Ae/Be objects have established the relevant spatial scales, and demonstrated that the characteristic sizes correlate with the slope of the mid infrared excess and, by induction, with the degree of outer disk flaring. Moreover, spatially resolved observations across spectrally resolved dust features have revealed radial gradients in dust chemistry, and a surprisingly large degree of dust crystallization in the inner disk regions, suggesting that dust processing is highly efficient and occurs well before the onset of planet formation. In addition to reviewing the observational state of the art and emerging interpretations, we examine the potential of second generation instrumentation currently being deployed, which boast vastly increased spatial frequency coverage, the ability to measure closure phases, fine spectral resolution, polarimetric capabilities and high calibration accuracy. With these additional capabilities, higher order morphology, additional emission mechanisms, gas and dust kinematics, detailed chemistry and direct imaging are becoming accessible not only for circumstellar disks but also for their associated winds and jets.

Models of Disk Structure, Spectra, and Evaporation
Cornelis Dullemond, David Hollenbach, *Inga Kamp*, and Paola D'Alessio

We review advances in the modeling of protoplanetary disks and the comparison of model spectra to observations. 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. It 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 flaring and possible self-shadowing of the disk (i.e. the shape of the "disk surface"), the dust size distribution, and the surface chemistry and thermal balance of the gas. For the gas thermal balance we are mostly concerned with the upper layers of the disk, where the gas and dust temperature decouple. We also briefly discuss optically thin disks, though focusing mainly on the gas, not the dust. The evolution from optically thick to optically thin disks is dominated by viscous spreading and accretion, photoevaporation, and dust settling and coagulation. The density and temperature structure arising from the static 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. We conclude with a speculative scenario of disk evolution from birth to dispersal.

Evolution of Circumstellar Disks Around Sun-like Stars: Placing Our Solar System in Context
Michael R. Meyer, Dana E. Backman, Alycia Weinberger, and Mark C. Wyatt

Over the past 10 years abundant evidence has emerged that many (if not all) stars are born with circumstellar disks. Understanding the evolution of disks can provide strong constraints on theories of planet formation. While concensus is emerging concerning the the early evolution of accretion disks (tau $<$ 10 Myr) and the characterization of older debris disks (tau $>$ 1 Gyr) continues at a rapid pace, little is known about the transition between these two extremes thought to occur during the epoch of planet formation. Recent studies undertaken with ground and space-based observatories are helping to address questions concerning the evolution of disks around sun-like stars, and how this evolution differs from that observed surrounding higher mass stars. We will review recent results from these programs, and compare these results to models for the evolution of our own solar system. We will focus on: 1) specific constraints these observations place on theories of planet formation; 2) comparison of the astronomical observational data to constraints on nebular evolution from solar system studies; 3) whether the data suggest that solar systems like our own are common or rare compared to the ensemble of sun-like stars in the disk of the Milky Way; and 4) compare these results to studies of other stellar types and the prospects for habitable planets in the galaxy.

VIII. BROWN DWARFS

The Formation of Brown Dwarfs: Theory
Anthony Whitworth, *Matthew Bate*, Aake Nordlund, Bo Reipurth, and Hans Zinnecker

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 prestellar cores; (iii) ejection of protostellar embryos from their placental envelopes;

(iv) disc fragmentation; and (v) photo-erosion of pre-existing cores overrun by HII regions. These mechanisms are considered from the viewpoint of their effectiveness at producing brown dwarfs, the resulting low-mass IMF, the distribution and kinematics of newly formed brown dwarfs, their binary statistics and the cause of the brown dwarf desert, their ability to retain discs, and hence their ability to sustain accretion and outflow. We discuss the minimum mass for brown dwarfs, and how stars - including brown dwarfs - should be distinguished from planets. Theoretical predictions are compared with available observations, and lines of future research identified.

The Formation of Brown Dwarfs: Observations
Kevin Luhman, *Charlie Lada*, James Muzerolle, Ilaria Pascucci, Viki Joergens, and Russel White

We review the current state of observational work on the formation of brown dwarfs. We first describe the latest measurements of various properties of brown dwarfs, including their initial mass function, binarity, circumstellar environment (disks, accretion, outflows, envelopes), and spatial and velocity distributions at birth. These observational constraints are compared to similar measurements for stars, and then compared to the predictions of theories for the formation of brown dwarfs, such as embryo ejection, turbulent fragmentation, and photo-evaporation.

