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From Disks to Planets – The Large Facilities

1. Introduction

The large diversity of detected exoplanetary systems, ranging from close-in hot Jupiters to planets in resonances and on eccentric orbits to the recently detected super Earths and directly imaged planets on wide orbits, has revived interest in the formation history of planetary systems. Population synthesis studies are now trying to build the bridge between the properties of protoplanetary disks, the early formation process of planets and the subsequent planet-disk and planet-planet interactions (Mordasini et al. 2009). Disk metallicity, mass, lifetime, and surface density profiles are among the various disk parameters setting the stage for the planet formation process.

Since the first detection of circumstellar disks around solar-type pre-main sequence stars through the measurement of their infrared excess emission (Strom et al. 1989) and the determination of their dust masses through submillimetre and millimetre observations (Beckwith et al. 1990), an enormous amount of data on these objects has been collected. These studies demonstrated that the analysis of their spectral energy distributions alone is not sufficient to reveal the structure of disks (e.g. Thamm et al. 1994); spatially resolved information and spectroscopy data have to be added. The variety of disk studies has led to a picture where stellar irradiation, inner disk structure, and dust evolution – such as grain growth and sedimentation – determine the global disk morphology and the observational appearance of disks. An example is the frequent observation of silicate emission features, which requires an optically thin surface layer or disk atmosphere on top of an optically thick dust disk. Another disk feature is the flaring angle which may have a direct connection to dust sedimentation.

There are a number of questions we want to answer with our studies of protoplanetary disks. What is the lifetime of disks? What is the influence of stellar parameters on disk properties? How is the dust and gas evolution coupled? What is the influence of environment on disk evolution? Is there a difference in disk evolution between single stars and close binaries? How important are the initial conditions of the molecular cores for the subsequent disk structure? What is the chemical evolution of disks and their content of water and complex organic molecules? We are just starting to answer these questions with comprehensive studies of larger samples of young stars and their protoplanetary disks.

The availability of large facilities played a major role in understanding disk structure. The data ranged from superb images coming from the Hubble Space Telescope to images from ground-based facilities for larger disks such as β Pictoris (see Figure 1). AO-assisted disk imaging from the ground with 8m-class telescopes had some success, but often needed the addition of a variety of contrast-enhancing techniques

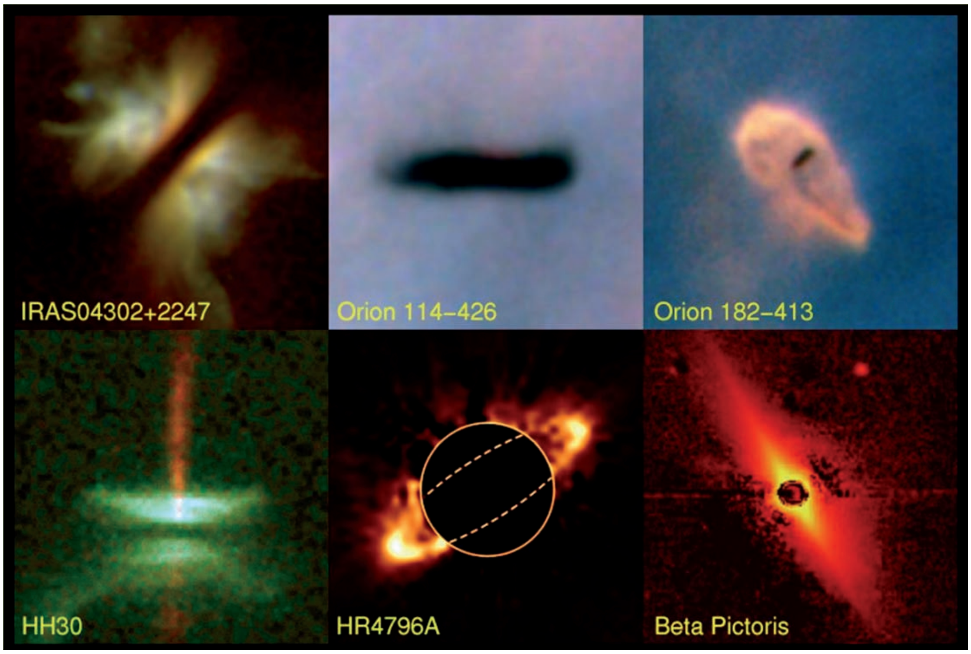

***Figure 1** Hubble Space Telescope Images of protoplanetary disks (Padgett et al. 1999: IRAS04302+2247; McCaughrean & O'Dell (1996): Orion disks; Burrows et al. 1996: HH30; Schneider et al. 1999: HR 4796A) and the early ground-based image of β Pictoris (Kalas & Jewitt 1995).*

such as polarimetry. The various submillimetre and millimetre interferometry facilities, including the IRAM-PdBI, SMA, and CARMA, provided images of the cold dust distribution and allowed us to find evidence for Keplerian rotation in disks. VLA observations at millimetre and centimetre wavelengths were essential to prove the presence of larger particles in disks. Recent advancements in long-baseline infrared interferometry with the Keck telescopes and with ESO's Very Large Telescope Interferometer allowed us to resolve the inner few AU of protoplanetary disks and provided evidence for a radial variation in dust properties.

