Observations of Circumstellar Disks

David W. Koerner
Dept. of Physics and Astronomy, University of Pennsylvania,
Philadelphia, PA 19104-6396

Abstract.

The imaging of disks around young stars presents extreme challenges in high dynamic range, angular resolution, and sensitivity. Recent instrumental advances have met these challenges admirably, leading to a marked increase in imaging discoveries. These have opened up a new era in studies of the origin of planetary systems. Questions about our own solar system’s formation, and of the prevalence of extra-solar planets, are now addressed with complementary techniques at different wavelengths. Optical and near-infrared images detail scattered light from disks at the highest possible resolution. Mid-infrared, sub-millimeter, and millimeter-wave techniques probe thermal dust continuum radiation. Millimeter-wave interferometry details the small-scale structure of the molecular gas. Kinematic imaging studies affirm the disk interpretation of mm-wave continuum surveys, and the high incidence rate for solar nebula analogs. Inner holes, azimuthal asymmetries, and gaps suggest the presence of underlying planetary bodies. The combined techniques provide a multi-dimensional picture of disks in time and have strengthened our understanding of the connection between disks and planets. Future progress is assured by the presence of much-improved imaging capability looming on the horizon.

1. Introduction

Credible observations of disks around young stars constitute a rather late entry in the annals of important astronomical discoveries, notwithstanding several earlier misguided attempts. Their existence was not firmly established until well over two centuries after the first telescopic observations of galaxies, with which they were occasionally confused. Eighteenth-century speculation that our own solar system may have formed from a disk is often touted as solely a logical deduction from the properties of our own solar system, but it was influenced in part by mis-interpretations of Herschel’s optical observations of galaxies. Laplace, in particular, envisioned a hot, incandescent nebula that contracted as it cooled, and V.M. Slipher was still testing this notion in the early twentieth century when he obtained spectroscopic observations of the Sombrero Galaxy. The kinematic result conflicted with a nebular interpretation, but eventually became the velocity half of Hubble’s Law (See Hoyt 1980 for a detailed account). For several decades, the whole idea of planet formation in a disk fell out of fashion and was
replaced by catastrophic theories that discouraged all attempts to even search for any other example of a forming solar system.

Today, we know that potentially planet-forming disks are cold and radiate predominantly at far infrared wavelengths. Optical imaging can be used to detect disks only in reflected stellar light and at levels that pale in comparison to the star’s direct output (the ratio of disk/star optical radiation is typically less than 0.0001). Such high contrast requirements pose an extreme challenge for optical imaging, since circumstellar disks at the distance of the nearest star-forming regions subtend angles of order 1″ or less, where glare from the star is still quite high. These dynamic range limitations are eased substantially for long-wavelength observations in which disk radiation overpowers that from the stellar photosphere. Here, however, angular resolution becomes a greater challenge, owing to its inverse proportionality with wavelength for a given aperture. High-resolution requirements are not so severe for a few waning disks around stars that are extremely close (< 20 pc), but these tend to radiate very faintly and pose a problem in sensitivity.

In the last two decades, all the obstacles listed above have been met by advances in astronomical instrumentation. Coronagraphic and Hubble Space Telescope images have surmounted dynamic range challenges; mm-wave interferometry and mid-infrared detectors at the Keck 10-m telescope have achieved sub-arcsecond resolution at long wavelengths, and bolometer-array imaging at the James Clark Maxwell Telescope has provided the requisite long-wavelength sensitivity to image nearby disks with low surface brightness. These techniques have functioned together as a complementary set of tools for investigating the properties of protostellar and protoplanetary disks. The results are reviewed here. They mark the end of the search for an existence proof for circumstellar disks, but the bare beginning of a new area of astrophysical research, one which promises to be as rich in diverse dynamical examples as is the study of galaxies and perhaps even more important to questions about the habitability of the cosmos.

2. “Indirect” Observations of Circumstellar Disks

The first observational evidence for the existence of circumstellar disks consisted largely of unresolved detections of long-wavelength emission from young stars at levels greater than could be expected from the stellar photosphere alone. The measurements were consistent with an origin in circumstellar dust, but the geometrical distribution was not apparent. Since a “disk” identification is tantamount to a statement about morphology, such evidence is considered circumstantial when applied to a disk interpretation and may be referred to as “indirect” to distinguish it from imaging results which directly identify a disk-like shape. This terminology – direct vs indirect – refers solely to the evidence for a disk morphology and not to the source of the radiation. “Indirect” observations are routinely interpreted as radiation emanating “directly” from an unresolved disk.