Not Alone: Tracing the Origins of Very Low Mass Stars and Brown Dwarfs through Multiplicity Studies
Adam J. Burgasser, Nick Siegler, Peter Allen, Laird Close, Patrick Lowrance, John Gizis, and I. Neill Reid

Studies of the frequency and character of multiple stellar systems have provided important empirical constraints on star formation theories, enabling (along with several other lines of evidence) a concrete, qualitative picture of the birth of a star. At lower masses, down to and below the hydrogen burning minimum mass, our picture of star and brown dwarf 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 low mass multiple systems. The relatively recent identification of hundreds of low mass stars and brown dwarfs - as field objects, stellar companions and members of young clusters and associations - has facilitated multiplicity studies of these objects through high resolution imaging and spectroscopy. In this contribution, we review the results of these studies to date and present a detailed statistical analysis of their findings, taking into consideration empirical biases, incompleteness and the thermal evolution of substellar objects. This analysis demonstrates that the lowest mass binaries are closely separated ($a < 20$ AU) and near equal-mass ($0.8 < M_2/M_1 < 1.0$) systems that occur with low frequency (10-15%). There are, however, a few interesting exceptions. Widely separated ($a > 100$ AU) brown dwarf companions to more massive (e.g., A-K type) stars may have a higher multiplicity fraction than their field counterparts, while some of the youngest substellar pairs have significantly wider projected separations. The frequency and maximum separation of stellar and brown dwarf binaries steadily decreases toward lower primary masses, but there is an abrupt decline in the number of long period systems below 0.1 $M_\odot$. This wide-separation 'desert', present for both field and older ($>$ 100 Myr) cluster brown dwarf systems, cannot be the result of disruption in the sparse open cluster and Galactic environments and must therefore arise at the earliest stages of formation. We compare the empirical results on brown dwarf multiplicity to predictions laid out by current formation theories, and outline future studies required to probe the full phase space of the lowest mass multiple systems.

IX. PLANET FORMATION AND EVOLUTION

Formation of Gas Giant Planets

Jack J. Lissauer and David J. Stevenson

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, which could not have condensed into solid planetesimals within the protoplanetary disk. All three (transiting) extrasolar giant planets with well determined masses and radii also must contain substantial amounts of these light gases. 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. HD 149026 b, which is slightly more massive than is Saturn, appears to have comparable quantities of light gases and heavy elements. HD 209458 b and TrES-1 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 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 growing giant planet cores become massive enough that they are able to accumulate substantial amounts of gas before the protoplanetary disk dissipates. The primary questions regarding the core nucleated growth model is under what conditions planets with small cores/total heavy element abundances can accrete gaseous 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, Tom Quinn, and W.K.M. Rice

Protoplanetary gas disks are likely to become marginally gravitationally unstable to the growth of density perturbations during some phase of their evolution from relatively massive protostellar disks to extremely low mass debris disks. Spiral arms form during phases of gravitational instability, leading to the efficient outward transfer of angular momentum and inward transfer of mass through the effects of gravitational torques. While the ionized surfaces of protoplanetary disks are likely to be magnetically active, the region of most interest for planet formation, the midplane from about 1 AU to 20 AU, is likely to be nearly neutral and so effectively “magnetically dead”. Gravitational instability then provides a means for driving disk evolution even in magnetically dead zones. The spiral arms in an unstable disk can form self-gravitating clumps, which might then contract to form gas giant planets. Whether a gravitationally unstable disk is able to form gas giant protoplanets is the primary question addressed by this review. We review the wide range of calculations undertaken by ourselves and other workers employing finite-difference and finite-volume hydrodynamics codes based on different numerical schemes, as well as smoothed-particle hydrodynamics codes. In particular, we address the major questions regarding the disk instability mechanism, such as (1) triggering phases of gravitational instability by ongoing mass accretion onto the disk, by gradual cooling, or by binary star companions, (2) the thermodynamic description of disks as they undergo heating by shock waves, convection, and surface cooling by radiation, (3) the orbital survival of clumps as they contract toward planetary densities, and (4) the need for standard test cases that can be used to isolate numerical from physical effects in extremely challenging computational problems such as these. Gravitationally unstable disks may also be important for driving shock fronts capable of flash-heating dust grain aggregates into chondrules, and for the mixing and transport of solids such as chondrules and refractory inclusions throughout the planet-forming region. Spiral arms can also enhance the growth of solids, as gas drag drives m-sized solids toward the centers of spiral arms or rings, leading to hybrid scenarios for gas giant planet formation. Finally, we review current and future observational constraints on giant planet formation and discuss how gravitational instability and core accretion scenarios fare in meeting these constraints.

