Evolution of Circumstellar Disks Around Young Stars: The Search for Gas and Remnant Dust

Program contacts: Michael R. Meyer, Ewine van Dishoek, Craig Kulesa, & Joan Najita
Scientific category: STAR FORMATION
Instruments: MIR/CAM, MIR/SPEC
Days of observation: 110

Abstract

Over the past 15 years, tremendous progress has been made in understanding the structure and evolution of optically–thick dust disks commonly observed to surround pre–main sequence stars. However, establishing a direct relationship between these young star+disk systems and the origin of our own solar system remains elusive. We propose to attack two of the outstanding problems that will likely remain when NGST is launched in 2007; the evolution of molecular gas and grain processing in circumstellar disks. By conducting a medium resolution mid–IR spectroscopic survey for H_2 in disks surrounding young stars from 1–100 Myr we can determine when gas dissipates in the disks, constraining the epoch of giant planet formation. Follow–up observations to search for trace molecular species in the warm inner disks detected will provide crucial inputs for models of nebular chemistry. Adding a high resolution ($R = 30,000$) mid–IR spectroscopic capability, would enable kinematic studies of the gas, allowing gas temperature and density to be mapped as a function of disk radius. In the second part of this program, we will perform a mid–IR imaging and low resolution spectroscopic survey of remnant dust disks aged 1–300 Myr. With direct images between 5–25 μm we can determine the density and temperature distribution of the dust in the remnant disk and discern the presence of inner holes (if present) in disks surrounding solar mass stars. By obtaining *spatially–resolved* spectra from 10–25 μm along the major axis of the resolved disks, we can investigate the distribution of the dust in these systems as traced by the solid state features populating the mid–infrared. This program of observations will help to answer three fundamental questions of disk evolution and planet formation; i) when does gas dissipate in circumstellar disks?; ii) do remnant dust disks surrounding solar mass stars exhibit similar inner holes to those inferred around early–type stars?; and iii) when and where does grain growth/processing occur in protoplanetary disks? Ultimately we wish to know when and where planets form in circumstellar disks surrounding young stars – a key goal of the NASA Origins program.

Observing Summary:

Target	RA	Dec	K_{AB}	Configuration/mode	Days
120 YSOS	$d <$	$500pc$	$N < 8.0^m$	MIR/SPEC R3000	50
80 DEBRIS DISKS	All Sky	All Sky	$N < 10.0^m$	MIR/SPEC R300	30
80 YSOS	$d <$	$500pc$	$N < 8.0^m$	MIR/SPEC R30000	30
				Grand total days	110

Scientific Objectives

1 Background

It is generally accepted that circumstellar disks are a common by–product of the star formation process (Beckwith and Sargent, 1996). Estimates of the ubiquity of accretion disks around young stars ranges from 50–100 % for the youngest star–forming regions (Hillenbrand et al. 1998; Kenyon and Hartmann, 1995). As young stars age, evidence of active accretion diminishes (Figure 1). However, the process by which these disks dissipate remains a mystery. One possibility is that such disks give rise to the formation of planetary systems. Based on near– and mid–IR observations of T Tauri stars, Skrutskie *et al.* (1990) estimated the timescale for dissipation of accretion disks around young stars to be $< 10^7$ yrs. Based on the small fraction of their sample thought to be in "transition", Skrutskie *et al.* derived a timescale of $< 1 \times 10^6$ yr for evolution from optically–thick accretion disk to optically–thin re-processing disk. These timescales are important for constraining the epoch of planet formation and providing insight into the disk dissipation process. For example, calculations by Pollack *et al.* (1997) require mass surface densities 3–4 times greater than implied by the minimum mass solar nebula (0.02 $M_\odot$) for Jupiter to form in < 10 Myr via runaway accretion. In contrast, earth mass planets are thought to take 100 Myr or more to form in the terrestrial planet zone (Wetherill, 1996). Because of the sensitivity limitations of the existing mid–infrared data, Skrutskie *et al.* were unable to constrain the lifetime of optically–thin circumstellar disks in the terrestrial planet zone surrounding nearby young stars.