Circumstellar dust emission was detected by means of near-infrared techniques nearly as soon as these were available (Mendoza 1966). Continuum observations taken over a broad spectral range, especially by the Infrared Astronomy
Satellite (IRAS), were interpreted with models of the corresponding Spectral Energy Distribution (SED) to represent snapshots in a circumstellar evolutionary sequence (Adams, Lada, & Shu 1987). Infrared point sources with no optical counterpart, often located in the center of molecular cloud cores, exhibited SEDs consistent with an origin in protostellar radiation reprocessed by both an infall envelope and a disk. Excess infrared radiation from $10^5$ to $10^7$ year-old T Tauri stars (TTs) matched that expected from viscous accretion disks without a surrounding envelope (See reviews by Rydgren & Cohen 1985 and Beckwith & Sargent 1993); a spherical dust configuration was ruled out by comparison of the flux density of thermal emission with extinction along the line of sight to the star (Adams et al. 1990; Beckwith et al. 1990). Finally, weak infrared excesses were interpreted as tenuous disks in a dispersive stage.

IRAS detections of infrared excess around nearby main-sequence stars were initially considered separately from this classification scheme (for example, compare review of Backman & Paresce 1993 with Shu et al. 1993). However, revised stellar age estimates (e.g., Barrado y Navascués et al. 1999) and renewed attention to the population of 10 million-year-old stars with enhanced debris disks (e.g., Jura et al. 1998) are supporting the idea that many of these “debris disks” should be associated with the late stages in the above evolutionary scenario.

The following sections of this review illustrate that recent images have largely confirmed the evolving-disk scenario implied by unresolved measurements. Indirect observations still have an important role to play in disk evolution studies, however. Surveys of disk properties in statistically significant samples are currently available only with indirect observations. These are essential to characterize variations in disk properties that depend on something other than time, and that may mask the identification of evolutionary trends. Multiplicity, spectral type, cluster environment, and variations in initial disk properties all add complications to the task of identifying age-dependent effects.

Stellar multiplicity has long been considered a factor that may dramatically affect the formation of planetary systems. Processes of disk formation and binary fragmentation both depend on the initial angular momentum budget of a collapsing cloud core (Bodenheimer 1995). Comparison of mm-wave continuum surveys of TTs with the results of speckle interferometric binary surveys has given some empirical insight into the nature of the influence of multiplicity on disks (Mathieu et al. 2000). Dust continuum radiation attributed to disks is reduced for binaries with separations of 50-100 AU, similar to a typical disk radius (Jensen, Mathieu, & Fuller 1994; 1996; Osterloh & Beckwith 1995). At both shorter and longer separations, however, the disk detection frequency appears to be unchanged. Circumbinary disks around spectroscopic binaries (Jensen & Mathieu 1997), and those around the individual members of wide binaries (Jensen et al. 1996), appear with the same incidence as for single stars. A few notable exceptions occur among binaries with $\sim$100 AU separations, including the eponymous T Tauri. High-resolution imaging is beginning to reveal the orientation and likely fate of the material in these systems (e.g., Akeson, Koerner, & Jensen 1998; Koerner et al. 2000).

Indirect observations of continuum excess from intermediate-mass stars suggest a disk-evolution scenario similar to that for solar-mass stars (Hillenbrand 1992). The disk interpretation of these measurements has been the subject of
considerable debate, however (see Natta, Grinnin, and Mannings 2000 for a review). Imaging results indicate that disks around Herbig Ae stars \((M \lesssim 5 \, M_\odot)\) appear to resemble those around TTs, at least for classical TTs with luminous continuum excess at millimeter wavelengths (Mannings & Sargent 1997). But higher-mass Herbig Be stars \((M > 5 \, M_\odot)\) show little evidence for similar circumstellar disks, probably as a result of dispersal under a more energetic radiation environment. A rich assemblage of solid-state infrared features was detected by ISO from the circumstellar environment of Herbig Ae stars. Crystalline and amorphous silicates, polycyclic aromatic hydrocarbons, and unidentified infrared bands differ from typical signatures of interstellar grains in ways that suggest grain growth and evolution (see chapter by van Dishoeck, this volume). Sufficient sensitivity has not been available to detect similar spectroscopic features in TTs counterparts.