Gaseous Planets and Protostars: Birth and Fate

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

(1) *Gaseous exoplanets: from birth to ashes.* We will examine the evolution of exoplanets, from their birth (within the modern version of the core-accretion model) to their subsequent evolution. Special attention will be devoted to close-in so-called ”hot-jupiters” and ”hot-neptunes” with the effect of irradiation and evaporation due to the parent star energy flux on the evolution and the observational properties of these objects. The effect of internal structure (core mass) and irradiation on the mass-radius-age relationship will be examined for the case of transiting planets. (2) *Early stages of low-mass star and brown dwarf evolution.* We will consider uncertainties in the early stages of star (PMS) and brown dwarf evolution. Special attention will be devoted to the effect of accretion. Uncertainties in the determination of the fundamental parameters of young objects will be examined, both on the theoretical and observational fronts. (3) *Issues in star and brown dwarf formation. Connection with the IMF.* The physics of collapse of protostars and proto brown dwarfs will be examined with special attention to present uncertainties in our understanding of this formation process. The effect of geometry (1D vs 3D collapse) in particular will be highlighted. The IMF of stars and brown dwarfs will be examined and compared with present detections in the field and in young clusters.

The Diverse Origins of Terrestrial-Planet Systems

Makiko Nagasawa, *Ed Thommes*, Doug Lin, and Scott Kenyon

We review the theory of terrestrial planet formation as it currently stands, together with the observations which constrain and test this picture. 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? We will summarize recent results on terrestrial planet formation in which a central role is played by both the giant planets (including short-period ones) and the dissipating gas disk. Important processes such as oligarchic growth, protoplanet-disk interaction, and sweeping secular resonances will be discussed along with cosmochemical constraints and dynamical architecture. Indirect observations of this process around other stars – of the T Tauri disks which serve as the birthplace of planets, and of the debris disks which are left behind – have provided a wealth of information with which to confront planet formation models, with far more to come. Central to interpreting this data is understanding what imprints planet formation leaves on the disk; we summarize the latest numerical results on this topic, and we provide some suggestions on preparing for observations with upcoming instruments: JWST, the next generation of 20m-class optical telescopes, and TPF.

Disk-Planet Interactions during Planet Formation

John Papaloizou, *Richard Nelson*, Willy Kley, Frederic Masset, and Pawel Artymowicz

The interaction between protoplanets and their surrounding protoplanetary disks is of great importance during planet formation. Disk-planet interactions cause planetary migration and can influence the evolution of orbital eccentricity. The discovery of short period extrasolar planets suggests that large scale disk-induced migration occurred in many of the known systems. We will review the theory of disk-planet interactions, emphasising recent developments and outstanding questions. Type I migration results from the interaction between a protoplanetary disk and a low mass protoplanet. We will review the basic mechanisms that drive type I migration, highlighting predictions of rapid inward migration and eccentricity damping. Type II migration occurs when the planet is massive enough to open a gap in the disk. We will review the processes of gap formation and type II migration, and discuss the still-controversial issue of whether disk interactions cause the growth or damping of orbital eccentricity for gap forming planets. Type III migration has been shown to occur for protoplanets which form partial gaps in fairly massive disks, and is driven by corotation torques. We will review the basic mechanism that drives type III migration, and describe the results of recent simulations. The interaction between protoplanets and turbulent protoplanetary disks has also been a recent topic of research. We will present the results of recent simulations for both high and low mass protoplanets, describing the 'stochastic migration' experienced by low mass protoplanets and planetesimals due to interaction with turbulent density fluctuations. The implications of this work for planet formation will be discussed.