Starting with the Infrared Space Observatory and followed by the Spitzer Infrared Space Telescope, the mineralogy of protoplanetary dust could be analysed. The main dust components are amorphous silicates and crystalline Mg-rich silicates. In addition, Spitzer's much increased sensitivity led to the detection and spectroscopic characterization of disks around brown dwarfs and to a statistical investigation of disk properties in quite a number of star-forming regions and nearby moving groups. Herschel will soon extend these studies to longer wavelengths; JWST will provide unprecedented sensitivity for disk imaging and spectroscopy.

Most of the previous studies dealt with the characterization of the dust in protoplanetary disks, an easier measurement due to the higher dust opacities compared with the gas. Dust evolution is certainly very important if one wants to understand the formation of planetesimals, Earth-like planets, and the cores of gas giants. On the other hand, dust is only a minor contributor to the total mass budget of disks, and the dynamics and angular momentum transport is regulated through the gas, which also provides the material reservoir for the formation of giant planets. Recently, we have seen enormous progress in the search for gas in inner disks, thanks to the sensitivity of Spitzer and a number of high-resolution spectrographs on 8 m-class telescopes such as CRIRES at ESO's Very Large Telescope and NIRSPEC at Keck. This will be an interesting avenue for both sensitive spectroscopy with JWST and high-resolution mid-infrared instruments on the new class of extremely large telescopes. Millimetre interferometry provides information on the vertical and radial structure of disks and allows us to measure molecular tracers of disk ionization. With the ALMA facility we will soon get much increased sensitivity and spatial resolution for disk studies.

Multi-object spectroscopy at optical and near-infrared wavelengths is being used to characterize the stellar properties and the accretion rates of statistically relevant samples of young stars and to relate these quantities to disk properties.

In this paper, I will summarize some of the major results coming from the various large ground-based and space-based facilities. For more extended reviews, I refer to the papers by Natta et al. (2007) and Henning (2008). I will also specifically discuss the Large Binocular Telescope and its potential for the investigation of protoplanetary disks and the planet formation process.

2. Disk lifetimes and global disk properties

Disk lifetimes have been studied using the disk frequency as an indicator for this important parameter. In determining disk frequencies, one has to make sure that the sensitivity of the infrared surveys is high enough to measure both the infrared excess emission and the emission from the stellar photospheres of the cluster members. In addition, disk emission may set in at different infrared wavelengths. Therefore, these studies require sufficient wavelength coverage. In addition, age estimates of young stars are notoriously difficult and often associated with large uncertainties.

Ground-based infrared surveys and sensitive studies with Spitzer have led to estimates of disk lifetimes with the latest values close to $10^{6.4\pm0.4}$ yrs (Hernandez et al. 2008 and references therein). In general, 90% of the systems have lifetimes less than 5 Myrs and only a very small percentage survive for 10 Myrs. Here we should stress that there is considerable scatter in disk lifetimes for individual clusters. Some stars loose their disks very early or were never associated with extended disks.

Disk lifetimes can be different in different environments. In a recent study of the NGC 2244 cluster, Balog et al. (2007) found a reduction in disk frequency by a factor of 2 in the inner cluster region, but concluded that the effect of high-mass stars on disk evolution is significant only in their immediate environment. In a study of young clusters in Orion, a difference in disk lifetime between objects in L 1630N and L 1641C (clustered populations) vs L 1641D (distributed population) has been found (Fang et al. 2009), with a reduced disk frequency in the clusters for the 2-3 Myr age bin. Finally, close binarity seems to be a very important factor for inner disk evolution. In a study of the η Chamaeleontis cluster, Bouwman et al. (2006) found that the presence of inner disks was anticorrelated with close binarity. The mean disk dissipation timescales were estimated to be 5 and 9 Myrs for the binary and single-star systems, respectively. All these studies illustrate that there are other "hidden" parameters beyond time which influence disk evolution.