New generations of sensitive mid–IR arrays have enabled considerable progress in ground–based surveys at 10 μm. Additional observations at 25 and 60 μm made possible by the Infrared Space Observatory have placed limits on the lifetime of optically–thick disks at radii from 1–5 AU around young systems (Meyer et al., 1998). A picture is beginning to emerge that optically–thick disks in the terrestrial planet region dissipate on timescales similar to the termination of the accretion phase traced by near–IR emission in the inner disk. Further, ISO observations of A, F, and G field stars have determined that $\sim$ 20 % are surrounded by optically–thin dust disks similar to that observed to surround Vega. Moreover, there is some hint that the optical–depth decreases with age (Dominik et al. 1998; Becklin et al. 1998). Future mid–IR surveys planned with WIRE and SIRTF will detect the presence of extremely tenuous dust disks placing strong constraints on the remaining material component surrounding young stars from 1–300 Myr old. By the time NGST is launched in 2007, we should have a clear picture of the evolution of dust mass in disks from 1–100 AU around stars from 1–300 Myr old.

However several fundamental questions will remain: what of the gas component of these disks, thought to comprise 99 % of their mass? Does the gas evolve over the same timescale as the dust? When do dust grains accumulate into into larger particles? Do forming planetary systems clear inner disk systems out to 30 AU (the distance of the Kuiper Belt from the Sun) such as observed in HR 4796? Are materials processed in the inner nebula scattered to larger radii as is thought to have taken place for comets in our solar system? We propose a two–part program to address these fundamental questions through; i) a moderate resolution mid–IR spectroscopy survey aimed at detecting H_2 and other molecular species in circumstellar disks ; and ii) broadband imaging of remnant disks and follow–up low resolution spectroscopy in order to look for inner disk holes as well as characterize the growth of dust grains into planetesimals through observation of mid–IR solid state features.

2 Significance to Astronomy

Understanding the formation of planetary systems is one of the most compelling questions in astronomy today. As such it commands tremendous public interest and is one of the main goals of the Origins program at NASA. This program takes full advantage of the unique capabilities of NGST operating in the thermal infrared to answer questions directly related to the evolution of circumstellar disks and planet formation. Constraining the timescale for gas dissipation and planetesimal formation in the circumstellar environment will place new constraints on theories of planetary systems, providing another crucial link between studies of star formation and the origin of our own solar system. Results from this study will inform future generations of space–based and ground–based searches for earth–like planets around other stars and ultimately the quest to discover evidence for life on other planets.

3 Scientific Goals

The goals of this program are two–fold; i) to search for and characterize the distribution of molecular gas surrounding young stars as a function of age; and ii) to investigate the properties of remnant dust disks during the dissipation phase.

Evolution of Molecular Gas in Circumstellar Disks We plan to survey approximately 120 well–studied young stellar objects within 500 pc for molecular gas associated with the dust disks known to accompany low mass pre–mains sequence stars. We will begin by searching for H_2 emission from 12–28 μm. These lines trace the bulk of the gas which lies at radii from 1–50 AU with temperatures between 50–300K. The ratio of the line intensities will provide rough temperature estimates from which we can estimate the total gas mass of the emitting region. We estimate that we will be sensitive to gas seen in emission against the stellar photosphere down to a limit of $\sim 0.001 M_\odot$ of H_2, more than $\times$ 10 lower than the minimum mass solar nebula. For those objects with optically–thick dust disks, the detection of H_2 emission would provide evidence of optically–thin continuum emission perhaps indicating a region evacuated by a very low mass brown dwarf or giant planet companion. For some subset of our sample, we will conduct follow–up observations of longer integration times in order to detect molecular species such as H_2O, NH_3, and CH_4 from 4.5–12.5 μm in order to investigate the chemical abundances of the gas as a function of age which are predicted by models of nebular evolution (e.g. Aikawa et al., 1997).

With the addition of a high dispersion capability ($R = 30,000$) operating in the mid–IR, kinematic studies could be undertaken with velocity resolution of 10 km/sec. This would enable determination of temperature and density in the circumstellar disks as a function of radius by combining the Keplerian velocity field with estimates of the central stellar mass. In sources where gas detections imply gaps in the circumstellar dust distribution, these high dispersion spectra could provide the first hints as to when and where planets form in circumstellar disks surrounding young stars! ISO has helped demonstrate the feasibility of this technique by detecting H_2 emission in the disk of GG Tau, known to have a gap in its circumstellar dust distribution based on mm–wave interferometric observations (Figure 2).

