NEAR-INFRARED SYNTHETIC IMAGES OF PROTOSTELLAR DISKS AND ENVELOPES

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ABSTRACT

We present a grid of near-infrared (IR) synthetic images of pre-main-sequence stars at different stages of evolution, which we simulate by varying envelope mass, disk radius and mass, and outflow cavity shape. Our aim is to determine how variations in physical properties of young stellar objects (e.g., mass infall rate, disk size) affect their observed colors and morphology, and use this information to highlight observable differences between different evolutionary states. We show that the near-IR colors are a function of envelope mass infall rate and inclination; hence both parameters must be constrained if colors are to be used to infer a source’s true evolutionary state. Sources with more opaque envelopes have redder diffuse colors, because the scattered light suffers reddening as it propagates through the envelope. Somewhat counterintuitively, colors are reddest at intermediate inclinations ($i \sim 45^\circ$ – 70°) and then become bluer edge-on, where light is $\sim 100\%$ scattered. Thus a source with relatively blue colors could be an evolved source or a younger source oriented edge-on. Importantly, we find that at inclinations where scattered light dominates, it is erroneous to derive extinction A_V from observed colors; fully half of all objects will underestimate A_V by at least an order of magnitude. We use our models to interpret six protostellar sources in the Taurus-Auriga molecular cloud observed with HST NICMOS. Of the six young stellar objects modeled in this paper, five require an infalling envelope to match the colors and should thus be classified as young embedded sources. The remaining source, Haro 6-5B, is a disk source, having already dispersed its envelope.

Subject headings: circumstellar matter — radiative transfer — scattering — stars: formation — stars: pre-main-sequence

1. INTRODUCTION

The low-mass star formation process can be understood as a progression through several evolutionary stages (Lada 1987). In the earliest stage, a pre-main-sequence star is deeply embedded in an infalling envelope of gas and dust. As matter in a rotating envelope falls inward, a disk is formed surrounding the central source as a result of angular momentum conservation (Cassen & Moosman 1981). As matter accretes onto the star from the disk, collimated jets and molecular outflows develop, carving out cavities along the rotational axis of the system. If the outflow cavity axis is oriented along the plane of the sky, the near-infrared emission will be dominated by scattered light as nearly all of the direct stellar light is absorbed and reradiated at longer wavelengths by the surrounding disk and envelope material (Adams et al. 1987; Kenyon et al. 1993a, 1993b).

Eventually the infalling envelope is dispersed, revealing the pre-main-sequence star and its surrounding accretion disk. The star continues to accrete matter from the disk throughout this stage. In absence of the extended infalling envelope, the nebulousity of such sources is more compact than in the earlier stage and is dominated by scattered light from the top and bottom surfaces of the disk (Whitney & Hartmann 1992). This stage lasts between 10^6 and 10^7 yr until the disk becomes optically thin due to planet formation or dispersal.

Access to large ground- and space-based telescopes has vastly increased the number of high-resolution near-IR (1 – $2 \mu\text{m}$) images

of young stellar objects. Some of the most striking images are of protostars in Taurus using the NICMOS camera on board the *Hubble Space Telescope* (HST; Padgett et al. 1999), showing clear extinction lanes and bipolar scattered light morphologies. Intuition suggests interpreting these features as arising from edge-on circumstellar disks, perhaps surrounded by a tenuous remnant envelope. However, intuition may fail when complex circumstellar geometries are involved and when scattering dominates the radiation transfer from the central source to the observer. Indeed, we show in this paper that in fact nearly all of the Taurus protostars observed by NICMOS are surrounded by substantial envelopes, indicating a younger evolutionary state than intuition may suggest.

The goal of this paper is to use radiative transfer models simulating young stars of various evolutionary stages to help correctly interpret these and other near-IR observations. The models we present in this paper demonstrate the effects of envelopes of various masses on the observed colors and morphology of a young stellar object, providing the means to correctly classify the evolutionary state of pre-main-sequence stars. We focus on distinguishing young sources that are still embedded in massive envelopes from more evolved sources that lack an infalling envelope yet are still accreting from an optically thick disk. These evolutionary stages are commonly known as the Class I and II stages (Lada 1987). However, this classification scheme is based on the slope of the 1 – $24 \mu\text{m}$ spectral energy distribution (SED) and does not take into account inclination effects (i.e., the same source could be classified in different ways depending on if it is observed edge-on or pole-on). To limit confusion, we therefore refer to the two distinct stages as “envelope” and “disk-only,” keeping in mind that the envelope stage also includes a disk and an outflow cavity.

