HIGH-RESOLUTION OPTICAL AND NEAR-INFRARED IMAGING OF YOUNG CIRCUMSTELLAR DISKS

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In the past five years, observations at optical and near-infrared wavelengths obtained with the Hubble Space Telescope and ground-based adaptive optics have provided the first well-resolved images of young circumstellar disks which may form planetary systems. We review these two observational techniques and highlight their results by presenting prototype examples of disks imaged in the Taurus-Auriga and Orion star-forming regions. As appropriate, we discuss the disk parameters that may be typically derived from the observations, as well as the implications that the observations may have on our understanding of, for example, the role of the ambient environment in shaping the disk evolution. We end with a brief summary of the prospects for future improvements in space- and ground-based optical/IR imaging techniques, and how they may impact disk studies.

I. DIRECT IMAGING OF CIRCUMSTELLAR DISKS

The Copernican demotion of humankind away from the center of our local planetary system also provided the shift in perspective required to understand its cosmogony. Once it was apparent that the solar system comprised a number of planets in essentially circular and coplanar orbits around the Sun, theories for its formation were developed involving condensation from a rotating disk-shaped primordial nebula, or Urnebel. The so-called "Kant-Laplace nebular hypothesis" eventually held sway in the latter half of the twentieth century after lengthy competition with rival "catastrophic" theories (see Koerner 1997 for a review), and was subsequently vindicated by the discovery of analogues to the Urnebel around young stars elsewhere in the galaxy.

These circumstellar disks were first detected indirectly, via infrared

The VLA provides this resolution at centimeter wavelengths, but emission from gas in thermal equilibrium in a disk at 10–50 K is impossible to detect until the millimeter/submillimeter regime is reached. Millimeter interferometer arrays including BIMA, OVRO, Plateau de Bure, and Nobeyama now provide ~ arcsec resolution, giving indications of the density and velocity structure in disks in Taurus-Auriga (e.g., Mundy et al. 1996; Koerner and Sargent 1995; Guilloteau et al. 1997; Kitamura et al. 1997; Mundy et al., this volume; Wilner and Lay, this volume), while planned larger interferometer arrays will deliver 0.1 arcsecond resolution and better.

The same fiducial 0.1 arcsec resolution is the diffraction limit of 2.4-m telescope at 1 μm wavelength, which can now be achieved via space-based imaging with the *Hubble Space Telescope* (HST) and ground-based adaptive optics (AO). Although the bulk of the disk gas cannot be detected directly in emission at optical/near-IR wavelengths, the scattering and absorbing properties of the associated dust can be used to obtain images of the disk. This chapter reviews the following: how young disks can be seen at optical/near-IR wavelengths; the relative merits and demerits of the various imaging techniques; example objects, including edge-on disks where the central star is completely obscured, disks seen in silhouette against bright emission lines in H II regions, and disks where the central star or binary is clearly visible; the inferences that can be made as to the structure, mass, and evolutionary status of the disks; the influence of environment on the disks; and the impact of future instrumentation developments on the field.

II. DETECTABILITY AND TECHNIQUES

A. The detectability of disks at optical/near-IR wavelengths

Millimeter and thermal-IR observations image the gas and warm dust in a disk directly in emission, while optical/near-IR observations rely on either dust scattering or absorption. At these wavelengths, the scattering cross-section and opacity of typical dust grains is high, and by virtue of their high masses and densities, young circumstellar disks should be optically thick. Thus the full geometrical area of a young disk is available to scatter light from the central star(s) (from the top surface of the disk or from more tenuous dust in an associated envelope) or to be seen in absorption against a bright background.

Observations of scattered or absorbed starlight are much more sensitive to small amounts of dust than observations of emission at longer wavelengths. For typical ISM dust grains, a uniform surface density disk with radius 100 AU containing as little as a few Earth masses of gas and dust would still have an optical depth at visible wavelengths greater than unity. Thus, in principle, nebulosity can be seen around young stellar objects to a limiting mass hundreds of times smaller than

3. HH 30: a prototype disk-jet system

Disks and jets associated with young stars are expected to be oriented perpendicularly, and recent high-resolution images have confirmed this expectation at the sub-arcsecond level. For example, HST images of Haro 6-5B and DG Tauri B show compact bipolar nebula structures and dust lanes several hundred AU in diameter (Krist et al. 1998; Padgett et al. 1999a). The sharpest and most symmetric system is HH 30 (see Fig. 1c; Burrows et al. 1996; Ray et al. 1996), the source of a spectacular jet in the Taurus L 1551 molecular cloud (Mundt et al. 1990).