Evolution of Circumstellar Dust: In a complementary study, we will conduct a three–color mid–infrared imaging survey of *solar–type stars* identified by WIRE and/or SIRTF to have optically thin dust dust disks ranging in age from 1–300 Myr. From the multi–color imaging photometry we will discern whether or not the disks display evidence for inner holes surrounding these solar analogues. Early–type stars exhibiting the "Vega phenomenon" often have SEDs which suggest large inner holes of approximately 30 AU in radius (Figure 3). It has been suggested that these holes are evidence that planetary systems have dynamically cleared the inner regions of the circumstellar environment. However, this distance is also close to the ice condensation boundary for these luminous A stars. If debris disks surrounding solar mass stars have inner disk holes closer to 5 AU than 30 AU this would provide powerful evidence for the ice–boundary hypothesis. If on the other hand there appears to be some characteristic distance of the inner boundary which does not depend on the spectral type of the star, perhaps we can conclude that the physics of accretion which controls the evolution of the disk mass surface density preferentially forms planets within 30 AU! Next we propose to obtain spatially–resolved low resolution mid–IR spectra from 10–30 microns for the objects in our sample. These spectra can be used to distinguish between different solid state features which provide important clues to the processing history of the material. As illustrated in Figure 4, emission features attributed to crystalline silicates have been identified in the spectra of some Herbig Ae/Be stars (more massive analogues of solar mass pre–main sequence T Tauri stars). These features are different from amorphous silicate features observed in the unprocessed interstellar medium. In contrast, the crystalline silicate dust (observed in meteoritic samples and the mid–IR spectra of comets) is thought to have formed in the hot, high density environment of the inner circumstellar disk. The presence of this dust in comets supports the hypothesis that after their formation in the solar nebular they were scattered into the Oort cloud due to dynamical interactions with the outer giant planets. It is tempting to speculate that such processes may be at work in the young stellar objects we observe today! In any case, spatially mapping the rich mid–IR spectra of these remnant disks as a function of stellar age will provide valuable insight into the composition and processing history of the dust.

NGST Uniqueness/Relationship to Other Facilities

This programs exploits the most powerful capability of NGST when compared to ground–based facilities; moderate resolution spectroscopy and imaging of faint objects in the thermal infrared. For an equivalent observation at $R = 3000$ for the 17 μm line of molecular hydrogen, NGST achieves SNR > 100 compared to a ground–based 8m telescope with a corresponding gain in speed of $\sim 10^4$. While SOFIA will operate at a cooler temperature (220K) compared to the ground, and at high dispersion compared to NGST, the smaller aperture (2.5m) makes it a magnitude less sensitive than a ground–based 8m for this project. SIRTF ($R \sim 500$) does not have the resolving power required to separate key molecular features nor the sensitivity (85 cm aperture) to detect gas in disks surrounding PMS stars. Only NGST is capable of surveying a representative sample of young stars and placing astrophysically interesting constraints on the remnant gas mass in their circumstellar disks. While this survey with NGST will probe molecular species in the inner circumstellar disk ($d < 5AU$), complementary surveys will be undertaken with the MMA probing the outer disk material ($d > 10AU$). NGST enjoys an even greater advantage over ground–based facilities in the thermal infrared at lower resolving powers. Whereas a ground based 8m telescope could just detect (5 σ) an extended dust disk (ala HR 4796) around a solar mass star in three hours of integration, NGST will be able to obtain moderate SNR (30σ) spatially resolved spectra of the dust at a resolving power of $R = 300$ in the same integration time. Neither WIRE nor SIRTF will have the spatial resolution required to resolve these debris disks.

Observing Strategy

In part one of this program, we will conduct a survey for molecular hydrogen gas found in the circumstellar stellar environment of young stars aged 1–100 Myr. Our sample of 120 stars will be drawn from nearby star–forming regions (d$<$ 500 pc) which have been searched for, and are known *not* to harbor stellar mass companions from 0.1–1000 AU. We will split our sample into bins with masses greater than and less 1 $M_\odot$, 3 logarithmic age bins 0.1–100 Myr (as derived from PMS evolutionary tracks), and isolated vs. clustered formation environments in order to investigate the evolution of gas disks as a function of these variables. We require 10 stars per bin in order to have reasonable statistics for investigating differences in gas content. Estimates suggest that in five hours of integration time, we can achieve a 3σ detection of a line flux 2.4×10^{-5} Jy in the 17.0 μm 0–0 S(1) line of molecular hydrogen against a stellar continuum of 0.001 Jy. This corresponds to detecting a gas mass of 0.001 $M_\odot$ assuming (conservatively) a temperature of 50 K towards a 10 Myr 1 $M_\odot$ star at the distance of the Taurus–Auriga dark cloud (150 pc). The 0–0 S(0) line of H_2 at 28 μm best probes the coolest gas, while the 0–0 S(2) 12.3 μm line would probe warmer material. It may even be possible to *spatially resolve* the gas emission in the disk between 10–30 AU for the nearest targets.