We compute a modest grid of high-resolution near-IR scattered light images of protostars, encompassing a range of disk and envelope parameters (e.g., mass infall rates, disk size, and

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disk mass) that should be applicable to young protostars in many star formation regions. The grid presented here is not meant to be comprehensive but rather illustrative of various features that can be used to interpret data. Our objectives in this paper are to (1) highlight observable differences between sources with and without massive infalling envelopes that will aid in the classification of observations and (2) apply our grid and more specific models to interpret the six sources observed with *HST* NICMOS by Padgett et al. (1999). Others can follow a similar approach to their data by first using the grid to roughly determine evolutionary state and inclination and then, if desired, running our publicly available codes to model their sources in more detail.⁵

We describe the modeling approach in § 2 and the general characteristics of the grid in § 3. We discuss morphological signposts of different evolutionary states, including (1) outflow cavity walls that appear V shaped at short wavelengths and curved at long wavelengths indicative of the young envelope stage, and (2) large fan-shaped shadows in the midplane of more evolved (less opaque) sources caused by the flared disk. We describe the young stellar objects observed by Padgett et al. (1999) with *HST* NICMOS in § 4. In § 5 we show that all but one of the sources observed by Padgett et al. (1999) require the presence of a disk and an envelope to match their observed morphology and colors. We summarize our results in § 6.

2. MODEL COMPONENTS

Our envelope model consists of a rotationally flattened envelope, a circumstellar disk, and an outflow cavity. The envelope infall rate, which is proportional to mass, is varied to represent evolution, with higher infall rates representing earlier stages and lower infall rates representing later stages.

The presence of each of these components is supported by both observations (Burrows et al. 1996; Padgett et al. 1999) and theory (e.g., Terebey et al. 1984; Shu et al. 1987; Whitworth & Ward-Thompson 2001; Hartmann 2002). We also consider disk-only and disk+outflow models with no envelopes. In this section we describe the physical structure of the envelopes, disks, and outflow cavities of models in the grid. We conclude the section by discussing the different dust grain mixtures used in the models and summarizing the radiative transfer procedure.

2.1. Envelope Structure

We adopt the envelope structure of a rotating envelope in free-fall collapse (Ulrich 1976; Cassen & Moosman 1981; Terebey et al. 1984). In this model, particles fall along parabolic orbits toward the central stellar object and stop when they encounter the disk. Material from the polar region has relatively little angular momentum and lands near the central star. Material falling from larger angles from the polar axis falls onto the disk at larger distances, reaching the centrifugal radius, r_c , along the disk plane. We include just the inner solution of the Terebey et al. (1984) model (the Ulrich [1976] solution) for the density because it can be described analytically:

$$\rho = \frac{\dot{M}_{\text{env}}}{4\pi(GM_*r_c^3)^{1/2}} \left(\frac{r}{r_c}\right)^{-3/2} \left(1 + \frac{\mu}{\mu_0}\right)^{-1/2} \left(\frac{\mu}{\mu_0} + \frac{2\mu_0^2 r_c}{r}\right)^{-1}, \quad (1)$$

where $\dot{M}_{\text{env}}$ is the envelope mass infall rate, r_c is the centrifugal radius, M_* is the stellar mass, θ is the polar angle, $\mu = \cos \theta$, and

μ_0 is cosine of the angle of a streamline of infalling particles as $r \rightarrow \infty$. The centrifugal radius r_c determines the approximate disk radius and flattening in the envelope structure. We solve for μ_0 from the equation for the streamline:

$$\mu_0^3 + \mu_0(r/r_c - 1) - \mu(r/r_c) = 0. \quad (2)$$

The optical depth through the envelope, which has a large effect on the radiative transfer, depends on the model parameters (not including inclination) approximately as (Whitney & Hartmann 1993)

$$\tau \propto \kappa \dot{M}_{\text{env}} (M_* r_c)^{-1/2} f(R_{\text{env}}), \quad (3)$$

where κ is the opacity, R_{env} is the outer radius of the envelope, and $f(R_{\text{env}})$ is a slowly varying function of outer radius R_{env} .