Disproportionate sensitivity to properties of disks around low-mass versus intermediate-mass stars is especially apparent for infrared excess observations of debris disks. IRAS detections of dust around nearby main sequence stars were largely confined to A stars like Vega, earning them the moniker “Vega-type” or “Vega-excess stars.” A relative paucity of detections around stars later than type F should not be construed as evidence of disk absence, however, since Vega-type disks would generally fail to radiate above IRAS sensitivity limits if placed in the same configuration around all but the very nearest Sun-like stars. ISO attempts showed a timescale for 400 million years for A star disks (Habing et al. 1999), but efforts to derive similar timescales for Sun-like stars are hampered by small sample size. Nevertheless, there is some indication that debris disks may survive for longer times around later type stars (Song et al. 2000). This might be explained as the result of radiation-driven dispersal processes which operate more efficiently around earlier type stars. Initial attempts to detect the rotational transition of CO from debris disks suggested that the molecular gas was dispersed well in advance of this stage (Dent et al. 1995; Zuckerman, Forveille, & Kastner 1995). However, these null results may arise from either photo-dissociation of CO or its depletion onto grains. Recent ISO detections of \(H_2\) in debris disks indicate a normal gas to dust ratio (Thi et al. 2001).

The future of indirect observations is bright. SIRTF will present an unparalleled opportunity to make spectroscopic and photometric measurements of circumstellar dust and gas with unprecedented sensitivity. From these measurements will arise the first timescales for waning disks around Sun-like stars. As such, these measurements will greatly aid our understanding of the connection between disks and planetary systems! Beyond that, such unresolved measurements will continue to provide the source lists for imaging efforts, and will yield critical ancillary information on sources for which imaging has already established the presence of a disk.

3. Imaging Disks in Scattered Light

At optical and near infrared wavelengths, high dynamic range constitutes the principal challenge to direct imaging of circumstellar disks. The stellar luminosity is typically more than \(10^4\)-\(10^5\) times that of the disk (Whitney & Hartmann 1992), and the wings of the point spread function (PSF) continue to veil any
potential disk emission out to several arcseconds from the star. This amounts to several hundred AU for objects in the nearest star-forming clouds, well beyond the typical outer disk radius.

Strategies for reducing PSF wing emission include methods which either occlude the stellar light, re-concentrate it with compensation for atmospheric blurring, or remove it by subtraction or deconvolution at the image processing stage. Techniques which have been applied to disk observations include 1) selection of targets with optically-thick edge-on disks which occlude the star, 2) searching against background nebulosity for disks which would be silhouetted ("proplyds"), 3) coronagraphy, 4) speckle interferometry, 5) adaptive optics, and 6) imaging from space. Most of these techniques must be aided by PSF subtraction or deconvolution with the aid of images of a similar but diskless star. Great care must be taken in assuring the uniform conditions for observing the target star and PSF. Otherwise, artifacts are easily introduced which mimic the appearance of a disk.

Visible and near infrared radiation is not detected at the very earliest stages of circumstellar evolution. It is first observed when optically thick envelope material is sufficiently dispersed along cavities aligned with the rotational axis. A scattering surface reflects the protostellar radiation as the envelope is flattened about a centrifugally supported circumstellar disk. Nebulosity is apparent in the surrounding cloud as well and may or may not trace the morphology of a circumstellar envelope or disk. In the case where the flattened disk and envelope are oriented edge-on to the line of sight, envelope clearing may proceed to an advanced degree before light from the central star is directly observed, and the vertical thickness of the disk may be derived from the silhouette against the surrounding reflected light. This fortuity has been used to good effect with the aid of Hubble Space Telescope (see articles by Padgett and Stapelfeldt, this volume) and, in one instance, speckle interferometry at the Keck telescope (Koresko 1998). In a similar vein, disks have been imaged in silhouette against background nebulosity such as the Orion Nebula (see review by Beckwith, this volume).

The detection of light scattered off the surface of a circumstellar disk is substantially more difficult if the star itself is unobscured by surrounding dust. High-contrast imaging techniques are essential for success and have resulted in a handful of resolved disks around T Tauri or Herbig Ae stars, including GG Tau (Roddier et al. 1996), GM Aur (Stapelfeldt et al. 1995; Koerner et al. 1998), UY Aur (Close et al. 1998), and HD 163296 (Grady et al. 1999). Recently, HST WFPC2 (Krist et al. 2000) and NICMOS (Weinberger et al. 1999) observations of a disk around the nearby TTs, TW Hydrae, were confirmed by Trilling et al. (2001) with ground-based coronagraphic images. The disk is oriented with its rotational axis parallel to the line of sight. Displayed in Fig. 1, ground-based near-infrared coronagraphic images of TW Hya show a face-on disk, in good agreement with HST/WFPC2 (Krist et al. 1999) and HST/NICMOS coronagraphic images of the scattered light (Weinberg et al. 1999). To first order, all three observations produce similar radial intensity profiles that fall off approximately as the third power of the radial distance from the star.