Measurement of at least two transitions are required in order to derive gas temperatures for the H_2 and thus mass estimates for the gas. At $R = 3000$, we can obtain 2.9 μm per order (at 17.0 μm) across a 1024 array. Assuming the initial survey for H_2 is performed in cross–dispersed mode at wavelengths 12–28 μm, with five hours integration per source our survey will require $120 \times 5 = 600$ hours of time. We anticipate that a large fraction of our sample will posses gas–rich circumstellar disks requiring further study at shorter wavelengths. With eight orders cross–dispersed over the array one could cover the wavelength range from 5–12.0

μm. This would enable searches for several molecular species thought to be important for the chemistry of circumstellar disks and planet formation such as H_2O, CH_4, and NH_3. As the abundances of these species are low compared to H_2, longer integrations are required. We anticipate that 25 % of our sample would benefit from increased integration times of up to 20 hours in order to study these trace species. Detection of these features would provide abundance estimates crucial to models of nebular evolution and the formation of planetary systems. We request $30 \times 20 = 600$ hours for follow–up spectroscopy for a total request of 1200 hours (50 days) for this part of the program.

For the kinematic part of the spectroscopic program we plan to survey 80 stars (10 per bin) sorted by spectral class of the primary star (F, G, K, and M stars) as a function of star–forming environment (isolated vs. clustered). According to the models of Carr and Najita (1997) we anticipate that 9 hours of integration time should be sufficient to *kinematically resolve* molecular species outlined above at $R = 30,000$ for selected features observed in cross–dispersed mode between 4.5–12.5 μm. With stellar mass estimates obtained from extant studies of the primary stars, the velocity resolved spectra will enable estimation of the radius at which gas of different temperatures and densities is emitting. We request $80 \times 9 = 720$ hours (30 days) for this high dispersion spectroscopic survey.

In the second part of this program, we propose to image, as well as obtain low resolution spectra in the mid–IR of a sample of 80 debris disks. The source list will be drawn largely from future IR missions (WIRE and SIRTF) sampling stars of F, G, K, and M spectral classes for both binary and single stars (eight bins of 10 objects each). The 200 AU disk recently resolved around the 10 Myr old A–star HR4796 at 20 μm (Figure 2) would subtend 4.0" at 50 pc (distance of the 15 Myr old TW Hydra association) corresponding to > 25 pixels sampling the disk at 0.15". An optically–thin dust disk with a mass of 0.1 $M_{\oplus}$ (similar to Kuiper Belt estimates) at a temperature of 50K would be resolved by NGST several minutes integration time (6.25×10^{-6} Jy arcsecond^{-2}). Obtaining images in at least three discrete wavelengths between 5–30 μm would permit determination of the temperature and density distribution of the dust as well as constraining the inclination of the star–disk system. These observations would easily detect the presence of a hole in the inner disk such as that observed in the HR 4796 system. In addition, the images will be crucial for aligning the slit for the spectroscopic observations along the disk major axis. Spatially resolved long–slit spectra could be obtained at $R = 300$ with $SNR \sim 30$ of these extremely tenuous disks in about nine hours of integration time. Spectra of this resolving power will permit separation of several solid state features (e.g. the 11.3 μm PAH feature from the 11.36 μm crystalline olivine feature) important for studying the processing history of the circumstellar dust. We request $80 \times 5 \times 3 = 1200$ minutes (20 hours) for the imaging portion of this program and $80 \times 9 = 720$ hours for the spectroscopic follow–up.

Special Requirements

Diffraction–limited imaging at 10.0 μm: This program requires high spatial resolution in order to investigate the inner regions of remnant circumstellar disks surrounding young solar mass stars. We require a minimum physical resolution of $0.3 \times 50pc = 16AU$ at 10 μm in order to test whether or not mid–IR emitting dust extends within 30 AU, the characteristic hole size of "Vega–phenomenon" objects.