All "disk lifetimes" discussed so far refer to the disappearance of thermal emission from small dust grains. This does not necessarily imply that gas evolution occurs on the same timescale. Pascucci et al. (2006) searched for gas in disks around Sun-like stars with ages between 3-100 Myrs and did not detect any gas-rich disks (i.e. gas mass greater than 0.1 Jupiter mass). This suggests that gas disks dissipate on a similar timescale to the dust disks. Recently comprehensive studies using multi-object spectroscopy showed that the accretion behaviour has a temporal dependence similar to the dust evolution, suggesting that dust and gas evolution are well coupled (see Figure 2).

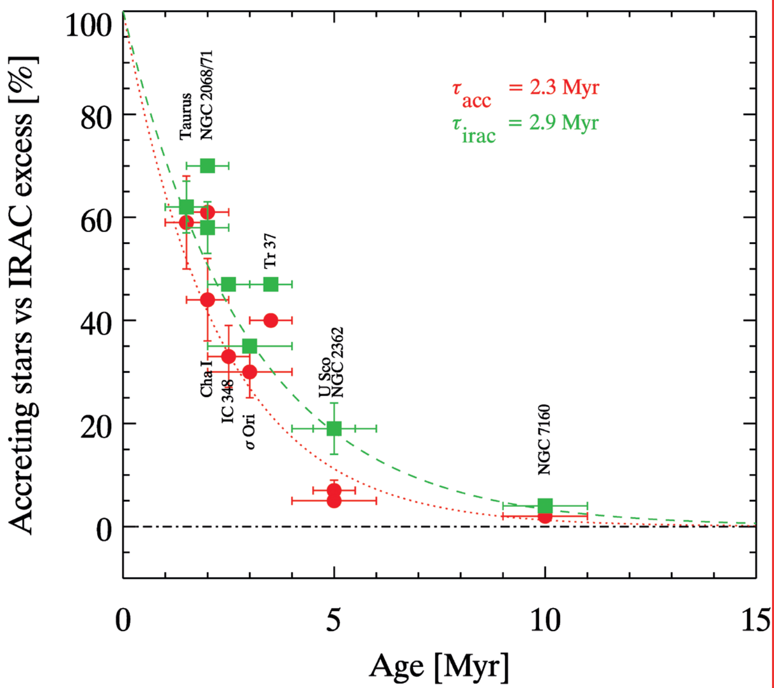

***Figure 2** Fraction of accreting stars (dots) vs near-infrared excess emission (squares). After Fedele et al. (2009).*

Global disk parameters, such as disk mass, inner and outer radii, and radial temperature and density profile, are of utmost importance for planet formation in disks. Large submillimeter surveys of disks in the Taurus and Ophiuchus star-forming regions lead to typical disk masses between 0.001

and 0.01 solar masses and a disk-to-stellar mass ratio of 1% (Andrews & Williams 2005, 2007a). Here, one has to keep in mind that the derivation of total disk masses from dust continuum observations includes assumptions on dust opacities and gas-to-dust ratios which remain uncertain. There is some evidence that the actual disk masses are somewhat higher than inferred from these observations. Submillimetre interferometry observations are starting to provide constraints on disk radii and surface density profiles. In a recent SMA study of 24 circumstellar disks, Andrews & Williams (2007b) found radial surface density profiles with a median exponent of -0.5 for a power law distribution, although values around -1.0 may be more reasonable taking systematic effects into account. The distribution of the outer radii has a distinct peak at 200 AU and only a very few disks remained completely unresolved. Observations with the Very Large Array provided convincing evidence for the presence of large centimeter-sized "boulders" in protoplanetary disks, thereby demonstrating rapid grain growth from small submicron-sized grains to larger planetesimals (e.g. Rodmann et al. 2006).

3. Dust and Gas Properties

Infrared dust spectroscopy, both from the ground and space, resulted in a comprehensive overview about the various dust components in disks (Henning & Meeus 2009). Despite the power of this technique, one also needs to be aware of its limitations: infrared spectroscopy only traces the composition of the optically thin surface layer, is only sensitive to certain radial regions of the disk, reflecting their temperatures, and is not able to provide sensitive information on featureless grain components, such as iron particles or pure carbon grains. The investigation of high-quality disk spectra showed that the main dust components are amorphous silicates with olivine and pyroxene stoichiometry, crystalline forsterite and enstatite and in some cases silica (e.g. Juhasz et al. 2009).

