NASA Origins of Solar Systmes FY01 Proposal Final Report

"The Structure of Young Stellar Systems:
Establishing the Initial Conditions for Planet Formation (NAG5-10467)"

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ORIGINAL PROPROSAL ABSTRACT.

We propose an integrated observational and modeling effort whose central themes are: (1) analyzing the molecular and physical structure of protostellar nebulae, and (2) understanding the topologies of early planetary and pre-planetary systems. The main thrust of the observational work involves high spatial and spectral resolution observations of young Sun-like stars over a wide range of ages in continuum dust and in molecular species that highlight the unique processes accompanying stellar and planetary formation. Modeling efforts will concentrate on the physical interpretation of the observations using state-of-the-art radiative transfer codes and on detailed tests of existing theories. The proposed high-resolution, long wavelength far-infrared and (sub)millimeter-wave observations are critical to understanding early planetary system topologies and the origins of hot Jupiters. In addition, by the end of the proposal period, the CARMA millimeter array should have sufficient sensitivity and image fidelity to detect surface density variations in circumstellar disks occuring in response to the gravitational influence of forming gas giants. It should be stressed that our observational approach allows detailed studies of systems in the deeply embedded through optically visible stages of low-mass star formation. The long wavelength ground based observations will be carried out at the OVRO Millimeter-Wave Interferometer, the BIMA Millimeter Array, the Caltech Submillimeter Observatory, and the James Clerck Maxwell Telescope; these primary data will be combined with supporting infrared and (sub)millimeter-wave imaging and spectrsocopic studies carried out with the Keck telescope(s), ISO, SOFIA, and SIRTF.

I. Progress Under the Current Grant

FY01-FY03 Origins support to the PI had been as part of an effort involving Profs. Blake, van Dishoeck and L.G. Mundy of the University of Maryland. As outlined below, the merging of BIMA+OVRO into the Combined Array for Research in Millimeter Astronomy (CARMA) and our mutual involvement in the Spitzer Legacy Science program now provides a more natural means of continuing the Caltech/Maryland collaboration. In addition, the spectroscopy/radiative transfer programs led by Profs. Blake, Hogerheijde, and van Dishoeck form a more cohesive basis for a single proposal. Students supported by our previous Origins grant have been involved in making some of the first sub-arcsecond resolution images of the morphology and chemistry of individual YSOs at OVRO and BIMA, in the analysis of IR spectra taken by ISO, and in continuing exploratory IR diffraction-limited imaging and spectroscopy at the Keck and VLT observatories.

Notable scientific accomplishments in the past grant period, summarized next, include:

◇ detecting high density & temperature "hot cores" in the dynamically accreting envelopes of low mass protostars that contain significant quantities of complex, prebioitc molecules,

◇ imaging chemical and isotopic zonation in the outer regions of T Tauri star accretion disks, particularly fractional ionization and D/H studies,

◇ acquiring and modeling the first extensive CO $v = 1 \rightarrow 0$ spectroscopy survey of the terrestrial planet-forming region of circumstellar accretion disks,

◇ optimizing detailed radiative transfer modeling of the molecular and dust emission from YSO envelopes and from comets, including a new parallelized implementation.

A. Chemical Zonation in Disks/Envelopes & the Connections to Comets

As material flows from a molecular cloud core toward a forming star, it experiences tremendous changes in its physical environment that can drive changes in the chemical composition of the gas and dust. However, the simultaneous processes of infall and outflow lead to a complex environment wherein it can be difficult to isolate physical versus chemical processes. In our recent work on very young, deeply embedded protostars, we have therefore taken a stepwise approach in which the large scale density and temperature structure of the source is fit using the spectral energy distribution (SED) and the high spatial resolution imaging of the optically thin dust emission provided by (sub)millimeter bolometer cameras and aperture synthesis observations. Once fit, this physical structure is used to examine the excitation and abundances of molecules using the statistical equilibrium Monte Carlo radiative transfer code developed by Hogerheijde & van der Tak (2000).

Our most recent work has been to examine the well known class 0 protostars IRAS16293-2422 and NGC1333 IRAS2. Both are wide binaries, and the OVRO+BIMA aperture synthesis observations require point sources, interpreted as circumstellar disks, in addition to the surrounding envelope in order to fit the continuum observations. A variety of complex molecules are seen in a compact source toward IRAS16293-2422. The chemistry and the isotopic systematics, specifically the D/H content (Parise et al. 2002), are reminiscent of the hot cores surrounding high mass stars. The size and time scales are quite different, however, thanks to the dynamically infalling nature of the envelope, and so we argue that the organics seen in this source must arise directly from grain mantle chemistry (Schöier et al. 2002). In IRAS2, complex chemical patterns are seen toward the three cores present in the interferometric field of view, and can be used to disentangle the competing effects of infall and outflow in addition to providing a relative age sequence (Jørgensen et al. 2004ab).