Minimum resolving power of $R = 3000$ *from 5–30* μ*m:* Needed to detect ground–state transitions of molecular hydrogen from 12.0–28.3 μm in a reasonable integration time for interesting gas mass and temperature limits; 4.5–12.5 μm spectra are required to detect several interesting chemical species in our sample of proto–planetary disks. Cross–dispersed capability required in order to sample the full spectral range.

Minimum resolving power of $R = 300$ *for long–slit mode:* Required to resolve several interesting solid state dust features that are blended together at lower resolution. Long–slit (120") required in order to obtain spatially–resolved spectra along the major–axis of the circumstellar dust disk (1000 AU at a distance of 10 pc).

Kinematic Studies Enabled with $R = 30000$ *from 5–30* μ*m:* At the temperatures which characterize molecular gas emission in the mid–IR, these lines probe the inner 5 AU of the circumstellar disk. As a result, both the thermal line–widths (at 50K) as well as the kinematic profiles ($V_{KEP} \sim 30$ km sec^{-1}) are narrow. Resolving powers of 10,000–100,000 are required in order to determine density and temperature as a function of radius in proto–planetary disks surrounding young PMS stars.

Precursor/Supporting Observations

Our survey for H_2 gas in the remnant disks surrounding young stars aged 1–100 Myr will be complimentary to observations that will be made for trace species with the MMA. In addition, the temperatures and densities probed by the MMA correspond to the cool outer disk ($>$ 10 AU) material whereas the NGST survey for additional molecular emission will probe the warm inner regions of the disks ($<$ 5 AU). ISO has made pioneering mid–infrared observations which have guided our choice of spectral resolution and wavelength. Preliminary observations of gas–rich disks found surrounding the brightest few objects will be conducted with ground–based 8–10m class telescopes as well as SOFIA at high spectral resolution. These observations will further inform surveys which can only be conducted with NGST.

Our target sample for the direct imaging and low resolution spectroscopic survey of debris disks will come largely from surveys carried out by the WIRE and SIRTF missions which will have been completed by the time NGST is launched in 2007.