As equation (1) shows, smaller r_c will lead to higher density and a more spherical envelope. In the limit of $r_c \rightarrow 0$, the density becomes the spherical infall solution (Shu 1977), with density $\rho \propto r^{-3/2}$. At $r \gg r_c$, the density follows this power law. Inside r_c the density approaches $\rho \propto r^{-1/2}$.

For our grid of models we fix the envelope radius at 5000 AU. This is a rather arbitrary value, but its effect on the radiative transfer is similar to that of foreground reddening. At large radii, where the density is proportional to $r^{-3/2}$, varying the outer radius by a factor of 2 changes the optical depth by relatively small amounts. Since the mass has an extra factor of r^2 in its integral, the effect of changing outer radius is much greater on mass. For a typical model considered in this paper, increasing the outer radius from 5000 to 10,000 AU changes the optical depth by $\sim 5\%$ and the mass by a factor of 2.9. Since the envelope mass is so dependent on outer radius, we prefer to use the envelope infall rate as an indicator of evolutionary state. The stated envelope masses in this paper can be scaled to different envelope radii by applying a factor approximately equal to $(R_{\text{env}}/5000 \text{ AU})^{3/2}$. We also note that the infall rate is dependent on the stellar mass. In this paper we assumed a stellar mass of $0.5 M_\odot$. If the stellar mass is known, the infall rate can be scaled by $(M_*/0.5 M_\odot)^{0.5}$. The derived infall rates and masses are also dependent on the chosen grain model, as discussed in § 2.2.

2.2. Circumstellar Disk Structure

Since most of the material falls onto a disk, we include a standard T Tauri accretion disk geometry (Shakura & Sunyaev 1973; Pringle 1981) in our models:

$$\rho = \frac{\rho_0 \exp\left\{-(1/2)[z/h(\varpi)]^2\right\}}{(\varpi/R_*)^\alpha}, \quad (4)$$

where ϖ is the radial coordinate in the disk midplane and the scale height increases with radius, $h = h_0(\varpi/R_*)^\beta$; ρ_0 and h_0 are the fiducial density and scale height, respectively, at the stellar radius (even though the disk inner radius is usually larger than this). For the grid we adopt $\beta = 1.25$, $\alpha = 2.25$, and $h_0 = 0.017 R_*$, which are parameters derived for average T Tauri disks (D'Alessio et al. 1998). To fit the *HST* NICMOS sources (§ 5), we sometimes varied these parameters. Estimates of disk mass are strongly dependent on the assumed grain properties since mass can hide in large grains that have little near-IR opacity (Cotera et al. 2001; Wood et al. 2002; D'Alessio et al. 2001). The parameter we are sensitive to is optical depth: the width of the dust lane in a near-edge-on disk is directly related to the disk optical depth. The optical depth is proportional to disk mass multiplied by grain

⁵ Our scattered light codes, including instructions for running and sample plotting tools, are available at <http://gemelli.spacescience.org/~bwhitney/codes>.

opacity, $M_{\text{disk}}\kappa$. Multiwavelength images help break the degeneracy between M_{disk} and κ since the grain model has to fit several wavelengths with the same disk mass. There are other degeneracies in fitting the scattered light images of disks. For example, the disk scale height h_0 can be lowered if the degree of flaring β is increased, as discussed in Wood et al. (1998). We choose to fix values of β and h_0 in the ranges appropriate for disks in hydrostatic equilibrium (Chiang & Goldreich 1997; D'Alessio et al. 1998; Walker et al. 2004). The value of α is varied so that $\beta - \alpha = 1$, which is appropriate for a disk in hydrostatic equilibrium with a constant accretion rate (D'Alessio et al. 1998).