In contrast to the rich chemistry observed toward deeply embedded protostars, most spectral line imaging of disks around T Tauri stars and Herbig Ae stars (TTs and HAe) to date has been carried out in isotopologues of CO for reasons of sensitivity (e.g. Sargent

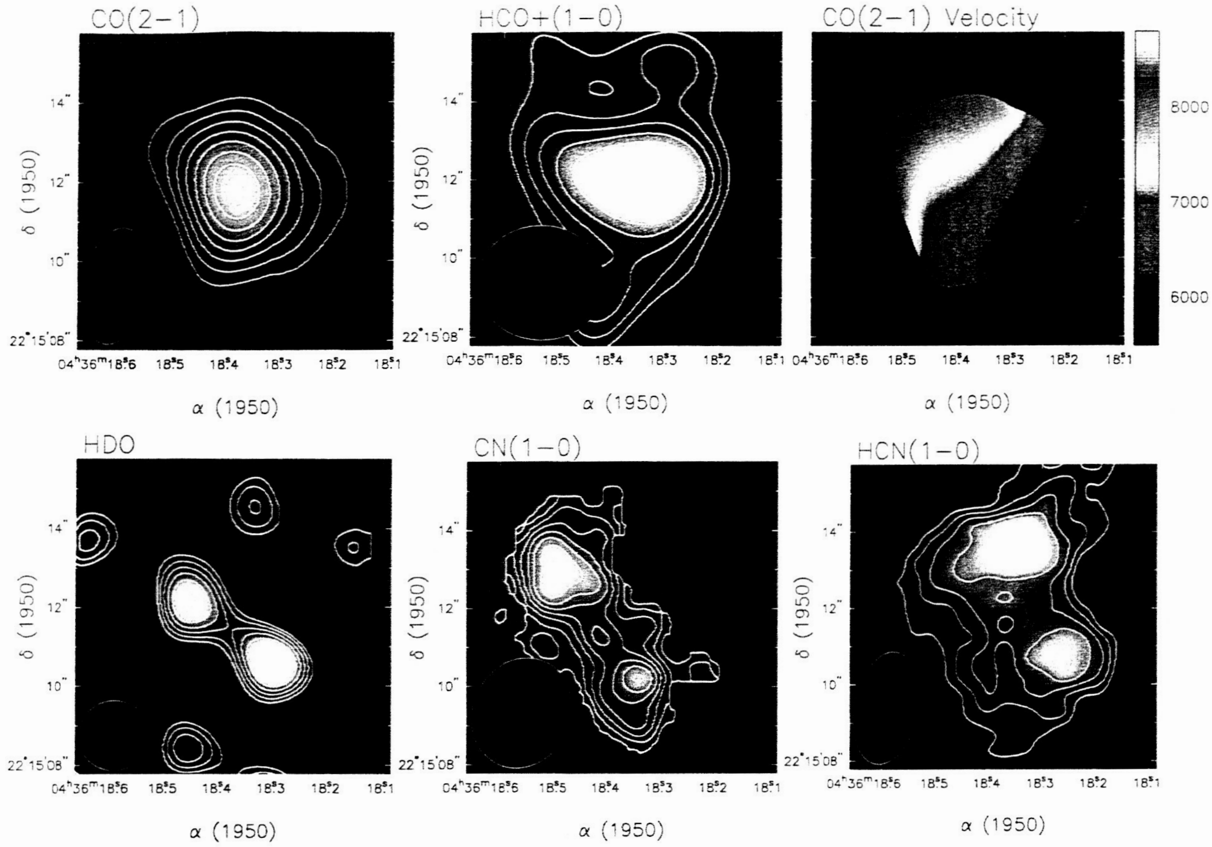


Figure 1. OVRO Millimeter Array observations of CO, HCO^+, HDO, CN, and HCN toward the T Tauri star LkCa 15. The disk velocity field derived from CO is shown at upper right, while the ellipse at the lower left of each panel depicts the FWHM of the synthesized beam.