Planet Migration in Debris Disks

H. Levison, *A. Morbidelli*, R. Gomes, K. Tsiganis, and D.A. Backman

Migration in debris disks is simply a consequence of angular momentum conservation as the planets scatter the planetesimals that they encounter. However, like chaos can arise from simple differential equations, a variety of interesting and complex dynamics can arise from this apparently simple process. We will review the two basic modes of migration: damped and forced, where the migration rate decreases/increases exponentially, respectively, with time. We will analyze the possible outcomes, depending on the properties of the disk and the planets. These include the possibility that planets open gaps in relatively quiescent and massive disks, or run up to the disk's internal or external edge. In the latter case a planet can bounce off the edge of the disk and reverse the direction of migration. These phenomena are relevant to observations of extrasolar planetary systems. They might explain the origin of some hot Jupiters and the presence of planets at large distances from the central star, and they are also relevant to the structure of our Solar System. The current location of the giant planets and the resonant structure of the Kuiper belt are probably the result of this migration. In addition, planet migration can easily trigger late instabilities in multi-planetary systems. These instabilities violently excite the disk, leading to a burst of collisional activity among planetesimals, and may leave the planets on eccentric orbits. In our Solar System, this process could explain the moderate eccentricities of Jupiter and Saturn. In addition, the cataclysmic Late Heavy Bombardment of the terrestrial planets, which occurred approximately 700 My after planetary formation, could be related to such an instability.

X. EXTRASOLAR PLANETS

A Decade of Radial-Velocity Exoplanet Discoveries

S. Udry, D. Fischer and D. Queloz

Since the detection a decade ago of the planetary companion of 51 Peg, more than 150 extra-solar planets have been unveiled by radial-velocity measurements. They present a wide variety of characteristics as e.g. large masses with small orbital separations, important eccentricities, period resonances in multi-planet systems, etc. The questions set by these peculiarities and the proposed answers will be discussed, as well as the meaningful features of the statistical distributions of orbital parameters or parent stellar properties that now allow us to put useful constraints on the planet formation models. We will also discuss the recent detection of extremely low-mass companions around solar-type stars. Neptune-mass planets in short-period orbits are beginning to emerge from RV surveys. We expect continued improvement in velocity precision and anticipate the detection of Neptune-mass planets in longer period orbits and even lower mass planets in short period orbits, giving us new information on the mass distribution function of exoplanets. Finally, detection limitations from the stars and/or the method itself will be discussed as well as.

When Extrasolar Planets Transit Their Parent Stars

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

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 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, more than a dozen transit surveys are active, and promise to deliver an ever-increasing number of these precious objects.

Direct Imaging of Extra-Solar Planets

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

Direct detection of extra-solar planets is nearly within reach of existing astronomical instruments. We will present an overview of what such detection methods can be expected to produce. 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 the orbital element determinations partially known from the radial velocity surveys. We will discuss the impact of these techniques on three differents timescales, corresponding to the currently available instruments, the new ”Planet Finder” systems under development and foreseen to be in operation in 5 to 10 years, and the more ambitious but more distant projects at the horizon of 2015/2020.

Atmospheres and Evolution of Extrasolar Giant Planets
Mark Marley, Jonathan Fortney, Sara Seager, and Travis Barman

The key to understanding extrasolar giant planet spectra–and hence detectability and evolution–lies with the atmosphere. Now that we have in hand observations of thermal emission from EGPs atmosphere models can be used to constrain atmospheric composition, temperature, and ultimately the formation and evolution of detected planets. We will review the current universe of extrasolar giant planet observations and models, focusing on what we have already learned from the first generation of direct detection data and modeling and what we will likely be able to learn from the next. We will discuss indicators of cloud structure, metallicity, and atmospheric chemistry that can be discerned from broad-band data, including the Spitzer Space Telescope observations of the transiting giant planets. Our review will stress the uncertainties that ultimately limit our ability to interpret EGP observations. We will briefly consider the evolution of giant planets and discuss the puzzle of their radii. 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.

XI. DUST AND PROTOPLANETARY DISKS

The Chemical Evolution of Proto-Planetary Disks
Edwin Bergin, *Yuri Aikawa*, Geoffrey Blake, and Ewine van Dishoeck

We will review our observational and theoretical understanding of the chemical evolution of protoplanetary disks. We outline the range of gas-phase and solid state molecular observations which have identified molecular species from the inner to outer disk. We will discuss how the development of static and dynamical chemical/physical models in tandem with new observations has 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. The chemistry is predicted to change as the disk evolves through grain sedimentation/coagulation, planet formation, and eventual dissipation. We will discuss the anticipated chemical effects in the transition from optically thick to optically thin disks that still contain gas and relate the chemistry to the observed abundances of cometary volatiles.