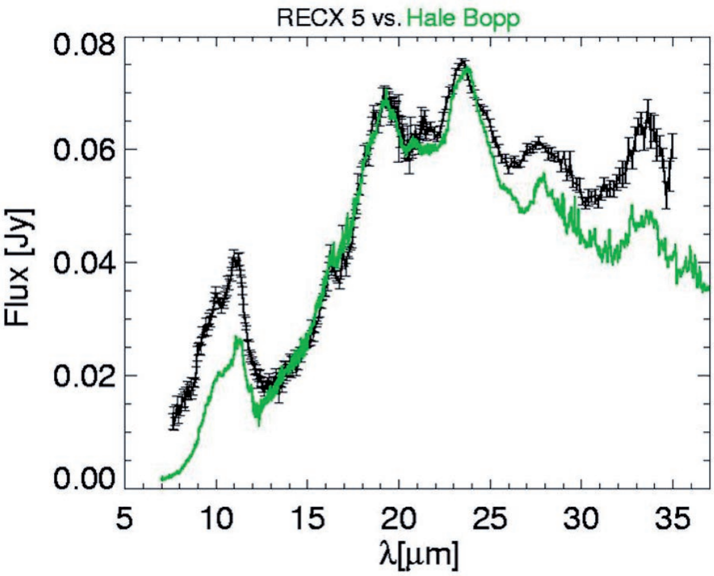

Figure 3 Comparison of the Spitzer infrared spectrum of the M4 star RECX 5 (Bouwman et al. 2009) with the ISO spectrum of comet Hale Bopp (Crovisier et al. 1997). Flux values of comet Hale Bopp scaled to fluxes of RECX 5.

The forsterite-to-enstatite ratio shows a radial dependence with more enstatite in the inner disk. The appearance of crystalline silicates in a large variety of protoplanetary disks (see Figure 3) indicates the importance of thermal annealing and mixing processes, because such grains are not abundant in the general diffuse interstellar medium or star-forming regions. In addition, spectra of the disks around predominantly intermediate-mass stars frequently display emission from Polyaromatic Hydrocarburbons (e.g. Geers et al. 2007, Boersma et al. 2008). A variety of molecular ices has also been detected in an edge-on disk by Pontoppidan et al. (2005).

Submillimetre and millimetre line observations are providing important information on chemistry, ionization degree, turbulent mixing, and surface density profiles in the colder outer regions of protoplanetary disks (e.g. Semenov et al. 2005, Bergin et al. 2007, Dutrey et al. 2007). More recently, infrared spectroscopy with both high-resolution instruments on the ground and the Spitzer telescope started to reveal the gas composition in inner disks. CO fundamental ro-vibrational lines, observed in the M band around 4.7 μm, can provide important kinematic information on inner disks and deliver lower bounds to the total inner gas mass (Brittain et al. 2003, Najita et al. 2003, Blake & Boogert 2004, Goto et al. 2006; see Figure 4). A recent study of transition disks demonstrates a large diversity of gas content and gas-to-dust mass ratios in the inner disk regions, revealing a variety of planet-forming conditions (Salyk et al. 2009). In addition to the CO molecule, molecu-