& Beckwith 1991; Dutrey et al. 1994; Koerner & Sargent 1995; Mannings & Sargent 1997). Work on the chemical properties of circumstellar disks – properties of great relevance to planet formation – is becoming increasingly important, however. Emission from more complex species such as HCO^+, HCN, and H_2CO has now been detected by single dishes and arrays toward a few of the brightest TTs disks, for example (Dutrey et al. 1997, Kastner et al. 1997, Duvert et al. 2000, van Zadelhoff et al. 2001, Aikawa et al. 2003).

In order to examine accretion disks in detail and to test models of disk chemistry and transport, we have begun an intensive multi-species OVRO imaging study of TTs and HAe circumstellar disks (J. Kessler PhD thesis, Caltech, supported by Origins). The targets are isolated and have ages of up to 10-15 MYr. All show CO 2–1 emission patterns consistent with Keplerian rotation. That surprises await the new mm-wavelength capabilities under development (specifically the SMA, CARMA, and, ultimately, ALMA) is reinforced by the OVRO LkCa 15 observations presented in Figure 1. The age, large size, and mass of the LkCa 15 disk make it an important system for further study since it may represent an important transitional phase in which viscous disk spreading and dispersal competes with planetary formation processes (TW Hya, DM Tau and GM Aur likely present additional examples).

As expected, the emission from CO (and its isotopologues) and HCO^+ peaks at the stellar position (Qi et al. 2003). When combined with the fluxes of higher-J lines (van Zadelhoff et al. 2001), the images directly constrain the radial and vertical run of disk parameters (density, temperature, velocity field, fractional ionization) critical to models of disk mass accretion (Hawley & Balbus 1999) via 2D statistical equilibrium radiative transfer

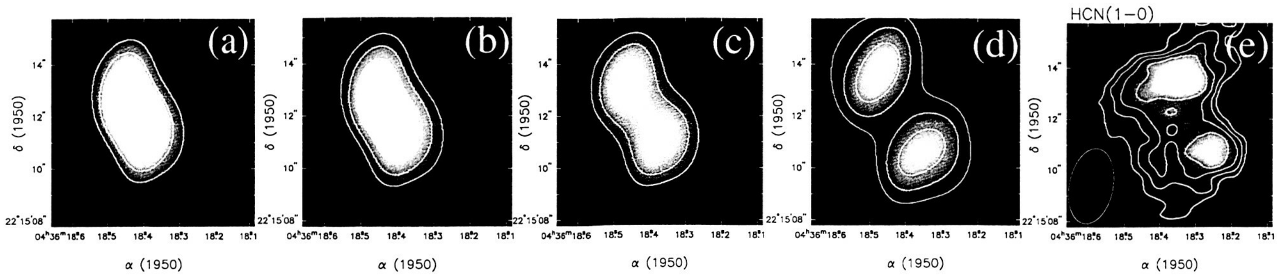


Figure 2. 2D Monte Carlo radiative transfer/statistical equilibrium fits to the HCN J=1-0 emission from LkCa 15. The observed HCN emission (e) is compared to a model of an annulus of HCN with an outer radius of 400 AU and an inner radius of 50 (a), 100 (b), 200 (c) and 300 AU (d). In each case, the total model flux is set to match that observed. The data are consistent with R_{inner}=200-300 AU (between (c) and (d)), while the models reveal that the current array cannot recover emission from the inner 50-75 AU of the disk.

models. Self-consistent treatments of the disk temperature structure (Calvet et al. 1991, 1992; d'Alessio et al. 1998; Chiang & Goldreich 1997, 1999) are used, and the molecular emission is found to arise from near-surface disk layers with $n_{\rm H_2} \approx 10^6$-10^8 cm^{-3}, $T \gtrsim 30$ K that are strongly influenced by radiation reprocessing of (inter)stellar optical, UV, and X-ray photons (van Zadelhoff et al. 2003, Aikawa et al. 2002). Extensive depletion of molecules onto the icy mantles of dust grains is proposed to occur near the dense, cold disk mid-plane, a topic to which we shall return later. Thus, molecules are excellent probes of the outer disk velocity field but do not robustly trace the disk mass (see also Simon et al. 2001).