TW Hya was identified as a TTs by Rucinski & Krautter (1983). It is unusually close by (56 pc), not associated with any molecular cloud, and has
a surprisingly advanced age ($10^7$ yr) in view of disk properties ordinarily associated with much younger stars. The dust continuum emission is considerable (Weintraub, Sandell, & Duncan 1989; Wilner et al. 2000), implying the disk is opaque in the mid-plane with a total mass like the minimum mass solar nebula ($\sim 0.03 M_\odot$). Molecular gas is abundant as measured by CO (Zuckerman et al. 1994) and $H_2$ (Weintraub, Kastner, & Bary 2000). Further, the disk appears to be still actively accreting onto the star, as inferred from ample $H\alpha$ emission (Muzerolle et al. 2000). Due to its proximity and orientation, TW Hya is a uniquely favorable candidate for studies of the radial properties of a viscous accretion disk and will no doubt yield a wealth of physical and chemical information when it is probed by a coming generation of mm-wave arrays that can access its low-declination sky position (e.g., SAO Sub-millimeter Array and NRAO’s ALMA).

Ground-based coronagraphic images of the debris disk around $\beta$ Pictoris marked the first success at direct imaging and the first proof of the existence of a plausible candidate environment for the formation of planetary systems (Smith & Terrile 1984). Initial attempts to duplicate this feat around other IRAS-selected stars were disappointingly unsuccessful, leading to speculation that $\beta$ Pic was highly unusual (Smith, Fountain, & Terrile 1992; Kalas & Jewitt 1995). It now appears, however, that its uniqueness lay mostly in its combined youth ($\sim 20$ Myr; Barrado y Navascués et al. 1999) and proximity (19 pc). Several examples of similar-age A stars that have comparable fractional excesses are now known; these indicate that $\sim 20\%$ of A stars pass through a $\beta$ Pic-like phase (Jura et al. 1998). Only $\beta$ Pic is close enough to be easily imaged with current ground-based coronagraphy, however (see Fig. 9 of Kalas & Jewitt 1996).

Since its discovery, the disk around $\beta$ Pic has been the target of diverse detailed imaging studies (see summary in review of Lagrange, Backman, & Artymowicz 2000). The results have led to the identification of a number of features which are hard to understand without invoking the dynamical influence of one or more substellar or planet-like companions. Most telling, perhaps, is a warp that is clearly evident in HST images (Burrows et al. 1995; Heap et al. 2000). A distinct difference in length and brightness between the two ansae is more difficult to understand, but is especially apparent in dust continuum images (Lagage & Pantin 1994; Holland et al. 1998). Recently, a fine ring structure has been discerned in modeling of HST images (Kalas et al. 2000).

The complementary utility of multi-wavelength imaging techniques in interpreting scattered-light images is apparent in images of $\beta$ Pic displayed in Fig. 2. It is clear, here, that different wavelengths probe distinctly different features of the disk. J-band images from ESO, using a combined coronagraphic and adaptive optics setup, show a warp in the disk plane consistent with HST images. Thermal infrared images at $20 \mu m$ register an asymmetry in the thickness and length of each of the ansae (Koerner et al. 2001). Since radiation from grains with temperatures cooler than 150 K peak increasingly longward of this wavelength, the image registers the distribution of grains with temperatures mostly above 100 K. Sub-millimeter wavelengths reveal peak emission off the southwest ansa that is not even apparent at the other wavelengths. Evidently, massive dust grains at that position are not scattering optical light efficiently. It is no surprise, either, that they are too cold to radiate at thermal infrared wavelengths.
A model of the disk which properly accounts for imaging at all these wavelengths is sorely needed!

The many features apparent in images of debris disks may testify of a link between disks and the formation of planetary systems (see article by Kenyon, this volume). Persistent dust features which would ordinarily disappear on orbital timescales are likely to be the result of recent dynamical perturbation. If planetary bodies are the cause, the study of these features is an indirect method of planet detection. Just as successful planet-hunters rely on the motion of a star to infer the gravitational effect of a planet (e.g., Mayor & Queloz 1995), so it may be that high-resolution imaging of disks, with the aid of refined theoretical interpretations, may provide clues to the presence of underlying bodies in advance of their direct detection.