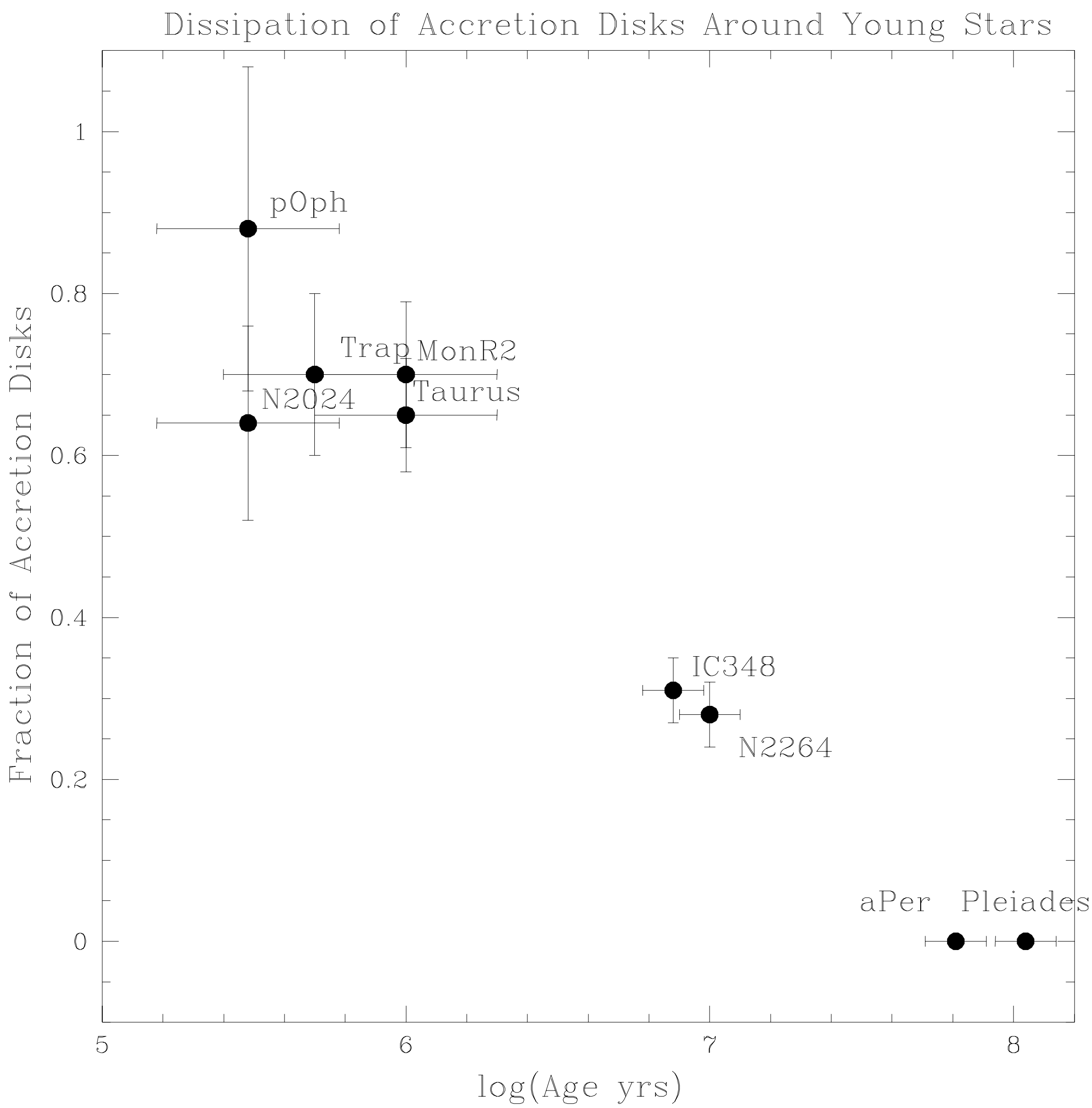

Figure 1: Frequency of active accretion disks in young clusters as a function of cluster age as traced by the occurrence of near–IR excess emission (Meyer et al., 1998). While some disks are observed to dissipate within 10^6 yrs, the characteristic timescale for the termination of accretion appears to be $\sim$ 10 Myr. Whereas ISO, WIRE, and SIRTF will address the timescale for dissipation of optically–thin dust emission, NGST will make observations complementary to the MMA in constraining the lifetime of molecular gas disks.