In contrast, the emission from HDO, CN, and HCN peak some 1-2″ from the star. In the case of HDO, this arises naturally from the extreme temperature sensitivity of deuterium fractionation reactions (Kessler et al. 2003), and the large D/H ratio deduced (~0.006) confirms the cold outer disk temperatures predicted by models (similar results for DCO^+/HCO^+ are found by van Dishoeck et al. 2003 for TW Hya). The CN/HCN and HNC/HCN ratios are too high to be accounted for by quiescent chemistry (Spaans 1996, Dutrey et al. 1997, Kastner et al. 1997), however, and the location of the maxima are likely related to the radiation environment near the disk surface and the sublimation behavior of various molecules (Aikawa & Herbst 1999, Bergin et al. 2003). Measurements of the chemistry in the outer regions of circumstellar disks tell us not only about the formation and evolution of protoplanetary nebula, but by inference about our own solar system through comparisons to the composition of comets and Kuiper belt objects.

To more reliably interpret such aperture synthesis images, various model emission patterns are convolved with the appropriate beams to model the observed intensities and to extract molecular abundances. Comparisons can be done in either the image- or *(uv)*-plane, and the results for HCN are illustrated in Figure 2. Such simulations are also invaluable in determining regions of the disk that *cannot* be accessed by current telescopes. We are in the process of developing more complex multi-D radiative transfer tools and chemical models, these are described at greater length in the Proposed Research section.

B. High Resolution L-/M-Band Spectroscopy of Protostars

The rotational spectroscopy outlined above principally traces the disk near-surface disk beyond ~75 AU with current sensitivities. While K-band interferometry has now resolved the inner ~0.5 AU of the brightest circumstellar disks (Monnier & Millan-Gabet 2002), it is the 1-10 AU region of disks that forms the target of future arrays such as the VLTI, KI and ALMA, for this is where the bulk of planet formation occurs. Indeed, recent theoretical studies (Armitage et al. 2002) suggest that a relatively constant rate of planet formation near 5 AU followed by migration is consistent with the presently known orbital distribution of extraterrestrial planets (Marcy, Cochran & Mayor 2000). The models further suggest that giant planets can migrate inward from their formation zones once gaps are opened (Lin et al. 2000, Ward & Hahn 2000, Goldreich & Sari 2003), and so the observational characterization of gaps and of the fraction of disks containing Jovian protoplanets therefore forms a pivotal counterpoint to the highly successful radial velocity extrasolar planet searches.

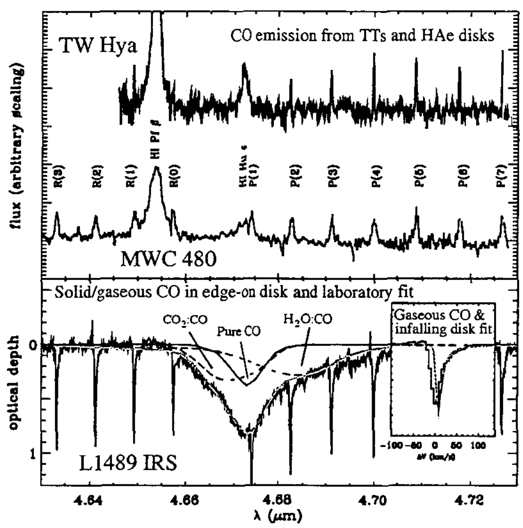
Only high resolution spectroscopy with 8-10 m class telescopes permits robust access to the disk physical conditions and velocity fields on these spatial scales at present (see Najita et al. 2000). Indeed, the potential kinematic signatures are easily resolvable with modern spectrographs. Jupiter induces a stellar velocity wobble of merely 13 m s^{-1}, for example, while alterations to the disk kinematics can be a large fraction of the orbital velocity of $\sim$13 km s^{-1} at 5 AU. Gas in and near the $\lesssim$AU gaps opened up by protoplanets can be heated by the star and, if the planet is massive enough, by shocks (Bryden et al. 1999, Kley 1999).

CO, the second most abundant molecule after H_2, is widespread through the disk (and any surrounding envelope) thanks to its stability, and so forms the first natural target for high resolution spectroscopy. While the pure rotational lines of CO trace cold gas in the outer disk and $\Delta v = 2$ overtone emission near 2.3 μm the several thousand degree gas immediately adjacent to the young star (Najita et al. 1996), the CO vibrational fundamental near 4.6 μm is potentially sensitive to very small amounts of gas in the critical protoplanet formation/migration region (see Najita et al. 2000; Carr, Mathieu, & Najita 2001).