HH 30 was the first YSO disk in which the vertical structure was clearly resolved. The disk is seen to flare (become thicker) with increasing radial distance, confirming longstanding predictions from disk structure theory and SED fitting (Lynden-Bell and Pringle 1974; Kenyon and Hartmann 1987; Bell et al. 1997). Modelling of the isophotes (Burrows et al. 1996; Wood et al. 1998) indicates that the disk is vertically hydrostatic with a scale height $H = 15\,\mathrm{AU}$ at $r = 100\,\mathrm{AU}$; furthermore Burrows et al. (1996) found that its scale height may flare with radius more rapidly than expected for a steady-state accretion disk. The disk outer radius is 225 AU, with an inclination angle of $\sim 7°$.

The disk molecular gas component and its kinematics have been resolved via millimeter interferometry by Stapelfeldt and Padgett (1999), while millimeter continuum measurements have yielded a surprisingly small total disk mass of $\sim 10^{-3}\,M_\odot$ assuming nominal dust properties, similar to the mass derived independently from the HST images. This mass is much less than typically inferred for Herbig-Haro jet sources (Reipurth et al. 1993). Implications are that the HH 30 disk must be largely optically thin to its own emergent thermal-IR radiation, and also that steady accretion would consume the system in less than 0.1 Myr. Apparently therefore, HH 30 represents a young star nearing the end of its disk accretion phase.

4. HK Tau/c: a circumstellar disk in a binary system

High-resolution imaging of the faint companion star to HK Tauri shows it to be a nebulous edge-on disk (Fig. 1d; Koresko 1998; Stapelfeldt et al. 1998), making it the first such object seen in a young binary system. HK Tau/c is very small, with a 1.5 arcsec size corresponding to a disk radius of 105 AU, and an extremely narrow 0.2 arcsec dust lane: objects like HK Tau/c would be difficult to recognize as edge-on disks beyond the nearest star-forming clouds.

Modelling of the isophotes (Stapelfeldt et al. 1998) indicates a disk inclination of $\sim 5°$ and a scale height $H = 3.8\,\mathrm{AU}$ at $r = 50\,\mathrm{AU}$, making the disk significantly flatter than that of HH 30. For its estimated age of 0.5 Myr, the disk mass appears to be extremely small: Stapelfeldt et al. (1998) find it to be $10^{-4}\,M_\odot$ ($0.1\,M_{\mathrm{Jup}}$) based on HST optical wavelength observations, while Koresko (1998) derives $10^{-3}\,M_\odot$

1. Internal disk evolution

Simple gravity-dominated models show that as circumstellar disks form via inside-out collapse, they comprise two distinct parts, an inner disk, rotating in quasi-equilibrium and an outer component contracting dynamically (Saigo and Hanawa 1998). The presence of a sharp transition zone between the two parts is predicted, and while it is possible that this corresponds to the edges seen in the silhouette images, there appears to be little evidence for more extended infalling envelopes around the Orion disks, which may have been removed by external effects. Also, such a simple model may be significantly modified if magnetic fields play an important role in the collapse.

2. OB star ionizing flux and stellar wind

Near the center of the Orion Nebula, low-mass stars are often accompanied by compact nebulae, externally ionized by the Trapezium OB stars. These so-called 'proplyds' are thought to have disks at their centers (O'Dell et al. 1993; O'Dell and Wong 1996; Bally et al. 1998a; Henney et al. 1996; Johnstone, Hollenbach, and Bally 1998; see also the chapter in this volume by Hollenbach et al.). The silhouette disks are simply thought to be far enough from the OB stars to escape ionization, but it is nevertheless plausible that smaller-scale effects are at work: for example, Orion 121-1925 has a faint tail that points away from the brightest OB star θ^1Ori C, perhaps being driven off by the stellar wind. Such an effect should truncate the disk, although modelling is required to determine the likely profile.

3. Star/disk interactions

The Trapezium Cluster contains many low-mass stars and tidal interactions between a star/disk system and interloper stars should lead to distortion, tidal tails, and truncation of the disk (Heller 1995; Hall, Clarke, and Pringle 1996; Larwood et al. 1996). Models by Hall (1997) show that repeated encounters with stars in a cluster can convert an original power-law radial profile into one with a sharper exponential edge, as observed for the silhouette disks.