Dust in Protoplanetary Disks: Properties and Evolution
A. Natta, N. Calvet, Th. Henning, *L. Testi*, L. Waters and D. Wilner

There is general agreement today that planets form in circumstellar disks during the pre-main sequence life of stars, as a final product of processes driven by the evolution of the solid component of such disks. In the relatively cold and dense disk environment, grains settle, collide, coalesce and fragment, changing dramatically their properties from those typical of the parent molecular cores. Our knowledge of dust properties in disks has grown rapidly in recent years, with the advent of high spatial resolution, high sensitivity instrumentation, both in the near and mid-infrared and at submillimeter and millimeter wavelengths. The results, some time unexpected, are beginning to shed light on the complex processes occurring in disks, and their implications need to be addressed by planet formation models. We plan to review the most recent observations of dust properties in proto-planetary disks, to discuss their limitations and to enlighten their implications for dust evolutionary models. The presentation will include: a brief description of current ideas on dust processing in disks; a discussion of which dust properties are accessible to observations; evidence of grain growth in the outer disk midplane and on the disk surface; grain mineralogy from mid-IR spectroscopy; some interesting objects; summary and conclusions.

Aggregation and Transport of Dust in Disks as Initial Steps toward Planet Formation
Carsten Dominik, Jürgen Blum, Jeffrey Cuzzi, and Gerhard Wurm

In our review, we will cover the basic growth of dust aggregates from dust grains, and the effects and importance of dust transport in disks. The focus of the review are experimental and theoretical results. The growth of dust by aggregation is a process inevitably happening during star formation, starting already during the collapse phase and accelerating in the disk. Dust aggregation is the initial step towards planet formation. The interaction between the dust aggregates and the gaseous disk is of critical importance for many processes in the disk. Aerodynamic and mechanical properties of aggregates will be determined by the aggregate structure. The coupling to the gas determines processes like settling in the disk, relative velocities in both turbulent and laminar disks, size sorting and concentration of particles in vortices. The mechanical properties of the bodies formed are critical to understand destruction in higher velocity collisions and are important to understand the continued growth to large bodies. Aggregation and destruction together govern the the small particle population in the disk and therefore the appearance of protoplanetary disks in imaging and spectroscopy. Over the last few years, breakthroughs have been achieved in the experimental study of dust aggregation. In laboratory, microgravity and space experiments, aggregation of dust has been studied under realistic conditions for the first time. At the same time, theoretical models of dust aggregation have become more sophisticated on three levels: (i) on the microscopic level in calculating dust aggregation and aggregate structure (ii) in the interaction of dust with vortices and general disk hydrodynamics, and (iii) in global disk models treating the growth, settling and migration of particles, and studying the observable effects of these processes.

XII. EARLY SOLAR SYSTEM

A Brief History of Trans-Neptunian Space
Eugene Chiang, Marc Buie, Matthew Holman, and Yoram Lithwick

The large-scale structure of the Edgeworth-Kuiper belt encodes the dynamical history of the outer solar system: accretionary processes, orbital annealing, and external perturbations from the solar birth environment. After delineating observed dynamical populations in the present-day Kuiper belt, we construct a timeline summarizing theories as to how these populations formed. In rough chronological order, epochs identified include (1) coagulation, (2) fusing of binaries, (3) ejection of planetary oligarchs, (4) planetary migration, (5) formation of the scattered (high-perihelion) and resonant belts, (6) stellar encounters, and (7) clean-up of debris. Connections to extra-solar systems are made throughout.

Physical Properties of Trans-Neptunian Objects

Dale P. Cruikshank, Antonella Barucci, Joshua P. Emery, Yanga Fernandez, Will Grundy, Keith Noll, and John A. Stansberry