2.3. Outflow Cavity

Outflow cavities are required to fit near-IR images of young sources still embedded in an envelope of gas and dust (Kenyon et al. 1993b; Whitney et al. 1997) and are thus included in the models. We employ two different outflow cavity morphologies in our models: curved and streamline, chosen because observed sources appear to exhibit both shapes. The streamline cavity shape might occur if precessing jets carve out a conical shape while infalling material outside of the outflow continues to fall in along streamlines. The physical mechanism causing a curved cavity shape is less certain.

The streamline cavity shape is defined by equation (2); at each (μ, r) , μ_0 is calculated, and if it is greater than the chosen cavity angle, the density is set to the cavity density. For the grid of models, we fix the streamline cavity size by setting $\cos^{-1}(\mu_0) = 20^\circ$. Our choice of cavity size is based on observed images such as those presented in §§ 4 and 5. Varying the cavity size will have some effect on the colors, with sources with larger cavities appearing more blue when viewed at near-edge-on inclinations. While the cavity size is held constant in our grid, we discuss the effects of varying cavity size on observed colors when pertinent.

The curved cavity follows $z = a\varpi^b$, where $\varpi = (x^2 + y^2)^{1/2}$ is the cylindrical radius. For all of our models, we fix $b = 1.5$ and a is set so that the cavity opening angle is $\theta = 25^\circ$ at $z = R_{\text{env}}$; thus, $a = R_{\text{env}}/[R_{\text{env}} \tan(25^\circ)]^{1.5}$. Since the cavity is curved, the opening angle is effectively larger at smaller radii, giving a similar opening angle to the streamline cavity at a radius of 1500 AU.

The dust density distribution within outflow cavities has not yet been well constrained by observations. As a starting place for our grid of models, we assume that nearly all of the dust in the cavity has been swept away by the bipolar outflow, resulting in an evacuated cavity. However, models of several of the sources observed by Padgett et al. (1999) require slightly more dust in the cavity. In § 5 we present the specific dust densities of the models used to fit the observed sources and discuss the observable effects of raising the dust density within an outflow cavity.

2.4. Dust

The dust properties used for the grid's envelope models (Figs. 1–5) are those of the interstellar medium (ISM) grain distribution calculated by Kim et al. (1994, hereafter KMH). Table 1 shows the relevant extinction and scattering properties of this grain model. Whittet et al. (2001) find that the ratio of total to selective extinction in Taurus ranges from $R_V = 3.3$ to 4.5, compared to the average diffuse interstellar value of $R_V = 3.1$. However, Martin & Whittet (1990) show that near-IR extinction properties vary little between dark clouds and the diffuse ISM. Previous scattered light models of the Taurus sources found that ISM grains fit the colors well (Kenyon et al. 1993a, 1993b; Whitney et al. 1997; Wolf et al. 2003). This may be because the near-IR is less sensitive to varying grain sizes and ice coatings than the ultraviolet and optical regimes. In addition, the Taurus cloud is less dense than

TABLE 1
PARAMETERS FOR DUST GRAINS

Name	Wave Band	κ ($\text{cm}^2 \text{ g}^{-1}$)	ω	g
KMH	$J_{110\text{W}}$	73	0.47	0.33
	$H_{160\text{W}}$	39	0.41	0.28
	$K_{205\text{W}}$	25	0.37	0.25
Large grain	$J_{110\text{W}}$	24	0.53	0.59
	$H_{160\text{W}}$	20	0.54	0.58
	$K_{205\text{W}}$	17	0.54	0.57

NOTES.—The dust properties are opacity κ , albedo ω , and average cosine of the scattering angle g . The dust properties are shown at the mean wavelength of filters, which are 1.14, 1.61, and 2.08 μm for the *HST* NIC2 F110W, F160W, and F205W filters, respectively. The filters are referred to in this paper as $J_{110\text{W}}$, $H_{160\text{W}}$, and $K_{205\text{W}}$ to aid the reader familiar with the J , H , and K bands. KMH dust grain properties are used in the envelope models; the large grain model is used for the disk-only models (Wood et al. 2002). See § 2.4 for details.

many molecular clouds so the grains in infalling envelopes may have undergone less processing.