The study of debris disk properties at high resolution received a recent boost with the installation of the NICMOS camera on HST. Its coronagraphic capability, coupled with a thorough program of PSF characterization, has led to imaging of gaps and holes for the very first time. Key imaging results include confirmation of a narrow ring around HR 4796A that was originally inferred from model-fitting to thermal infrared images (Koerner et al. 1998; Schneider et al. 1999) and the discovery of a gap in the disk around HD 141569 (Augereau et al. 1999; Weinberger et al. 1999). In the case of HR 4796A, the images confirmed what was deduced from models of the spectral distribution of radiated energy (Jura et al. 1995), namely that the dust surrounded a large inner hole. This is readily apparent in thermal IR and HST images of HR 4796A shown in Figure 3, where the dust is confined largely to a circumstellar ring. There is also an asymmetry in the brightness distribution evident in HST images. The correct explanation for these features is a matter of continued theoretical investigation (see chapter by Kenyon, this volume).

The recent coronagraphic detection of disks around main sequence stars with known planets have great potential for further strengthening our understanding of the disk-planet connection. The zodiacal dust in our own solar system is its most readily detectable feature from distances of tens of parsecs, and many such disks around Sun-like stars could have evaded detection by IRAS. The first image of such a disk was obtained for 55 Cnc by Trilling & Brown (1998) using the same instrumentation which imaged TW Hya in Fig. 1. This was followed by reports of disks around 3 more such stars (Trilling, Brown, & Rivkin 1999). Indirect detections of the disk around 55 Cnc were first reported in support of ISO observations by Dominik et al. (1998). A recent attempt by Schneider et al. (2001) to image 55 Cnc with the HST/NICMOS coronagraph failed to confirm the presence of a disk with emission at the level reported by Trilling & Brown (1998). This conflict may be the result of a flux calibration error in the initial discovery paper (Trilling, private communication). However, independent confirmation of this observation remains highly desirable. Nevertheless, the case for a non-artefactual origin of disks like those reported by Trilling & Brown (1998) and Trilling et al. (1999) is strengthened by the detection of a similar disk by an independent system. The ESO coronagraphic/adaptive-optics system that produced the β Pic image in Fig. 2 (ADONIS) has revealed a disk around the star ϵ Horologii. The image, together with that of a diskless reference star, is shown in Fig. 4.
4. Thermal Infrared Imaging of Disks

In the last few years, mid-infrared detectors have been incorporated into cameras suitable for interfacing with large aperture telescopes. These arrays are capable of detecting thermal dust radiation at temperatures as low as 100 K. This technique has several unique advantages for disk imaging studies. At the corresponding wavelengths of 10–20 µm, stellar photospheric luminosity is greatly reduced, and high dynamic range is not as great a challenge. Further, when used in combination with large aperture telescopes, sub-arcsecond resolution can be achieved. Although the diffraction limit is less favorable than for optical wavelengths (Airy disk FWHM ∝ λ), improved seeing provides considerable compensation at wavelengths longward of 10 µm (Seeing Disk FWHM ∝ λ⁻¹/₅). Near diffraction-limited resolution of 0.2–0.4′′ at λ = 10–20 µm is routinely achieved using the Keck telescope, for example. In nearby star-forming clouds, this corresponds to spatial scales of 30–60 AU. This is generally insufficient to resolve thermal infrared emission from accretion disks around Sun-like stars in the T-Tauri phase or earlier. Effective temperatures of disk surfaces are typically too cold at these radial distances. However, the situation is much more favorable for disks around earlier type stars that are not quite so distant. The greater stellar luminosity and concomitant elevated temperature of the circumstellar dust, coupled with better spatial resolution due to close proximity, have resulted in several exciting new imaging results.

After β Pic, the first disk resolved in images by both thermal infrared and optical techniques was HR 4796A (Koerner et al. 1998; Jayawardhana et al. 1998; Teleco et al. 2000; Wahhaj et al. 2000). The dimensions, orientation, and morphology of an outer dust ring were first inferred in detail with the aid of Bayesian fitting to Keck infrared imaging (Koerner et al. 1998). As evident in Fig. 3, the result was dramatically confirmed in HST images at higher resolution. A brightness asymmetry is clearly evident in the ring at both optical and infrared wavelengths, and has been interpreted by Teleco et al. (2000) and Wyatt et al. (1999) as evidence for hidden planets. This feature is evident in images at 12.5 and 24.5 µm displayed in Fig. 5. Other asymmetries are apparent in independently obtained images as well, including a slight offset between the ring center and the stellar position. In addition, the inner hole is not completely evacuated of dust; central peak emission in 24.5 µm image in Fig. 5 is in excess over photospheric emission by factors of several. Rough estimates of the color temperature locate this dust between 5 and 10 AU from the star (Wahhaj et al. 2000). Much work remains to be done to securely derive the properties of this system in order to properly guide theoretical interpretations.