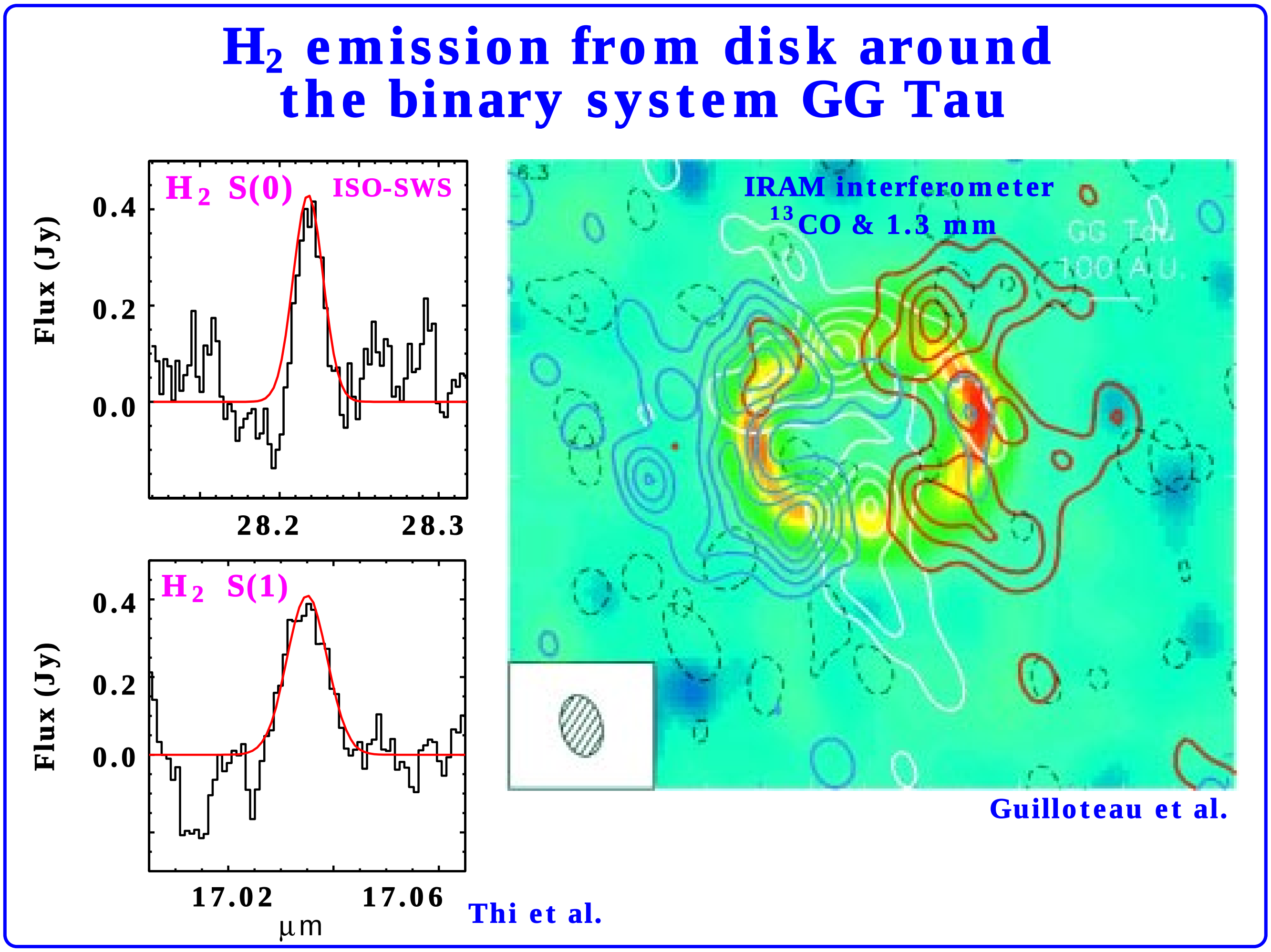

Figure 2: ISO–SWS observations of cool H_2 gas in the young PMS binary system GG Tau. Because the binary companion has cleared a large gap in the circumstellar dust distribution (Guilloteau et al.) the H_2 is detected where the dust is optically–thin (Thi et al., 1998). NGST will be capable of detecting gas masses << than the minimum mass solar nebula disk detected here, enabling studies which will determine the lifetime of gas disks.