Accordingly, we are carrying out extensive high resolution (Δv~12 km/s) observations in the M- and L-band atmospheric windows with the NIRSPEC/ISAACS spectrographs at Keck/VLT. As Figures 3 and 4 show, this program has been highly successful, having acquired the first direct observations of infalling gas in the surface layers of accretion disks (L1489), a wide range of examples of the CO emission from disks (the Herbig Ae (HAe) star MWC 480 and the T Tauri star (TTs) TW Hya are shown here for illustration), and the first detection of methane ice and gas via the C–H stretching vibration. While similar work is underway elsewhere (Brittain et al. 2003; Najita, Carr, & Mathieu 2003), our approach is distinct in the wide range of evolutionary states under investigation and the large size of well characterized Spitzer Legacy Science sample that forms its basis (c.f. §V).

In Figure 3, the two H I lines, Pf β and Hu ϵ, in TW Hya arise from the accretion flow at a few stellar radii, while the redshifted wings on the L1489 lines trace infalling gas to within $\sim$0.1 AU of the central star (Boogert, Hogerheijde, & Blake 2002). Interestingly, no H I emission is seen in L1489 despite the measured radial inflow. The fits to the solid state CO feature (Boogert, Blake & Tielens 2002) show that the grain mantles possess both polar and apolar components, which can be used to examine the nature of the icy grain mantle and thereby thermal state and history of the disk material. Similar results have been obtained for southern sources using the VLT (Pontoppidan et al. 2003). The CH_4 detection in NGC7538 IRS9 demonstrates that the weak absorption lines of other pivotal species can be detected toward protostars (disk observations are proposed below) even if they are present in significant abundance in the atmosphere – *provided* the observations are undertaken in periods of maximum doppler shifts due to the Earth's orbital velocity.

Once the envelope has dissipated, CO emission is observed that is unresolved with the typical $\sim$0.″5 seeing at Keck. As Figure 5a shows, the line widths are well correlated with inclination angle. While optically thick disk thermal emission models over the inner $\sim$1 AU can account for the ^{12}CO integrated intensities (as is argued for TTs disks, Najita, Carr, & Mathieu 2003), both the centrally peaked lines and the cooler ^{13}CO excitation temperatures (Figure 5) dictate that resonance fluorescence over R$\sim$1-50 AU also forms an important



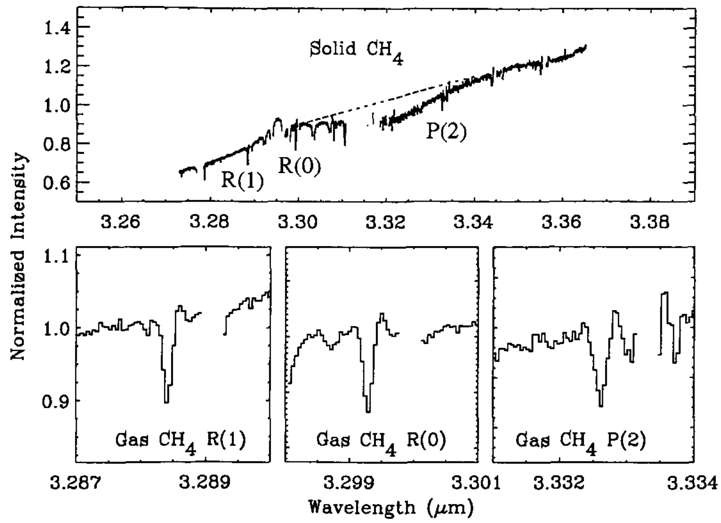
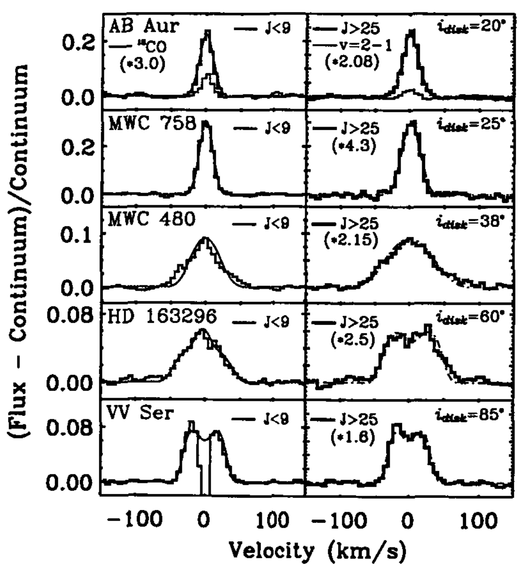