While the grain properties in the envelopes may be similar to dust in the ISM, the grains in the disk are likely to be much larger (Wood et al. 2002; D'Alessio et al. 2001; Wolf et al. 2003). We therefore use a large-grain model from Wood et al. (2002) for the disk-only models in the grid. The properties of this grain model are also shown in Table 1.

It may seem contradictory that disks in our envelope models are equipped with ISM grains rather than the large grains used to model the disk-only sources. However, Whitney et al. (2003a) showed that grain growth in the disk affects only the long-wavelength spectrum ($>100 \mu\text{m}$), allowing such objects to be accurately modeled in the near-infrared without large grains in the disk. However, we note that in using the small-grain models in these disks, we are likely underestimating the total mass of these disks.

2.5. Radiative Transfer Procedure

The radiative transfer calculations are similar to those described in Whitney & Hartmann (1992, 1993). The Monte Carlo code follows photons as they are emitted from a central source and scatter in the circumstellar material, and those that escape are collected into images. The code employs a three-dimensional spherical polar grid for dealing with arbitrary density distributions. The grid has variable spacing in r and θ to deal with the extremely large variations in density and size scales between the disk and envelope.

3. A GRID OF MODELS

We have created a grid of 200+ scattered light models of protostars representing various evolutionary states. Near-IR images are produced at three wavelengths corresponding to the *HST* NICMOS NIC2 filters, F110W, F160W, and F205W, with mean wavelengths of 1.14, 1.61, and 2.08 μm , respectively. These are similar enough to the J , H , and K wavelengths that the results can be applied to those as well. In this section we present an illustrative subset of this grid and discuss in separate subsections synthetic images of envelope+disk sources (§§ 3.1 and 3.2, Figs. 1–4) and disk-only sources (§ 3.4, Fig. 8). In each subsection we discuss observable differences between young sources embedded in massive envelopes and more evolved sources in which the envelope has been dispersed.

Table 2 shows values of fixed parameters in the grid (e.g., stellar mass, disk flaring), while Table 3 summarizes the parameters

TABLE 2
GRID PARAMETERS: FIXED

Parameter	Value
Stellar radius ($R_\odot$).....	2.5
Stellar effective temperature (K).....	3800
Mass of central star ($M_\odot$).....	0.5
Disk flaring	$a = 2.25, b = 1.25$
Envelope radius (AU)	5000
Minimum disk radius ($R_\odot$).....	7.5
Scale height of disk at R_*	$0.0095R_*$
ρ_{cav} (g cm^{-3})	$(1.0 \times 10^{-19})r^{-0.5}$
θ_{cav} :	
Streamline (deg)	20
Curved (deg).....	25

varied in the grid (envelope mass infall rate, centrifugal radius, cavity shape, and inclination). For all models presented in this section, we assume that the central source is a $1 L_\odot$ M0 star. These models assume a stellar temperature of 3800 K, which is a very common value in the Taurus molecular cloud over a range of evolutionary stages and stellar masses, due to the fact that most of the sources in Taurus are $< 1 M_\odot$ (Kenyon & Hartmann 1995). In all of the models presented in this paper, the envelope centrifugal radius r_c is equal to the disk radius. The infall rates sampled in this work were chosen based on observations and models that suggest $\dot{M}_{\text{env}} \sim (2-5) \times 10^{-6} M_\odot \text{ yr}^{-1}$ in the Taurus molecular cloud (Kenyon et al. 1993a, 1993b; Whitney et al. 1997); we use a slightly wider range of infall rates in our grid to more clearly illustrate its effect on the observed scattered light. The different parameters employed in the grid may represent different physical conditions or evolutionary stages within the envelope phase. In general, we would expect a low-mass envelope (i.e., lower infall rate) to correspond to a later evolutionary stage (Hartmann 1998), but it could also be due to a lower mass star forming in a more quiescent region of the molecular cloud.

The envelope models consist of a central illuminating star, a flared circumstellar disk, a rotationally flattened infalling envelope, and bipolar outflow cavities carved out of the envelope. The disk-only models are equipped with flared disks but no infalling envelopes. Two parameters are varied in the disk-only models: disk mass and outer radius. The specific values used are shown in Table 3 and discussed in § 3.4.