A more global form of tidal stripping may truncate a disk at the radius where its Keplerian velocity is of the same order as the cluster velocity dispersion, inasmuch that the latter reflects the general gravitational potential of the cluster. The Keplerian velocities at the outer edges of the silhouettes, calculated from their radii and central stellar masses, are typically ~ 1.5–$2.5\,\mathrm{km\,s^{-1}}$. By comparison, the 3D cluster velocity dispersion is $\sim 4\,\mathrm{km\,s^{-1}}$ (Jones and Walker 1988), and a proper analysis would be required to determine whether or not the field corresponding to that velocity would indeed truncate the disks at the observed radii.

4. Pressure balance

An edge may also be expected when the cold gas in the disk comes line of sight, thus swamping the faint scattered light from the disk. Furthermore, if the disk is not flared, the inner disk may cast the outer regions in shadow.

The detection of a disk in such systems is difficult but not impossible, with a stable, largely symmetric, and well-calibrated PSF the basic requirement. The visibility of the faint disk nebulosity increases rapidly with distance from the central star, and estimates of the detectable disk mass and size completeness curves can be made for a given inclination, using empirical PSFs (Close et al. 1998b). For example, assuming an ISM-like distribution of dust grains (Mathis and Whiffen 1989), Mie scattering calculations show that a $\sim 0.01\,M_{\odot}$ disk at an inclination of 45° is detectable at radii $\gtrsim 1$ arcsec from the central star providing 0.1 arcsec resolution can be achieved. For a fully-sampled pixel scale (e.g., ~ 0.05 arcsec), such a disk has a typical per-pixel surface brightness 10^5 times fainter than the central star. At the 150 pc distance to the nearest star-forming regions, only the largest disks ($\gtrsim 100$ AU radius) have been studied so far: imaging of smaller disks is challenging.

As discussed in the introduction, millimeter interferometry provides an important tool for studying the outer parts of large circumstellar disks, with the advantages that emission from the central star is negligible, and that the gas kinematics can be studied directly. For example, the millimeter emission from GG Tau (Dutrey et al. 1994), GM Aur (Dutrey et al. 1998), DM Tau (Saito et al. 1995; Guilloteau and Dutrey 1998), and UY Aur (Duvert et al. 1998) have all been resolved and found to be consistent with Keplerian disks. HL Tau appears to have signs of rotation as well (Sargent and Beckwith 1991), although infall (Hayashi et al. 1993) and perhaps outflow (Cabrit et al. 1996) have also been observed, underlining how complex the kinematics can be. Since each of these systems are known to have disks in Keplerian rotation with resolved diameters of a few arcseconds, they are natural candidates for direct imaging in light scattered by associated dust. All have been imaged by the HST in the optical and by AO in the near-IR, with HL Tau, GM Aur, GG Tau, and UY Aur all detected. Surprisingly, the DL Tau and DM Tau disks have yet to be seen: it is plausible that the dust in these systems has already condensed to form grains too large ($>10\,\mu$m) to scatter efficiently.

1. HL Tau: a young embedded source

HL Tau is likely the youngest such system. Although the central star is obscured by ~ 24 magnitudes of visual extinction (Stapelfeldt et al. 1995; Beckwith and Birk 1995; Close et al. 1997a), it is not an edge-on system, with inclination estimates varying between 20–40° (cf. Mundy et al. 1996). The large visual extinction is apparently caused by the dusty upper part of the disk/envelope. There is significant infall in the envelope (Hayashi et al. 1993), and a strong 300 km s^{-1} outflow (Mundt mass of the binary can be estimated: for GG Tau, Dutrey et al. (1994) estimated a total mass of $1.2\,M_\odot$. This can be independently checked by monitoring the relative motion of the two binary stars (separation 0.25 arcsec) via speckle and AO observations (Leinert et al. 1993; Ghez et al. 1993, 1995; Roddier et al. 1996). The presently measured orbital velocity of ~ 1.45 AU/yr (under the assumption that the stars are coplanar with the $35°$ inclination disk), suggests that the binary is close to minimum separation and contains a total mass of $\sim 1.5\,M_\odot$. Distance and velocity uncertainties yield a possible 40% error in this mass estimate, making it consistent with that determined from the millimeter kinematics. Interestingly, both estimates are considerably higher than the masses derived from the stellar fluxes using current PMS evolution models (D'Antona and Mazzitelli 1994; Roddier et al. 1996).