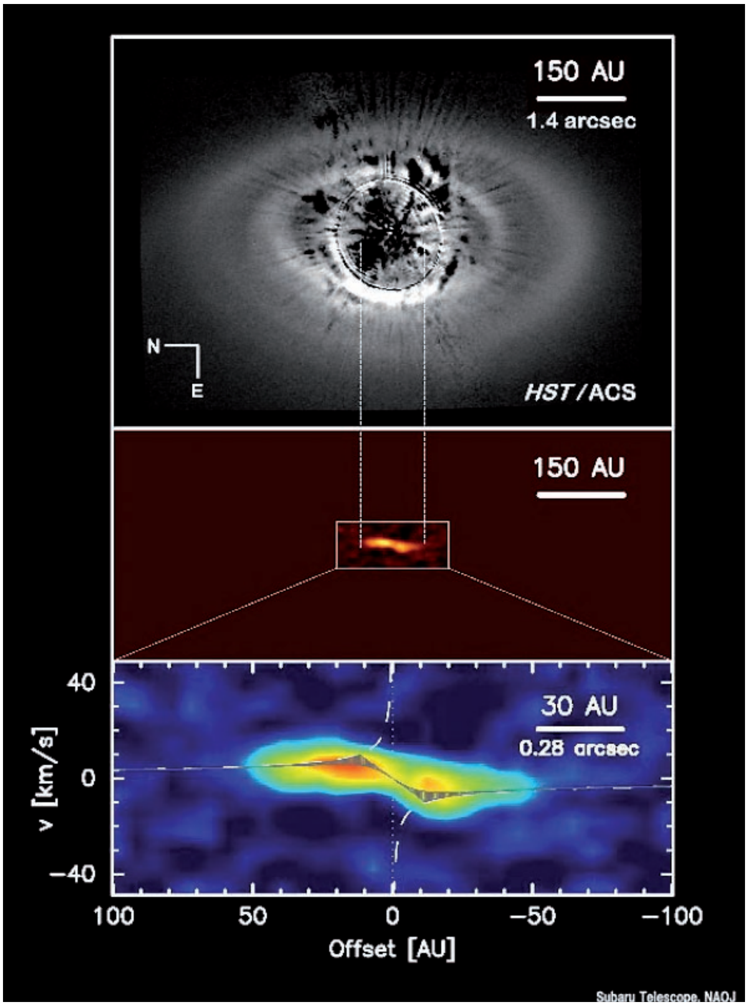

Figure 4 The upper part of the figure shows the HST/ACS image of the disk around HD 141569A (Clampin et al. 2003). The lower part shows the CO emission and reveals an inner cavity with 11 AU radius and a Keplerian velocity curve (Goto et al. 2006).

lar hydrogen emission (Bitner et al. 2008) and water (Carr et al. 2004) have been detected with high-resolution spectroscopy.

Despite the relatively low spectral resolution, the sensitivity of the Spitzer telescope allowed the observation of the rich molecular emission spectrum of inner regions of protoplanetary disks and revealed a high abundance of simple organic molecules (HCN, C_2H_2, CO_2) (Carr & Najita 2008, Lahuis et al. 2008, Salyk et al. 2008, Pascucci et al. 2009). In the inner disk of AA Tauri, Carr & Najita (2008) found the first evidence not only for organic molecules, but also for water vapour and OH molecules. In a comprehensive study of protoplanetary disks, Pascucci et al. (2009) revealed differences in the abundance of organic molecules between disks around solar-type stars (K1-M5) and disks around low-mass objects and brown dwarfs (M5-M9). These authors found a significant underabundance of HCN relative to C_2H_2 in the disk surface of cool stars, probably pointing to the importance of UV radiation for defining the chemical composition of these regions (see Figure 5).

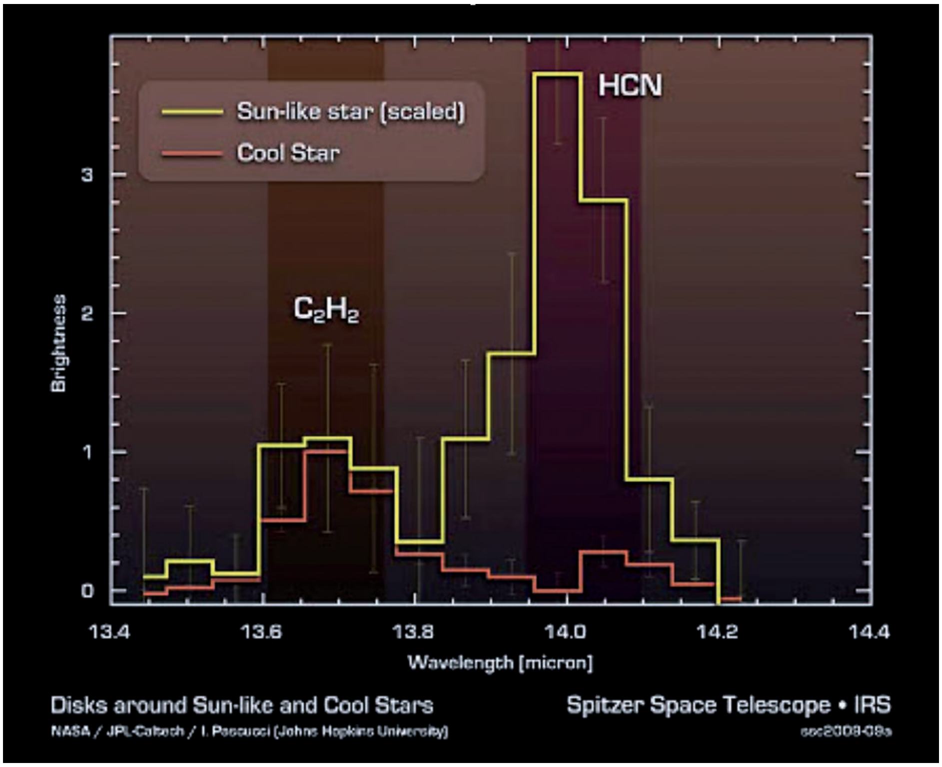

Figure 5 Spitzer infrared spectroscopy of disks around sun-like stars and cool stars. After Pascucci et al. (2009).