We summarize current understanding of the physical properties of the large and diverse population of small bodies beyond Neptune, broadly termed Trans-Neptunian Objects (TNOs). A dynamical subset of the TNOs is the Kuiper Belt Objects (KBOs); we also consider the family of Centaurs, which are dynamically derived from the Kuiper Belt. Since the first post-Pluto discovery of a TNO in 1992, about 1000 objects have been found. Photometry, radiometry, spectroscopy, and high-resolution direct imagery have established for several objects their dimensions, surface compositions, rotation parameters, thermal properties, binary nature, and in some cases, their mean densities. Statistical analysis of multicolor photometry shows the presence of four distinct color groups, ranging from neutral to very red. Model studies suggest that the red objects are colored with organic solid materials such as tholins. Hydrous silicates, and ices of water and methanol appear in some objects; Sedna shows solid nitrogen and methane. The Centaur Asbolus shows evidence for fine-grained silicates in the mid-IR. As of mid-2005, 20 TNOs and 10 Centaurs have been detected with the Spitzer Space Telescope at wavelengths of 24 and 70 micron, and a few have detections at sub-mm wavelengths. When combined with a visual magnitude, these thermal measurements constrain the albedos and diameters of the targets. While the sample is small, it reveals that the albedos of TNOs and Centaurs are quite diverse, and generally significantly higher than the canonical 4% value assumed prior to Spitzer. A surprisingly large fraction of Kuiper Belt objects, particularly those in the dynamically cold disk, are binary. Binary orbits provide a direct determination of the system mass; system masses combined with size estimates from thermal observations enable estimates of the bulk densities, providing important constraints on composition and interior structure. Binaries in the Kuiper Belt can be formed through multi-body interactions only if the total mass of the primordial Kuiper Belt is orders of magnitude greater than the mass of the present-day Kuiper Belt. This more massive primordial belt may have shared characteristics of debris disks observed around other stars.

Water in Small Solar System Bodies

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

In this talk we discuss research results concerning the distribution and role of water in the small-body populations of the solar system. Many chondritic meteorites, derived from asteroids, show geochemical evidence for past aqueous alteration at balmy reaction temperatures from 0 to 25 C. Astronomical evidence suggests that ice may persist even to the present epoch in some main-belt asteroids, thereby blurring the distinction between these objects and comets and providing direct evidence for migration of the “snow-line”. Comets are, of course, ice rich, as are their

Centaur and Kuiper Belt precursors. All of the small body populations may have contributed, to different degrees, to the water and volatile abundances of the Earth and other terrestrial planets. Long-term stability of water is endangered by heating from the decay of radioactive nuclei, by exothermic phase change from the amorphous to the crystalline state and, where the liquid phase is reached, by powerful serpentinization reactions with rock. All of this motivates an examination of the role and long-term stability of water in small bodies from the inner regions of the asteroid belt to the outer extremities of the Kuiper Belt. Our main purpose is to bring together related research results from disparate fields and to make them known to the Protostars and Planets community.

Comet Grains and Implications for Heating and Radial Mixing in the Protoplanetary Disk
D. H. Wooden, S. J. Desch, H.-P. Gail, *D. E. Harker*, and L. P. Keller

The nuclei of comets contain dust grains, volatile ices, volatile gases, and organics extant in the solar nebula at the time of the formation of the giant planets. The coexistence of high temperature crystals and low temperature volatiles in cometary nuclei attests to the radial transport of crystals, which formed at temperatures above 1000K, to heliocentric distances where icy planetesimals were forming, outside of the ‘snow line. The coma of comet Hale-Bopp contained a preponderance of submicron grains and crystalline silicates, bearing remarkable resemblance to external protoplanetary disk HD100546. Recent observations and analysis of Herbig Ae/Be disks indicate that inner disks are enhanced in crystals. Comparing comets and the surfaces of outer solar system icy bodies to asteroids and meteorites suggests inner disks are deficient in amorphous carbon. The mechanisms that potentially transmute outer-disk grain constituents into inner-disk grain constituents are discussed. A radial gradient in mineralogy results in a radial-dependent opacity, which potentially affects the vertical scale height and structure of the disk. The Deep Impact Mission encounter with 9P/Tempel 1 produced a transient ejecta plume. The ejecta plume of 9P/Tempel 1 contained crystalline silicates and volatiles similar to OC comets such as Hale-Bopp. What characterizes the impact-driven ejecta from ’normal’ activity may be the expulsion of intimate mixtures of volatiles and dust that subsequently fragment in the coma. In ’normal’ jets, volatiles may be depleted or expend their sublimation energies promoting jet activity. Another possibility is that there are significant differences between subsurface ’fresh’ grains and surface grains ’aged’ by irradiation of UV or cosmic rays, or by resurfacing via similar impact events. Laboratory investigations into the organic materials in anhydrous chondritic porous interplanetary dust particles of probable cometary origin are discussed and compared to observations of comae species in Hale-Bopp and 9P/Tempel 1. The alteration of grain organics and volatiles may play a role in the evolution of protoplanetary disk grain properties, and hence, disk opacities and disk structure.