4. UY Aur: a large circumbinary disk

Millimeter interferometry has also revealed a circumbinary disk around UY Aur (Dutrey et al. 1996; Duvert et al. 1998), as also seen via AO imaging (Fig. 3d; Close et al. 1998a). Compared to GG Tau, the UY Aur disk is larger, with an inner hole radius ~ 420 AU. This is unsurprising however, since the UY Aur binary has a larger projected separation of 0.88 arcsec, corresponding to a semi-major axis of ~ 190 AU, and thus the observations confirm the prediction that wider binaries should have larger gaps in their disks.

The millimeter interferometry suggests that the disk gas is in Keplerian rotation around a $1.2\,M_\odot$ binary (Duvert et al. 1998), while the binary orbital motion yields the slightly higher mass of $1.6\pm0.5\,M_\odot$. As with GG Tau, the kinematic masses are higher than those derived from stellar fluxes combined with PMS tracks. In both GG Tau and UY Aur, in addition to the large (300–500 AU) circumbinary disks, much smaller (5–10 AU) circumstellar disks must be present around each binary component in order to account for near-IR excesses seen in their SEDs (Close et al. 1998a). Short estimated lifetimes for these inner disks makes it likely that they are replenished via accretion from the outer large circumbinary disks, in line with theoretical expectations (cf. Duvert et al. 1998; Close et al. 1998a; Lubow and Artymowicz, this volume).

Finally, the large size of the UY Aur disk makes it possible to obtain imaging polarimetry, a difficult proposition requiring a stable and sharp PSF (Close et al. 1997b). AO imaging polarimetry with 0.09 arcsec resolution indicates that the light from the UY Aur disk is strongly polarized ($\sim$80%) due to single scattering off mainly small ($< 0.1\,\mu$m) dust grains (Potter et al. 1998). The observed polarization pattern around UY Aur was found to be in good agreement with the dust grains distributed in a disk: other distributions, such as a spherical envelope, can be rejected by comparison with suitable models (Potter et al. 1998).

with a grid of models, although this simple trend can break down if significant scattered light from an envelope is present. The inclination derived in this way can be independently checked using measurements of the kinematics in an associated jet, assuming perpendicularity.

C. Mass

In principle, the brightness of the scattered light can be used to estimate the disk mass, but as found for the corresponding absorption in the silhouette disks, very little material is required to account for the observations, due to the large optical depths at optical/IR wavelengths. Thus only lower limits are derived, typically just $\sim 10^{-5} M_{\odot}$ for the scattered light. However, in an edge-on system, the nebular structure is strongly affected by the total mass in the disk, with the thickness of the central dust lane increasing monotonically with disk mass, as shown in Fig. 4. Thus, high-resolution images of an edge-on disk can be compared with a grid of models to determine its mass. For the two edge-on systems where millimeter continuum observations are currently available, IRAS 04302+2247 and HH 30, the millimeter-derived masses are in reasonable agreement with those obtained from scattered light models, giving some some confidence in the applicability of a disk density law to these systems, and in the current knowledge of dust opacities at optical and millimeter wavelengths.

D. Radial density profile

The radial density distribution is not well determined by observations at wavelengths where disks are optically thick. It is only in the very outermost sections of the silhouette disks, for example, that their structure can be traced, revealing their strongly truncated outer edges (see Section III.B). In HH 30 and HK Tau/c, models using only the nebula light distribution as a constraint suggest a surface density weakly *increasing* with radius, although the same models produce too little extinction to obscure the central star. To reproduce the minimum necessary extinction, a radially decreasing surface density is required, but since p is seen to be strongly degenerate with the scale height index β, only a weak conclusion can be drawn, namely that $p < -0.3$ in both systems.