Models in the grid (Figs. 1–5, Figs. 8 and 9) are displayed with a dynamic range of $\sim 3 \times 10^4$, with flux density ranging from 0.01 to $300 \mu\text{Jy arcsec}^{-2}$, under the assumption that the central source has a luminosity of $1 L_\odot$ (here we use a distance of 140 pc, the distance to Taurus). The relatively large dynamic range was chosen to maximize the amount of diffuse scattered light seen in the

models. Note that the intensity of the diffuse radiation within our display range is much fainter than the central star: a $1 L_\odot$ M0 star at a distance of $d = 140$ pc produces a flux density of 0.46 Jy at K , or $4 \times 10^7 \mu\text{Jy arcsec}^{-2}$, several orders of magnitude higher than the upper intensity limit presented in our grid of models.

In our direct comparisons to data (§ 5), we scale the luminosity of the central source to that reported by Padgett et al. (1999) or Kenyon & Hartmann (1995). Most of these luminosities were determined from the bolometric flux. We choose an intensity scale that maximizes the diffuse structure seen in the observations of a given source and enforce the same intensity scale in our models of that source. The intensity scale of the models may thus differ slightly from that used for our grid (as described in the previous paragraph).

All of the model images in this paper were convolved with a $0''.15$ FWHM Gaussian point-spread function (PSF), which should be similar to the deconvolved NICMOS images we are modeling (§§ 4 and 5). The images are displayed as “three-color” images in Figures 1–5 and 8–15 in the standard way, with the $1.14 \mu\text{m}$ image in the blue plane, the $1.61 \mu\text{m}$ image in green, and the $2.08 \mu\text{m}$ image in red.

3.1. Envelope Models Viewed Close to Edge-on

The primary difference between the morphology of the envelope and disk-only stages of evolution is the presence of an envelope surrounding the disk and star. To examine the effects of an envelope on the observed colors and morphology of young stellar objects, we display a grid of models including disks and envelopes viewed at near-edge-on inclinations.

Our highly inclined (85°) envelope+disk models are presented in Figures 1 and 2. In each of the two figures, mass infall rate varies along the vertical axis and centrifugal radius is varied along the horizontal axis. Mass infall rates range from $10^{-5} M_\odot \text{ yr}^{-1}$ in the top row, to $5 \times 10^{-6} M_\odot \text{ yr}^{-1}$ in the middle row, to $5 \times 10^{-7} M_\odot \text{ yr}^{-1}$ in the bottom row. The centrifugal radius is 10 AU in the left column, 100 AU in the middle column, and 300 AU in the right column. The only difference between these two figures is the cavity shape: the models in Figure 1 have curved cavities, while the models in Figure 2 have conical cavities. The curved cavity models, displayed in Figure 1, have envelope masses ranging from $0.0159(R_{\text{max}}/5000 \text{ AU})^{3/2} M_\odot$ (model in bottom left panel) to $0.336(R_{\text{max}}/5000 \text{ AU})^{3/2} M_\odot$ (model in top right panel). Envelope masses are slightly greater for models with conical cavities since these cavities carve out a smaller fraction of the envelope than the curved cavities. Envelope masses in Figure 2 range from $0.0176(R_{\text{max}}/5000 \text{ AU})^{3/2} M_\odot$ (model in bottom left panel) to $0.359(R_{\text{max}}/5000 \text{ AU})^{3/2} M_\odot$ (model in top right panel). In each figure, the envelope masses are a significant fraction of the stellar mass, $0.5 M_\odot$.

TABLE 3
GRID PARAMETERS: VARIED

Name	r_c (AU)	$\dot{M}_7$ ($10^{-7} M_\odot \text{ yr}^{-1}$)	Cavity Shape	i (deg)	Dust Properties	M_{disk} ($M_\odot$)
Envelope+disk suite 1	10, 100, 300	5, 50, 100	Curved	85	KMH	0.01
Envelope+disk suite 2	10, 100, 300	5, 50, 100	Conical	85	KMH	0.01
Envelope+disk suite 3	10, 100, 300	5, 50, 100	Curved	60	KMH	0.01
Envelope+disk suite 4	10, 100, 300	5, 50, 100	Conical	60	KMH	0.01
Disk-only suite.....	100, 300, 1000	...	...	85	W02 ^a	0.001, 0.01, 0.1

NOTES.—Suites 1–4 correspond to Figs. 1–4, respectively. The envelope, disk, and cavity parameters are described in § 3. The infall rate, $\dot{M}$, assumes a stellar mass of $0.5 M_\odot$ and can be scaled by $(M_*/0.5 M_\odot)^{1/2}$ if the central mass is known.