Other disks which have been resolved with mid-infrared techniques include HD 141569 (Fisher et al. 2000; Marsh et al. 2001), and 49 Cet (Koerner, Guild, & Sargent 2001). Imaging of HD 141569 forms a great complement to HST images, providing an estimate of the dust content close to the star where optical techniques are insensitive. In keeping with its close association with temperature, the mid-infrared emission is detected only to a distance of 100 AU from the star (Fisher et al. 2000), in contrast to HST imaging which traces material out to a radius of 400 AU (Augereau et al. 1999; Weinberger et al. 1999). Keck imaging of dust around 49 Cet traces material out to a similar distance (Koerner et al. 2001); Bayesian modeling of both the SED and image provide
strong evidence for an inner hole radius of $\sim 20$ AU. In contrast to HR 4796A, however, the SED does not support truncation of the outer radius. 49 Cet may, in fact, most resemble $\beta$ Pic in its overall properties. Its greater distance (3 times further away) and lack of edge-on orientation may be the only reasons that it has not yet succumbed to coronagraphic imaging attempts.

Of the four disks imaged at thermal infrared wavelengths, all surround A stars with ages estimated to be about 10 Myr. This provides strong evidence that $\beta$ Pic is not an oddity! But it also points out a detection bias inherent in infrared techniques to date: they are luminosity limited at levels which preclude a fair sampling of the dust systems around later type stars. If disks at this age generally have inner holes with radii of several times 10 AU, then the dust in outer regions is less likely to be heated by later-type stars to levels commensurate with detection at mid-infrared wavelengths. Fortunately, there are alternatives at even longer wavelengths.

5. Observations with Submillimeter-wave Telescopes

Dust continuum radiation from disks typically peaks at far infrared and submillimeter wavelengths. Consequently, imaging at submillimeter to millimeter wavelengths is optimum for tracing the dust density distribution. Single-dish telescopes have very low angular resolution at these wavelengths, however (15'' at $\lambda = 850 \mu$m for the JCMT). Observations of disks in the nearest star-forming regions are thus restricted to indirect measurements of continuum flux densities (e.g., Beckwith et al. 1990) or molecular-line spectra (Dutrey, Guilloteau, & Guelin 1997). In contrast, the closest debris disk candidates have expected angular extents of up to several times the resolution element of single-dish submillimeter telescopes. Nevertheless, their radiation per unit surface area is quite low. The development of highly sensitive bolometer arrays has opened a window onto these systems with truly exciting results.

In addition to the image of $\beta$ Pic shown in Fig. 2, the first images of debris disks around several of the strongest excess sources (as determined by IRAS) were accomplished using the SCUBA bolometer array at the JCMT. Images of $\alpha$ Psa (Holland et al. 1998) and $\epsilon$ Eri (Greaves et al. 1998) provided the first unambiguous evidence for inner holes in these systems. SCUBA/JCMT imaging also brought forth the discovery image of a disk around the first such star identified: Vega. The presence of circumstellar dust around $\epsilon$ Eri, shown in Fig. 6, is notable on several counts. An inner evacuated region is clearly evident. And the ring of dust, itself, shows pronounced azimuthal asymmetries in brightness and thickness. Theoretical simulations can reproduce these features with the aid of embedded planetary bodies (Liou & Zook 1999). Perhaps most important, however, is the fact that this disk surrounds a K star with an age of 0.5-1.0 Gyr. Such a detection is only possible because of the extremely small distance to the star, 3.2 pc. Recent radial velocity measurements strengthen the disk-planet connection further; a Jupiter-mass planet has been detected indirectly at a radial distance of about 3 AU from the star (Hatzes et al. 2000). If it emerges that $\epsilon$ Eri is no more unusual than $\beta$ Pic, then the nearby stellar population is potentially teeming with similar signatures of planetary systems.
6. Aperture Synthesis Imaging

Millimeter and sub-millimeter wavelengths are best for discerning the properties of circumstellar disks at their earliest formation times. Photospheric emission is entirely negligible, dust optical depth is more favorable for probing total mass, and key molecular species can be identified by rotational transitions. Heterodyne measurements of molecular-line transitions also have the spectral resolution to enable kinematic studies of gas in the envelope and disk. At these wavelengths, however, the requirements on aperture size for the requisite angular resolution present show-stopping economic and technical challenges. The most successful strategy has been to forsake filled apertures for interferometric arrays. To date, these have produced the most important successes in imaging disks in the gas-rich accretion phase.