E. Vertical structure and its radial dependence

In edge-on systems, gradients in the nebular brightness adjacent to the dark lane allow the scale height near the disk outer radius to be derived. This parameter is interesting since it can be directly related to the local temperature in a disk which is vertically hydrostatic; its radial variation is diagnostic of the radial temperature structure. In addition, changes in the vertical distribution of scattering dust grains may accompany the initial stages of particle growth which lead to planetesimal formation.

for the scattered light seen in the circumbinary disks around GG Tau and UY Aur systems where the inclination was well-established from the millimeter kinematics. They found the best results were obtained using a power-law index of $\eta = 4.7$, and radii ranging from 0.03 up to 0.5–0.6 μm, i.e., similar to ISM grains. A significant population of grains with radii >0.6 μm was found to be unlikely, since such large grains would increase the contrast between the near and far sides of the disk to levels higher than observed. Burrows et al. (1996) and Stapelfeldt et al. (1998) derived similar results for their models of the HH 30 and HK Tau/c edge-on disks, although the presence of a population of somewhat larger ($\sim$1 μm) grains was implied based on the apparently enhanced forward scattering at 0.8 μm wavelength. Nevertheless, the larger millimeter-sized grains inferred by millimeter observations apparently do not play a major role in the scattering process: it is possible that they may have sunk to the central (optically thick) plane of the disks, remaining hidden from view in scattered light, but nevertheless still dominating the millimeter continuum emission.

VI. FUTURE DEVELOPMENTS

Almost all of the results presented in this review have been obtained since the Protostars and Planets III meeting in 1990, and clearly, before the next meeting in the series, substantial progress will be made in studying the most important phases in the formation and evolution of young circumstellar disks and proto-planetary systems.

Foremost is the need to find more examples of disks around young stellar objects at all evolutionary stages, by continuing surveys of nearby dark clouds and H II regions. Existing techniques will be used to the full, including AO on the ground and the HST in space. The next HST servicing mission will see the installation of the wide-field fully-sampled Advanced Camera for Surveys at optical wavelengths and the possible return to operation of NICMOS in the near-IR.

Second, improvements in angular resolution are required to allow more detailed studies of nearby sources, and to extend the surveys to encompass the more distant star-forming regions with reasonable linear resolution. In the near-term, this will be achieved on the ground by equipping the 8–10 m class telescopes with AO systems; in the longer-term, significant gains will be made by the passively-cooled IR-optimized Next Generation Space Telescope (NGST) and through multi-telescope optical/IR interferometry, using, for example, the Keck, VLTI, and LBT interferometers on the ground, and SIM in space. Malbet et al. (1998) have very recently shown the way forward in this regard, using the Palomar Testbed Interferometer to resolve thermal emission from a disk around FU Ori at near-IR wavelengths, at spatial scales around 4 milliarcsec or just 2 AU at 450 pc.

Finally, there is a strong case for increased-contrast imaging, in order to study low-surface brightness scattered light in the presence of a bright central star. There are several known examples of YSOs with disks which have been resolved via millimeter interferometry, and yet which show just bare PSFs in HST and/or AO images at optical/near-IR wavelengths. These systems, including DL Tau, DM Tau, CY Tau, V 892 Tau, MWC 480, LkCa 15, and AS 209, clearly have disks, but current optical/near-IR instrumentation is simply not up to the contrast challenge. Future ameliorating developments will include improved forms of coronagraphy and optical/IR nulling interferometry on the ground and in space.

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Figure 1. Continuum HST images of four edge-on disks, all plotted at the same equivalent linear scale and orientation for direct comparison. IRAS 04302+2247 (top left; Padgett et al. 1999a) and Orion 114-426 (top right; McCaughrean et al., in preparation) are shown as near-infrared truecolor JHK composites. Both HH 30 (bottom left; Burrows et al. 1996) and HK Tau/c (bottom right; Stapelfeldt et al. 1998) are shown as optical pseudocolor RI composites. Each panel is 1200 AU square and all intensities are logarithmically scaled.

Figure 3. Four circumstellar disks detected in scattered light. The HL Tau image (top left) is a composite of an HST R-band image as blue (from Stapelfeldt et al. 1995), and AO images at J and H as green and red respectively (from Close et al. 1997a). The green extension is likely infrared light scattered off the front surface of the disk. Both GM Aur (top right) and GG Tau (bottom left) are represented with J-band AO images: note that the GG Tau logarithmic intensity scale is wrapped in order to show both the faint nebulosity and the fully-resolved central binary (from Roddier et al. 1996). UY Aur (lower right) is shown as a composite JHK (as blue, green, red) AO image (from Close et al. 1998a). This circumbinary disk is somewhat closer to edge-on than that seen in GG Tau, and thus emission from the near-side of the disk is strongly scattered into the line-of-sight.