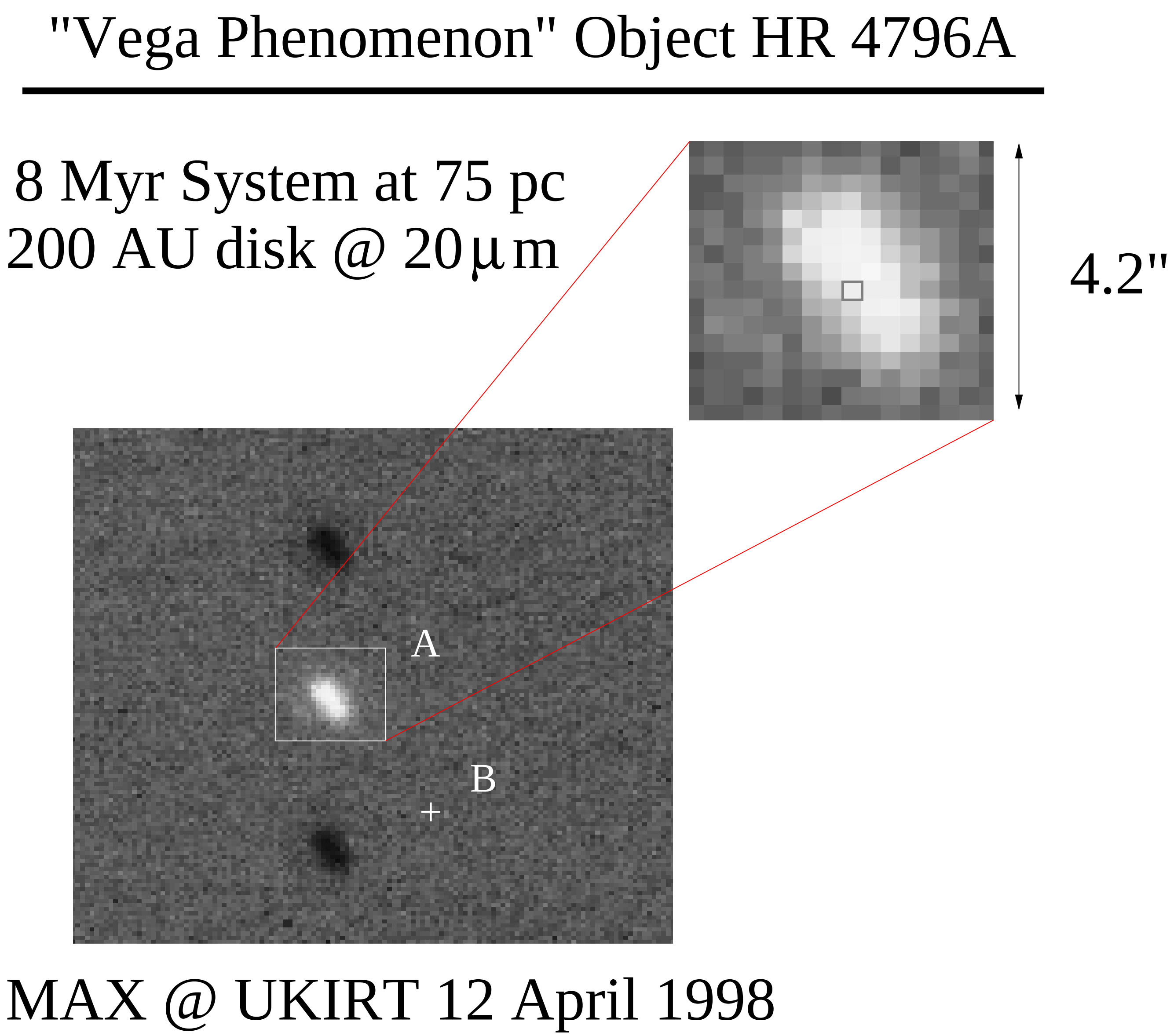

Figure 3: Twenty micron image of the disk surrounding the A–star HR 4796A obtained with the MPIA mid–infrared camera MAX at the UKIRT 3.8m telescope. The disk appears to lie in the plane of the binary orbit and displays evidence for an inner hole of 30 AU (Koerner et al., 1998). NGST is capable of imaging a disk with $\times$ 10 less mass surrounding a solar type star as well as obtaining spatially resolved $R = 300$ spectra. These spectra could be used to study the composition of the dust providing clues to the formation of planetesimals.

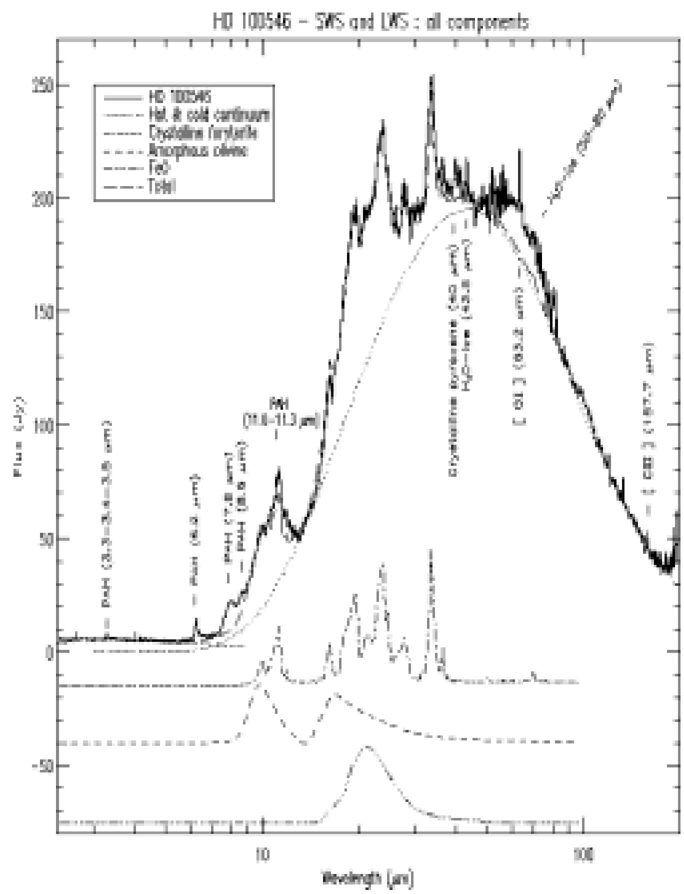

Figure 4: Combined ISO (SWS+LWS) spectrum of HD 100546 (from Malfait et al., 1998): The spectrum shows a large number of optically–thin emission features which are comprised of both amorphous and crystalline silicates, FeO, H_2O ices, and PAHs. The dust continuum emission is shown as the upper dotted line while the individual spectra of various components are shown at the bottom. The presence of crystalline fosterite indicates grain growth at high densities and temperatures. Similar spectra are observed in comets such as Hale–Bopp suggesting the presence of similarly processed materials in the circumstellar environment of stars like HD 100546.