4. The Large Binocular Telescope

The Large Binocular Telescope (LBT), with its two 8.4 m mirrors, adaptive secondaries, large-array optical cameras and multi-object optical and infrared spectrographs, will provide unique opportunities for studying young stars and their protoplanetary disks. When operated together, the two mirrors will have the light gathering power equivalent to a single 11.8 meter telescope. A new spin casting technique, developed by the University of Arizona, resulted in very lightweight, stiff mirrors. Their steep curvature (f/1.14) permitted the construction of a compact, solid telescope structure, and hence a smaller, less expensive enclosure. The open telescope structure represents a significant departure from traditional designs. The J-shaped vertical braces are each about 19 m long. On their outer faces a variety of swing arms are mounted. These hold the various mirrors and instruments. This modularity provides great flexibility and allows the observing configuration to be changed in approximately 15 minutes.

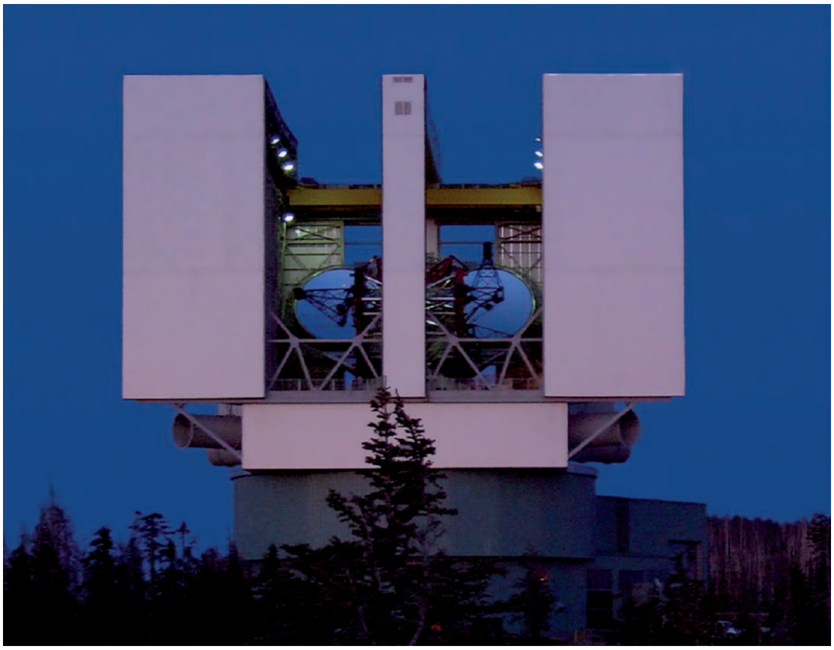

Figure 6 The Large Binocular Telescope (LBT). The LBT is a joint American-German-Italian project with the University of Arizona, Ohio State University, the US Research Corporation, the Italian INAF and the German LBTB (led by the MPI for Astronomy, Heidelberg) as partners.

The entire telescope is 24 meters wide by 15 meters deep and 21 meters high. Despite carrying two 8.4 meter mirrors, the innovative design leads to a total moving telescope weight of only 900 tons, not much larger than that of a conventional telescope with a single 3.5 meter mirror. The LBT is mounted 30 meters above the ground on a large, cement pier. This height is necessary to get into clear air above the surrounding trees. A large rectangular enclosure protects the telescope. Occasional storms on the 3200 meter peak can be severe, so the telescope and enclosure are designed to withstand sustained winds of 225 km/hr.

An especially interesting feature is the possibility to combine the light of the two telescopes interferometrically, thereby providing the resolution of a 23 m telescope. Two instruments will make use of this possibility: The thermal infrared imager and nulling instrument LBTI provided by the Steward Observatory and the near-infrared instrument LINC-NIRVANA (see Figure 7) being built at the Max Planck Institute for Astronomy together with other partners in Germany and Italy. Both instruments will provide superb resolution imaging capabilities in the infrared and will start regular operation in the 2011-2012 timeframe. LINC-NIRVANA will provide 10 times higher resolution in the near infrared than the Hubble Space Telescope. In contrast to the Very Large Telescope Interferometer, this instrument will allow true Fizeau imaging of complex regions. It will provide rich information on AU-scales