Figure 3. (Left) R=25,000 Keck spectroscopy of the 4.67 μm CO $v = 1-0$ vibration toward low mass protostars at various stages of evolution. The CO ice band is visible in the youngest sources with surrounding cores or extended disks (L1489), while the narrow absorption lines directly trace the physical conditions and velocity fields of the surrounding gas. In "bare" disks (MWC 480, TW Hya), CO emission becomes visible, and traces warm, dense gas at the disk surface over R$\lesssim$50 AU. **Figure 4.** (Right) Keck L-band observations of the gas phase and solid state methane toward the high mass protostar NGC7538 IRS9 (Boogert, Oberg & Blake 2004). The velocity offset for these observations was 70 km/s, nearly 50 km/s of offset is possible with observations of low mass protostars in Taurus/Ophiuchus at the appropriate times of year. Laboratory studies of the CH_4 ice feature are underway in Leiden.



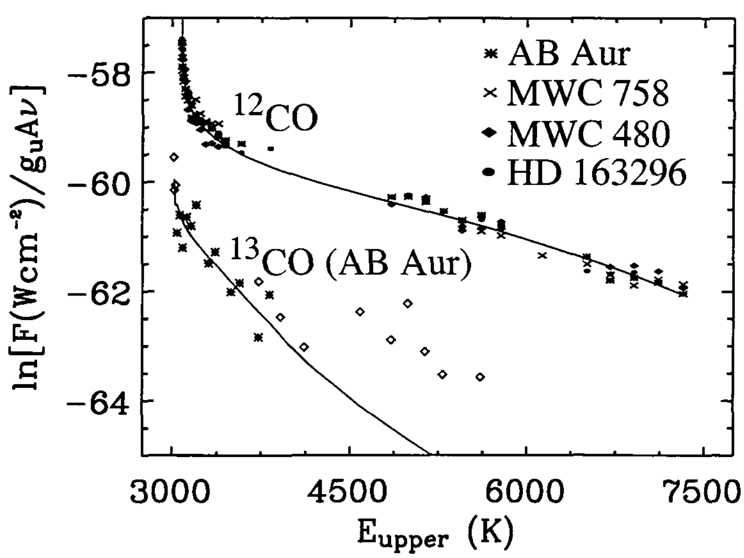


Figure 5.a. (Left) HAe Disk CO line profiles, produced by averaging over all low-J (left panel) and high-J (right panel) levels. The high-J average was normalized to that at low-J by the factor in parenthesis. The smooth lines depict disk fits to the low-J data, the dashed-dot curves to the high-J lines. The inclination angles used in the fits are listed at upper right (uncertainties $\pm$5-10°). **Figure 5.b.** (Right) ^{12}CO $v = 1 \rightarrow 0$ rotation diagrams, normalized to the inclination angle and distance of AB Aur. ^{13}CO data from AB Aur are included, upper limits are plotted as open diamonds. The disk model fits, including both thermal emission and resonance fluorescence, are indicated by the solid lines, for ^{12}CO/^{13}CO=80.

component the overall line emission (Blake & Boogert 2004). The combined fits in Figure 5 have inner radii that are somewhat larger than the 2 μm sizes derived interferometrically (Eisner et al. 2003, Muzerolle et al. 2003), temperature profiles that are consistent with recent 2D disk simulations (Dullemond 2002), and small total amounts ($\sim$1 $M_\oplus$) of radiating material defined by the surface region where $\tau_{dust}(5\ \mu m) \lesssim 1$. Thus, the disk midplane is again inaccessible, but now thanks to continuum optical depth, not molecular depletion.

These properties are consistent with disk structures recently invoked to explain the hot dust needed to generate the near-IR continuum in HAe star disks (Dullemond, Dominik, & Natta 2001). As shown by Brittain et al. (2003), the degree of *vibrational* excitation is sensitive to UV- versus IR-mediated fluorescence (high vibrational excitation indicates the scattering of UV photons), and so even cursory inspections of high resolution line profiles and intensity ratios strongly constrain the disk geometry. Similar process will occur for any molecule with active vibrations, and the examination of several species would provide exceptional probes of the planet-forming regions of disks. In this regard, we argue below that our and other group's recent results using large aperture infrared telescopes (Brittain & Rettig 2002) heralds the advent of an exciting era of discovery in which specific tracers of disk/planetary system evolution (the assembly of proto-Jovian sub-nebulae, gap formation, planet migration, etc.) can be investigated in large samples of objects. Interferometry could then be used to follow up such spectroscopic surveys with high spatial resolution images.