Astronomical and Meteoritic Evidence for Thermal Processing of Interstellar Dust in Protoplanetary Disks
C.M.O’D. Alexander, A.P. Boss, L.P. Keller, J.A. Nuth, and A. Weinberger

The high crystallinity of silicate dust in YSOs compared to interstellar dust suggests that dust in YSOs has been annealed at $\sim$1000 K. Chondritic meteorites and interplanetary dust particles (IDPs) contain circumstellar grains, interstellar grains, interstellar organic matter (IOM) and early solar system materials that formed at high temperatures. Annealing may explain why $\sim$1/3 of all circumstellar silicates in meteorites and IDPs are crystalline. The abundances of IOM in chondrites, even CIs, are much lower than in IDPs and comets. IDPs have a significant crystalline component and regions of what appear to be annealed material, so even their IOM contents may be low compared to primordial interstellar dust. The CI, IDP and solar volatile element abundances are very similar. If large fractions of CIs and IDPs were heated, it was achieved without significantly fractionating the more volatile elements. We will compare the microstructures of the most primitive meteorites and IDPs with the inferred properties of interstellar dust and with annealed interstellar dust analogs. We will also review the various thermal processes recorded in meteorites and discus which if any could be responsible for the crystallinity of silicates in YSOs.

From Dust to Planetesimals:
Time Scales from Short-lived Radionuclides in the Early Solar System

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

We will review recent results (particularly those reported since the Protostars and Planets IV conference in 1998) from the investigation of meteorites and their components, which have provided new constraints on early solar system time scales involved in the formation of objects ranging from mm- to cm-sized particles, i.e., calcium-aluminum-rich inclusions (CAIs) and chondrules, to km-sized bodies, i.e., planetesimals. These constraints are complementary to astronomical observations that provide independent estimates of the lifetimes of protoplanetary disks around young stars. Specific topics to be discussed will include the following: (1) the Pb-Pb and 26Al-26Mg systematics in CAIs and chondrules from various types of primitive chondritic meteorites; (2) 182Hf-182W systematics in undifferentiated and differentiated meteorites; (3) 26Al-26Mg, 53Mn-53Cr and Pb-Pb systematics in eucrites and angrites.

Origin and Evolution of Oxygen Isotopic Compositions of the Solar System

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

Oxygen is the third abundant element in the solar system and the most abundant element in the solid phase. The oxygen has large mass-independent isotopic variations among planets, chondrite and achondrite asteroids, and meteoritic components (refractory inclusions, chondrules, and matrix). The oxygen isotopic variations in solar system materials are far larger than observed for other elements, and do not reflect nucleosynthetic processes in stars. Instead they seem to be a result from processes in the parent molecular cloud and the protoplanetary disk. Therefore the oxygen isotopic variations provide key constraints for understanding the origin and evolution of protoplanetary disks. In this paper we review recent and anticipated major advances in characterizing oxygen isotopic compositions of chondrites, chondritic components, igneous meteorites, terrestrial planets, and the Sun, and models explaining the origin of oxygen isotope anomalies and the observed variations in oxygen isotopic compositions of solar system materials. The mass-independent oxygen isotopic variations are not unique to our solar system but instead ubiquitous in any planetary systems.

XIII. ASTROBIOLOGY

From Protoplanets to Protolife: The Emergence and Maintenance of Life

Eric Gaidos, Nicholas Moskovitz and Franck Selsis

Our understanding of what makes the Earth habitable, and what planetary conditions may be suitable or necessary for the emergence of life, has progressed steadily since the first prebiotic chemistry experiments (Miller 1953) and habitable zone calculations (Huang 1959). We will review significant work on planetary habitability and the emergence of life that has been published since the PPIV conference in 1998. We will also include important aspects of planetary habitability and the appearance of life not covered in the previous review (Chyba 1999). These will include the stability of planets in the habitable zone, the stabilty of primordial atmospheres against loss by hydrodynamic escape, the geology of the planet, and newly proposed mechanisms for the delivery of volatiles to the habitable zone.