^a Large grain dust mixture from Wood et al. (2002). See Table 1 for details.

FIG. 1.—Envelope models viewed nearly edge-on, with curved outflow cavities. The three-color (1.14, 1.61, and $2.08 \mu\text{m}$) synthetic images vary envelope mass infall rate and centrifugal radius for sources viewed at an inclination of 85° . From left to right, $r_c = 10, 100$, and 300 AU , and from top to bottom, $\dot{M} = 10^{-5}, 5 \times 10^{-6}$, and $5 \times 10^{-7} M_\odot \text{ yr}^{-1}$. Each model is $3181.36 \text{ AU} \times 3181.36 \text{ AU}$ and is displayed from 0.01 to $300 \mu\text{Jy arcsec}^{-2}$. See Table 2 for additional disk and envelope properties.

The colors and morphology of the reflection nebula are affected by the optical depth through the envelope, which is proportional to $r_c^{-1/2}$ and directly proportional to the mass infall rate (see eq. [3]). Thus, models with the greatest line-of-sight optical depth have high infall rates and small centrifugal radii and are located in the top left panel of Figures 1 and 2.

3.1.1. Variations in Color

In this section we show how observed colors can reveal the evolutionary state of a young stellar object. By “color,” we refer initially to the visual appearance of the three-color images. We quantify this discussion in terms of astronomical colors in § 3.2.2. In § 3.2.1 we show that in addition to colors, the source inclination should also be considered when classifying a source’s evolutionary state.

Reddening of the *scattered* light by the opaque envelope causes models in the top left panel of Figures 1 and 2 (with high infall rates and small disk radii) to appear distinctly red. The envelope mass associated with these models is $\sim 0.3 M_\odot$, slightly more than half the mass of the central star. Near-edge-on sources with red colors similar to these models are likely young sources, still embedded in a massive envelope. Additional reddening could occur if the source is significantly embedded in the molecular cloud.

Models in the bottom right panel of Figures 1 and 2 (with low infall rates and large centrifugal radii) exhibit bluer colors expected from nonreddened scattered light. Envelope masses in these models are as low as $0.02 M_\odot$, suggesting that most of the envelope has dissipated.

As the size of the outflow cavity increases, the source colors become bluer since more of the envelope mass is carved out, and consequently the scattered light is less reddened. Since cavity opening angle is held constant in our grid, we illustrate this point by

FIG. 2.—Envelope models viewed nearly edge-on, with conical outflow cavities. The three-color images vary envelope mass infall rate and centrifugal radius for sources viewed at an inclination of 85° . From left to right, $r_c = 10, 100$, and 300 AU , and from top to bottom, $\dot{M} = 10^{-5}, 5 \times 10^{-6}$, and $5 \times 10^{-7} M_\odot \text{ yr}^{-1}$. Each model is $3181.36 \text{ AU} \times 3181.36 \text{ AU}$ and is displayed from 0.01 to $300 \mu\text{Jy arcsec}^{-2}$. See Table 2 for additional disk and envelope properties.

comparing the results for conical and curved cavities. Curved cavities carve out more envelope mass close to the star than the conical cavities. Comparing each conical cavity model in Figure 2 to its curved cavity counterpart in Figure 1, it is clear that models with conical cavities are typically redder than those with curved cavities.