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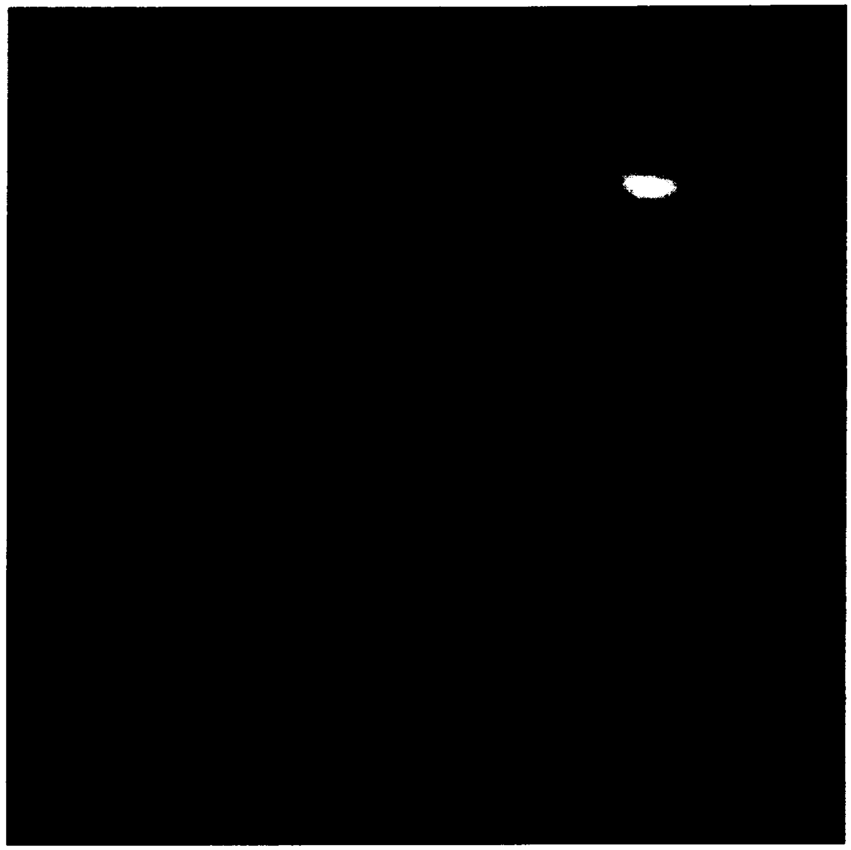