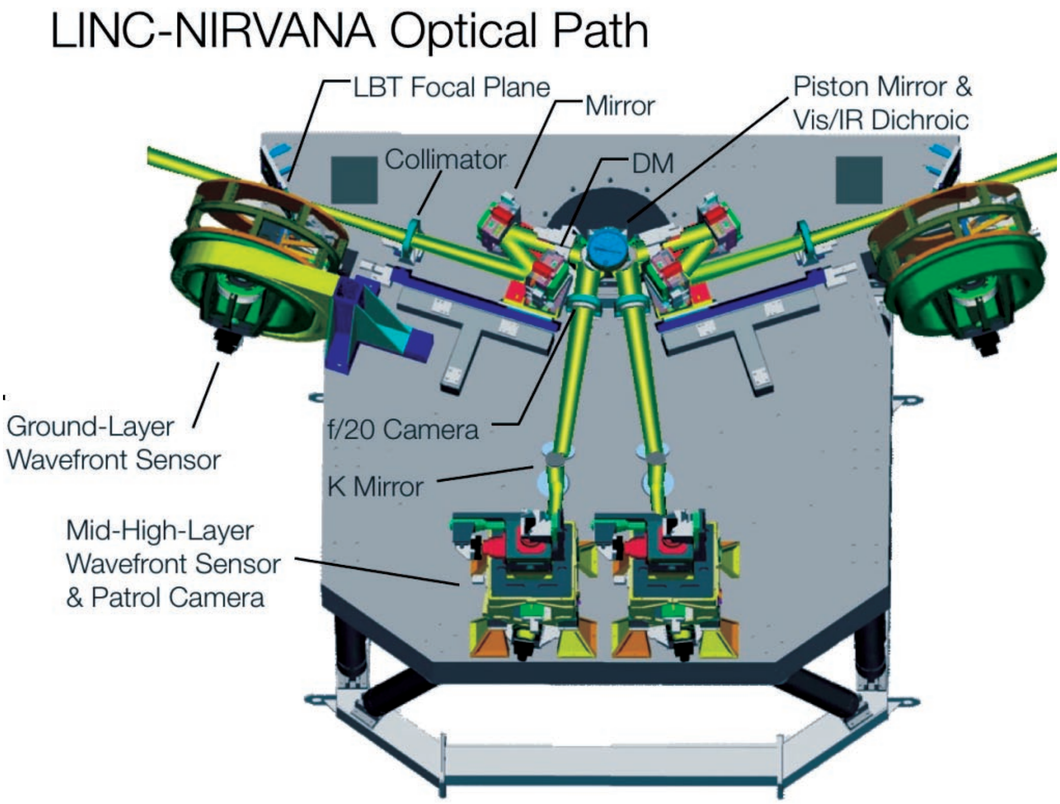

Figure 7 Optical path in the LINC-NIRVANA instrument

of complicated structures in nearby star-forming regions and their protoplanetary disks. It will cover the 1.0-2.45 μm range and will provide a FoV of 10.5”x10.5”. The LBTI instrument is especially designed for high spatial resolution, high dynamic range imaging in the thermal infrared. Key science programs include a survey of nearby stars for debris disks down to levels which may obscure detection of Earth-like planets by space missions (nulling in the N band) and the direct imaging search for giant planets (M band).

5. Lessons Learned from Building a Large Telescope

The design, construction, and commissioning of a large facility such as the LBT remains a considerable challenge and adventure. In return, it provides the tools to advance observational astronomy to the next level of sophistication. The unique interferometry capabilities of the LBT will enable a better understanding of the evolution from protoplanetary disks to debris disks. In addition, such large-scale projects always result in "lessons learned" which should be transferred to the next projects in order to increase their efficiency. This is especially true for the LBT, which can be seen as our first step towards the new class of 20 - 40 m telescopes.

What have we learned? From an observatory perspective, it turned out to be very important to work together with all the stakeholders to secure the site for development under the least restrictive terms. Upfront investment in system engineering, subsystem design, and software development is likely to be balanced by a shorter period required for integration and commissioning of the telescope. Realization of state-of-the-art concepts requires assignment of a substantial contingency in both schedule and budget. Building a complex machine sometimes leads to an underestimate of the importance of basic and "simple" features. In a multi-partner international project it is important that the partners define clear technical and science goals and set priorities. Finally, one always has to be prepared for the unexpected.

6. Acknowledgements

I would like to thank all partners of the Large Binocular Telescope, the observatory staff and the director Richard Green for building a wonderful and innovative telescope. I thank Phil Hinz (Steward Observatory, PI of LBTI) and Tom Herbst (Max Planck Institute for Astronomy, PI of LINC-NIRVANA) for interesting discussions.

7. References

Andrews, S.M., Williams, J.P., 2005, ApJ, 631, 1134.

Andrews, S.M., Williams, J.P., 2007a, ApJ, 671, 1800.

Andrews, S.M., Williams, J.P., 2007b, ApJ, 659, 705

Balog, Z., Muzerolle, J., Rieke, G.H., Su, Kate Y.L., Young, E.T., Megeath, S.T., 2007, ApJ, 660, 1532

Beckwith, S.V.W., Sargent, A.I., Chini, R.S., Güsten, R., 1990, AJ, 99, 924.

Bergin, E., Aikawa, Y., Blake, G.A., van Dishoeck, E.F.: In: Reipurth, B., Jewitt, D., Keil, K. (eds.), Protostars and Planets V. Univ. of Arizona Press. Tucson. 2007. p.751-766.