The first image of a gas-rich analog of the solar nebula followed on the heels of the discovery of a debris disk around β Pic (Beckwith et al. 1986). Aperture synthesis imaging of HL Tau carried out with the millimeter array at Owens Valley Radio Observatory (OVRO) revealed a molecular structure with a diameter of 2000 AU and a velocity structure that was originally interpreted as Keplerian rotation in a disk (Sargent & Beckwith 1987). More detailed analyses led to the identification of an infall component dominating the velocity structure in the outer regions (Hayashi et al. 1993). Sub-arcsecond continuum observations were interpreted as tracing an inner protoplanetary disk with a radius of order 100 AU (Lay et al. 1994; Mundy et al. 1996; Wilner, Ho, & Rodríguez 1996). Flattened structures of similar size and kinematics have recently been imaged around other embedded young stars (see review by Ohashi 2000). As for HL Tau, continuum observations at the longest wavelengths (3-7 mm) are best at piercing through envelope material and revealing early disk formation (see Section IV of review by Mundy, Looney, & Welch). Sub-arcsecond continuum imaging of the embedded protostar L1551 IRS5, for example, has revealed a binary source with individual circumstellar disks (Looney et al. 1997; Rodríguez et al. 1998).

It is at the classical T Tauri phase that aperture synthesis imaging of disks has been most productive. Kinematic analysis of OVRO observations of GM Aurigae in CO(2→1) emission provided the first evidence of solely centrifugal support in a solar nebula analog (Koerner, Sargent, & Beckwith 1993). Imaging at higher resolution and with improved signal to noise with the IRAM interferometer confirmed this interpretation (Dutrey et al. 1998). A rapidly growing list of targets have yielded similar results, including the intermediate-mass star MWC 48O. CO line emission at distinct velocities is plotted in Fig. 7 together with models of how the emission should appear if the gas is in Keplerian rotation around the star. The correspondence provides definitive proof that the gas is confined to a rotating circumstellar disk (Mannings, Koerner, & Sargent 1997). Other examples for which adequate observations have produced similar results include GG Tau (Dutrey, Guillochon, & Simon 1994), DM Tau (Guillochon & Dutrey 1998), and LkCa 15 (Koerner & Sargent 2001).

Imaging surveys mark the continued success of this technique. Resolved CO emission from DL Tau, RY Tau, DO Tau, and AS 209 also shows velocity gradients in support of a disk interpretation in OVRO images (Koerner & Sargent 1995). Continuum observations of 33 TTs at λ = 2.7 mm were carried out with the IRAM interferometer; model fitting to visibilities indicated a typical
angular size of 1.5" (~225 AU) at this wavelength (Dutrey et al. 1996). An OVRO survey in the CO(2→1) line was carried out for the most luminous continuum emitters. Molecular gas emission is resolved for over 20 classical TTs (Koerner & Sargent 2001). These have outer radii in the range 100-600 AU and provide direct confirmation of the disk interpretation for mm-wave continuum surveys (e.g., Beckwith et al. 1990; André & Montmerle 1994). In contrast, an IRAM survey for line emission from weakline TTs has produced largely null results (Duvert et al. 2000). It is tempting to conclude that this result marks the absence of molecular gas in these systems, but the recent ISO detection of H$_2$ in debris disks by Thi et al. (2001) suggests this may apply only to the presence of CO. Indeed, models predict that, as dust settles to the midplane, stellar photons have sufficient energy to photo-dissociate CO. See Dutrey (2000) for a review on depletion of CO in disks around classical TTs, as well as a discussion of other molecular species detected in disks.

7. Future Directions

High-resolution images of circumstellar disks have provided insights into the size, morphology, and luminosity of circumstellar disks in a luminosity-biased sample. Sophisticated modeling efforts enable a further step to estimates of temperature, mass, chemical composition, and dynamical history. In this respect, the field of disk studies resembles the early history of classification and analysis of galaxies. However, the most sought-after goal of disk studies is likely to be our effort to understand the formation mechanisms and prevalence of planetary systems. In this respect, the most important future for disk studies lies in making the disk-planet connection. Many questions remain along a path which should eventually see the census of planets, themselves.

- What is the initial distribution of disk masses and how does it evolve with time?
- What is the timescale for grain growth to planetesimal sizes?
- What is the timescale for molecular gas persistence?
- What does the gas timescale imply for theories of the formation and migration of Jovian planets?
- How do stellar and sub-stellar companions affect the dynamic evolution of disks?
- What is the planetary output of typical disks?