II. Publications in 2001-04 Under the Previous Origins Grant

The PI has published twenty peer reviewed papers and five invited reviews detailed research supported in part by the NASA Origins program over the course of the previous proposal. A full listing of these publications may be found in the Curriculum Vitae.

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IV. CURRICULUM VITAE - Nov. 2004

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BIOGRAPHICAL

Born:	[redacted]
Married:	Karen L. Blake, 1982. One child, Garrett Alexander Blake, b. 14 March 1988.

DEGREES

May, 1981	B. S., *summa cum laude*, with distinction in Chemistry, Duke University, Durham, NC (Physics minor). Thesis advisor - Prof. W.L. Luken.
June, 1986	Ph.D., Chemistry, California Institute of Technology, Pasadena, CA. Thesis advisor - Prof. T.G. Phillips (Physics).

PROFESSIONAL HISTORY

9/81-9/84	NSF Predoctoral Fellow, California Institute of Technology. Thesis research: Laboratory and astronomical rotational spectroscopy of reactive intermediates at millimeter and submillimeter wavelengths.
9/85-9/87	Miller Basic Research Postdoctoral Fellow, University of California, Berkeley. Research areas: Millimeter-wave astrophysics, infrared and far-infrared spectroscopy of molecular ions and weakly bonded clusters.
9/87-7/93	Assistant Professor of Cosmochemistry and Planetary Science.
7/93-7/97	Associate Professor of Cosmochemistry and Planetary Science.
7/97-	Professor of Cosmochemistry and Planetary Science.
9/99-	Professor of Chemistry, California Institute of Technology.
4/00-	Deputy Director, Owens Valley Radio Observatory. Research areas: Observational analyses of stellar and planetary genesis, laboratory and *in situ* studies of biogeochemical cycles.

HONORS AND AWARDS

5/81	Phi Beta Kappa, Sigma Xi, *summa cum laude*, Chemistry Department Award for Outstanding Undergraduate Thesis, Duke University.
9/81-9/84	NSF Predoctoral Fellow, California Institute of Technology.
9/85-9/87	Miller Basic Research Fellow, University of California, Berkeley.
9/87-9/88	Boeing Faculty Development Fund, California Institute of Technology.
9/87-9/88	IBM Young Faculty Development Fund, California Institute of Technology.
9/88-9/93	David and Lucille Packard Fellow, California Institute of Technology.
9/89-9/91	Alfred P. Sloan Research Fellow, California Institute of Technology.
6/89-6/94	NSF Presidential Young Investigator, California Institute of Technology.

RECENT PROFESSIONAL ACTIVITIES

3/90-8/93	Origins of Solar Systems Review Panel, OSS, NASA.
1/90-	Project SEED/CAPSI Science Professional, Pasadena/LA Unified Districts.
6/94-6/96	Origins of Solar Systems MOWG, OSS, NASA.
8/97-8/99	Exobiology Review Panel, OSS, NASA.
11/98-10/99	Astronomy and Astrophysics Decadal Review Committee, Radio Subpanel.
9/99-4/03	ALMA Science Advisory Committee (3/01-9/01 Vice Chair, 9/01-3/02 Chair)

RECENT MOLECULAR ASTROPHYSICS THESIS STUDENTS

Jacqueline Kesser (SIRTF Fellow, 10/03) – "Chemical Processes in Circumstellar Accretion Disks"

Chunhua Qi (Now SMA postdoc) – "Aperture Synthesis Studies of the Chemical Composition of Circumstellar Accretion Disks and Comets"

Michiel Hogerheijde (Leiden University, E.F. van Dishoeck primary advisor, Bok Fellow) – "The Molecular Environment of Low Mass Protostars"

REFEREED PUBLICATIONS SINCE 2001 (* = Support from the Origins Program)

* "Substantial Reservoirs of Molecular Gas in the Debris Disks around Young Stars" W.-F. Thi, G.A. Blake et al. 2001, *Nature* **409**, 60.

* "Spectral Energy Distributions of Passive T Tauri and Herbig Ae/Be Disks" E.I. Chiang et al. 2001, *Ap. J.* **547**, 1077.

* "Submm Lines from the Circumstellar Disks around Pre-Main Sequence Stars" G.-J. van Zadelhoff, E.F. van Dishoeck, W.-F. Thi, & G.A. Blake 2001, *Astron. Ap.* **377**, 566.

* "H_2 and CO Rotational Line Emission from the Disks around T Tauri and Herbig Ae Stars" W.-F. Thi, E.F. van Dishoeck, G.A. Blake et al. 2001, *Ap. J.* **561**, 1074.