Bitner, M.A. et al., 2008, ApJ, 688, 1326.

Blake, G.A., Boogert, A.C.A., 2004, ApJ, 606, L73.

Boersma, C., Bouwman, J., Lahuis, F., van Kerckhoven, L., Tielens, A.G.G.M., Waters, L.B.F.M., Henning, Th., 2008, A&A, 484, 241.

Bouwman, J., Lawson, W.A., Dominik, C., Feigelson, E.D., Henning, Th., Tielens,

A.G.G.M., Waters, L.B.F.M., 2006, ApJ, 653, 57

Bouwman, J. et al. 2009, in preparation.

Brittain, S.D., Rettig, T.W., Simon, T., Kulesa, C., DiSanti, M.A., Dello Russo, N., 2003, ApJ, 588, 535.

Burrows, C.J. et al., 1996, ApJ, 473, 437.

Carr, J.S., Najita, J.R., 2008, Science, 319, 1504.

Carr, J.S., Tokunaga, A.T., Najita, J., 2004, ApJ, 603, 213.

Clampin, M. et al., 2003, AJ, 126, 385.

Crovisier, J. et al. 1997, Science, 275, 1904.

Dutrey, A. et al., 2007, A&A, 464, 615.

Fang, M., van Boekel, R., Wang, W., Carmona, A., Sicilia-Aguilar, A., Henning, Th.,

2009, A&A, in press.

Fedele, D., van den Ancker, M., Henning, Th., Jayawardhana, R., Oliveira, J. 2009, A&A, in press.

Geers, V.C., van Dishoeck, E.F., Visser, R., Pontoppidan, K.M., Augereau, J.-C., Habart, E., Lagrange, A.M., 2007, A&A, 476, 279.

Goto, M., Usuda, T., Dullemond, C.P., Henning, Th., Linz, H., Stecklum, B., Suto, H., 2006, ApJ, 652, 758.

Henning, Th., 2008, Physica Scripta, 130, 014019.

Henning, Th., Meeus, G., In: P.J.V. Garcia (ed.), Physical Processes in Circumstellar Disks around Young Stars, Chicago University Press. 2009, in press.

Hernández, J., Hartmann, L., Calvet, N. Jeffries, R.D., Gutermuth, R., Muzerolle, J., Stauffer, J., 2008, ApJ, 686, 1195.

Juhasz, A. et al., 2009, ApJ, submitted.

Kalas, P., Jewitt, D., 1995, AJ, 110, 794.

Lahuis, F. et al., 2006, ApJ, 636, L145.

McCaughrean, M.J., O'Dell, R., 1996, AJ, 111, 1977.

Mordasini, C., Alibert, Y., Benz, W., 2009, A&A, 507, 1139.

Najita, J., Carr, J.S., Mathieu, R.D., 2003, ApJ, 589, 931.

Natta, A., Testi, L., Calvet, N., Henning, Th., Waters, R., Wilner, D.: In: Reipurth, B., Jewitt, D., Keil, K. (eds.), Protostars and Planets V. Univ. of Arizona Press. Tucson. 2007. p.767-781.

Padgett, D.L., Brandner, W., Stapelfeldt, K.R., Strom, S.E., Terebey, S., Koerner, D., 1999, AJ, 117, 1490.

Pascucci, I., Gorti, U., Hollenbach, D. et al., 2006, ApJ, 651, 1177.

Pontoppidan, K.M. et al. 2005, ApJ, 622, 463.

Pascucci, J., Apai, D., Luhman, K., Henning, Th., Bouwman, J., Meyer, M.R., Lahuis, F., Natta, A., 2009, ApJ, 696, 143.

Rodmann, J., Henning, Th., Chandler, C.J., Mundy, L.G., Wilner, D.J., 2006, A&A, 446, 211.

Salyk, C., Pontoppidan, K.M., Blake, G.A., Lahuis, F., van Dishoeck, E.F., Evans, N.J. II, 2008, ApJ, 676, L49.

Salyk, C., Blake, G.A., Boogert, A.C.A., Brown, J.M., 2009, ApJ, 699, 330.

Schneider, G.A. et al., 1999, ApJ, 473, 437.

Semenov, D., Pavlyuchenko, Y., Schreyer, K., Henning, Th., Dullemond, C., Bacman, A., 2005, ApJ, 621, 853.

Strom, K.M., Strom, S.E., Edwards, S., Cabrit, S., Skrutskie, M.F., 1989, AJ, 97, 1451.

Thamm, E., Steinacker, J., Henning, Th., 1994, A&A, 287, 493.