Several instrumental advances lie on the horizon to aid the search for answers to the above questions. Indirect observations will receive an enormous boost from SIRTF studies aimed at unraveling the dust detection rate and its early evolution. A large number of team programs, including 2 Legacy projects, are poised ready to survey young stars and entire molecular clouds for the presence and character of circumstellar dust emission in statistically significant samples. From these studies we will find out the incidence of dust disks around solar-mass stars up to main sequence ages for the first time. These programs
will also provide useful source lists for a new decade of follow-up imaging studies at high resolution.

Exciting improvements in high-resolution imaging capability are looming on the horizon. New adaptive optics systems and coronagraphic systems are coming on-line together with a new generation of large-aperture telescopes. Optical and infrared interferometric techniques are also imminent and will achieve milli-arcsecond resolution with greatly enhanced dynamic range. These techniques will support the study of disk morphologies with a view to understanding features diagnostic of undetected planetary bodies. Aperture sizes of several times 10 m are under consideration which, when coupled with mid-infrared detectors, will resolve the emission from TTs and provide a clear picture of AU-scale details in nearby debris disks. Increased aperture for single-dish mm-wave studies and improvements in existing mm-wave arrays will likely provide more than incremental progress in disk studies, since current studies lie just above a productive detection threshold. The completion of the Atacama Large Millimeter Array will undoubtedly launch a heyday in our understanding of the physical and chemical formation processes at work in the origin of planetary systems. Taken together, these improvements are likely to bring steady fast-paced progress in disk studies. As such, they support important scientific goals which will augment a further revolutionary aim: a thorough census of planets themselves.

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Figure 1. Scattered-light images of the circumstellar disk around TW Hydrae from Trilling et al. (2001). An H-band PSF-subtracted image taken with a ground-based cooled coronagraph is shown at left. For comparison, the center panel shows the typical artifact due to subtraction of two different PSF images. The panel at right features the WFPC2 image of Krist et al. (2000) in greyscale overlain with contours from the ground-based coronographic image. All three panels are 7 arcseconds on a side.
Figure 2. Contrasting imaging techniques applied to the disk around β Pictoris. (Left) J-band image of scattered light from the circumstellar disk acquired by combined coronagraphic and adaptive optics techniques by ESO. (Center) Mid-infrared image at $\lambda = 20 \mu m$ obtained with JPL’s mid-infrared imaging camera, MIRLIN, at the Keck telescope. (Right) Sub-millimeter emission from β Pic acquired with the SCUBA bolometer array at the James Clark Maxwell Telescope.
Figure 3. (Left) Keck/MIRLIN image of HR 4796A at 24.5 µm. The elongated structure is \(\sim 2''\) in diameter, corresponding to \(\sim 150\) AU. (Center) A model of the underlying emission structure that was obtained by fitting to an image at 20 µm from Koerner et al. (1998). (Right) HST/NICMOS coronagraphic image of scattered light from the ring around HR 4796A at \(\lambda = 1.1\) µm taken from Schneider et al. (1999).
Figure 4. Image of circumstellar dust around the star $\iota$ Horologii (left) compared to that of a “reference” star (right). At a distance of 17 pc, $\iota$ Horologii was already known to possess an extrasolar planet. Observations were obtained with a coronagraphic mask in conjunction with the ADONIS adaptive optics instrument at the ESO 3.6-m telescope on La Silla.
Figure 5. Keck/MIRLIN images of HR 4796A at 12 (left) and 24.5 \( \mu m \) (right) taken from Wahhaj et al. 2001. Photospheric emission dominates the image at 12 \( \mu m \), although warm dust associated with the inner ring can still be detected. At \( \lambda = 24.5 \mu m \), the ring emission has a larger radius, commensurate with that of HST images, and emission is detected at the stellar position at levels substantially above the expected photospheric contribution.
Figure 6. Taken from Greaves et al. (1998), a SCUBA/JCMT 850 μm image of dust around ε Eri, a nearby K star for which radial velocity techniques have identified a Jupiter-mass planet at a distance of 3.2 AU from the central star.
Figure 7. Taken from Mannings, Koerner, & Sargent (1997), spectral line maps of CO(2→1) emission are shown adjacent to simulations of the emission predicted by a kinematic model of a disk in Keplerian rotation. A contour plot of the velocity-integrated emission is displayed in the upper central panel above the total emission from the model. The resulting model spectrum is plotted at the bottom, together with the total flux from each of the maps.
Figure is available in web version.

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