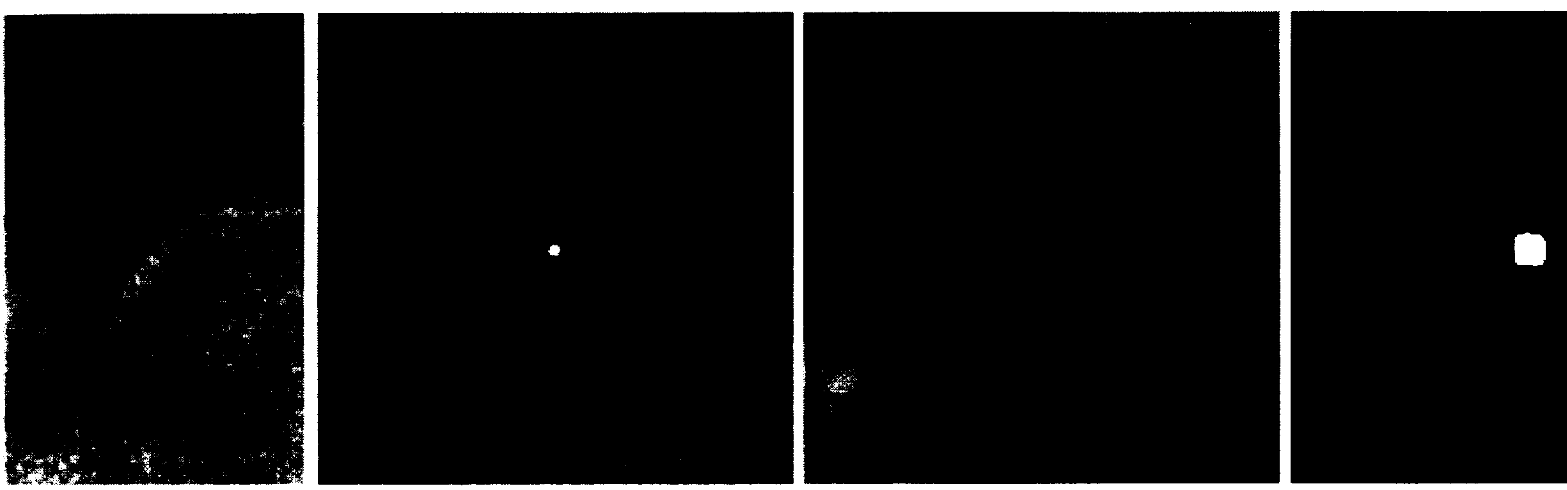

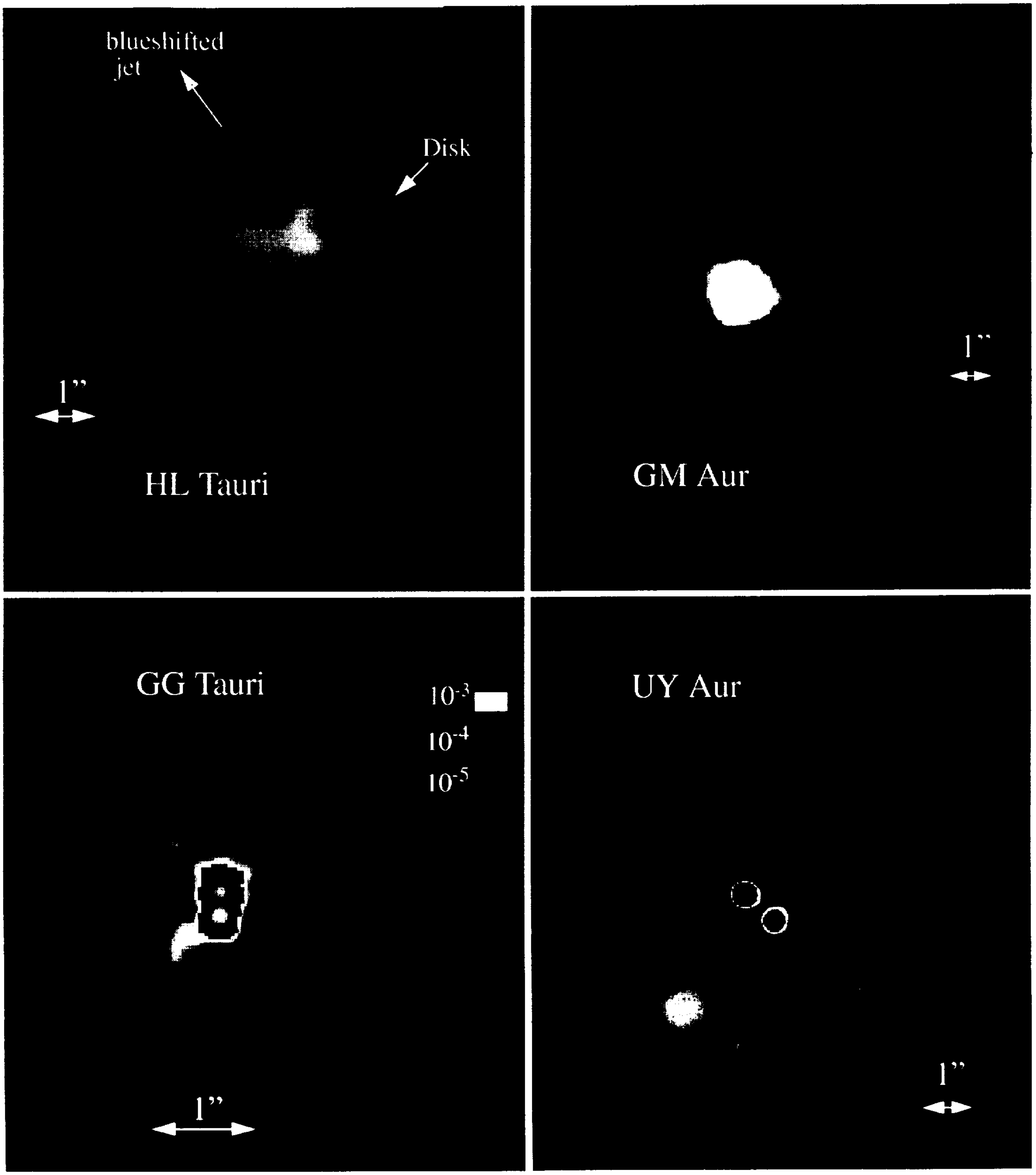
blueshifted
jet
Disk
1"
HL Tauri
1"
GM Aur
GG Tauri
10-3
10-4
10-5
1"
UY Aur
1"