"Photodissociation of Peroxynitric Acid in the Near-IR" C.M. Roehl, S.A. Nizkorodov, H. Zhang, G.A. Blake, & P.O. Wennberg 2002, *J. Phys. Chem. A* **106**, 3766.

* "ISO LWS Spectra of T Tauri and HAeBe Stars in Taurus & Ophiuchus" M. Creech-Eakman, E. Chiang, E. van Dishoeck, & G.A. Blake 2002, *Astron. Ap.*, 385, 546.

* "High Resolution 4.7 μm Keck/NIRSPEC Spectra of Protostars. I: Ices and Infalling Gas in L1489 IRS" A.C. Boogert, M. Hogerheijdge, & G.A. Blake 2002, *Ap. J.* **568**, 761.

* "The Environment and Nature of the Class I Protostar Elias 29: Molecular Gas Observations and the Location of Ices" A.C. Boogert, M.R. Hogerheijde, C. Ceccarelli, A. Tielens, E.F. van Dishoeck, G.A. Blake, W.B. Latter, & F. Motte 2002, *Ap. J.* **570**, 708.

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* "Does IRAS 16293-2422 Have a Hot Core?" F. L. Schöier, J. K. Jørgensen, E. F. van Dishoeck, & Geoffrey A. Blake 2002, *Astron. Ap.* **390**, 1001.

* "High Resolution 4.7 μm Keck/NIRSPEC Spectra of Protostars. II: The ^{13}CO Isotope in Icy Grain Mantles" A.C.A. Boogert, G.A. Blake, & A. Tielens 2002, *Ap. J.* **577**, 271.

* "Millimeter-wave Searches for Cold Dust and Molecular Gas around T Tauri Stars in MBM 12" M.R. Hogerheijde, R. Jayawardhana, D. Johnstone, G.A. Blake & J.E. Kessler 2002, *Astron. J.* **124**, 3387.

"Millimeter Wavelength Measurements of the Rotational Spectrum of 2-Aminoethanol" S. Widicus, B.J. Drouin, K.A. Dyl, & G.A. Blake 2003, *J. Mol. Spec.* **217**, 278.

* "Interferometric Observations of H_2CO in the Disk around LkCa15" Y. Aikawa, M. Momose, W. Thi, G. van Zadelhoff, C. Qi, G. Blake, E. van Dishoeck 2003, *P.A.S.J.* **55**, 11.

"A Born-Oppenheimer Photolysis Model and its Application to N_2O Fractionation" G.A. Blake, M.-C. Liang, C. Morgan, & Y. Yung 2003, *Geophys. Res. Lett.* **30**, 1656.

"Observations of Rotationally Resolved C_3 in Translucent Sight Lines" Máté Ádámkovics, Geoffrey A. Blake, & Benjamin J. McCall 2003, *Ap. J.* **595**, 235.

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* "The Structure of the NGC 1333-IRAS2 Protostellar System on 500 AU Scales" J.K. Jørgensen, M.R. Hogerheijde, E.F. van Dishoeck, Geoffrey A. Blake, & F. L. Schöier 2004, *Astron. Ap.* **413**, 993.

"Isotopic Fractionation of Nitrous Oxide in the Stratosphere: Comparison between Model and Observations" C.G. Morgan, M. Allen, M.C. Liang, R.L. Shia, G.A. Blake, & Y.L. Yung 2004, *J. Geophys. Res.* **109**, D04305.

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* "Unravelling the Chemical Structure of Young Stellar Objects with ALMA"" Ewine F. van Dishoeck & Geoffrey A. Blake 2001, *Science with the Atacama Large Millimeter Array*, A. Wootten, ed. (ASP Conf. Series, Vol. 235), pp.89-98.

* "High Resolution Mm-Wave to Infrared Spectroscopy of Circumstellar Disks" Geoffrey A. Blake 2003, *Debris Disks & the Formation of Planets: A Symposium in Memory of Fred Gillett*, D. Backman & L. Caroff, eds. (ASP Conf. Series, Vol. XXX), in press.

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* "Chemistry in Circumstellar Disks as Traced by Millimeter and IR Spectroscopy" Geoffrey A. Blake 2003, *Chemistry as a Diagnostic of Star Formation*, pp. 178-187.

* "Deuterium in Protoplanetary Disks" Jacqueline E. Kssler, Geoffrey A. Blake, & C. Qi 2003, *Chemistry as a Diagnostic of Star Formation*, pp. 188-192.