3.1.2. Variations in Morphology

One of the most striking features in the grid is the shadow cast by the disk in the lower infall rate models (dark regions projecting to the left and right of the central source in the bottom panels of Figs. 1 and 2). In the top panels, the images are brightest in the bipolar cavities; regions of the envelope beyond the cavity walls are dark because the envelope is too optically thick to be illuminated by the central star. But in the bottom panels, where the envelope optical depths are lower, the images are brightest throughout the envelope, *except where they are shadowed by the flared disk*. Such shadows indicate that a very small flared disk can affect the morphology of scattered light at very large scales: a 10 AU disk will shadow roughly 20° of light 1500 AU away from the disk. This effect was discussed in detail by Pontoppidan & Dullemond (2005) and is also evident in observations of ASR 41 (Hodapp et al. 2004). Hodapp et al. (2004) suggest that the shadow in ASR 41 can be produced by a disk source illuminating either a constant density molecular cloud or a low-mass envelope. In either case, the size scale of the shadow is orders of magnitude larger than the size scale of the disk. Since the disk shadow requires a surrounding envelope (or molecular cloud) of low density, its presence is a signpost of a source nearing the end of its envelope phase or a disk-only source embedded in a molecular cloud. The shadow is cast by the upper layers of the outer region of the flared disk. Thus, the inner edge of the shadow marks the outer radius of the disk. This can be used to determine the disk radius, or an upper limit when the inner edge of the shadow is unresolved.

FIG. 3.—Envelope models viewed at 60° inclination, with curved outflow cavities. The three-color images vary the envelope mass infall rate and centrifugal radius. From left to right, $r_c = 10, 100$, and 300 AU, and from top to bottom, $\dot{M} = 10^{-5}, 5 \times 10^{-6}$, and $5 \times 10^{-7} M_\odot \text{ yr}^{-1}$. Each model is $3181.36 \text{ AU} \times 3181.36 \text{ AU}$ and is displayed from 0.01 to $300 \mu\text{Jy arcsec}^{-2}$. See Table 2 for additional disk and envelope properties.

Scattered light is concentrated within the cavity walls for models with massive envelopes. Hence, the model in the top left panel of Figure 1 (with $r_c = 10$ AU and $\dot{M} = 10^{-5} M_\odot \text{ yr}^{-1}$) has a curved morphology, highlighting the curved cavity shape; likewise, the model in the top left panel of Figure 2 appears V shaped due to the conical cavity shape. As infall rate decreases and centrifugal radius increases, the mean free path in the envelope becomes large enough for a substantial number of photons to escape from the cavity before being scattered, as is seen in models in the lower right corner of the grid.

Another effect of the dust opacity law is in the cavity wall appearances. In the case of the conical cavities, the scattered light appears V shaped at shorter wavelengths and curved at longer wavelengths. The variation in morphology with wavelength is especially apparent in the models located in the middle and top right panels of Figure 2. This effect was observed by Padgett et al. (1999) and is due to the fact that longer wavelength light can propagate farther into the cavity walls. The effect is also reproduced in the curved cavity models (Fig. 1). The change in cavity shape with wavelength requires the presence of an envelope, signaling a young evolutionary stage.

In the bottom three models, the envelope is thin enough such that the compact and more dense disk is lit up. The presence of a lit-up disk surrounded by diffuse scattered light in an observed source hints at the presence of a low-mass envelope.

3.2. Inclination

Several features appear quite different at inclinations less than 85° . To illustrate these differences, we display a grid of models with envelopes and disks viewed at an inclination of 60° (Figs. 3 and 4). The inclination is in the sense of the upper hemisphere being tilted toward the observer.

The layout of the models in these grids is the same as in the edge-on envelope+disk models (Figs. 1 and 2). Mass infall rate

FIG. 4.—Envelope models viewed at 60° inclination, with conical outflow cavities. The three-color images vary envelope mass infall rate and centrifugal radius. From left to right, $r_c = 10, 100$, and 300 AU, and from top to bottom, $\dot{M} = 10^{-5}, 5 \times 10^{-6}$, and $5 \times 10^{-7} M_\odot \text{ yr}^{-1}$. Each model is $3181.36 \text{ AU} \times 3181.36 \text{ AU}$ and is displayed from 0.01 to $300 \mu\text{Jy arcsec}^{-2}$. See Table 2 for additional disk and envelope properties.

is varied along the vertical axis ($10^{-5} M_\odot \text{ yr}^{-1}$ in the top row, $5 \times 10^{-6} M_\odot \text{ yr}^{-1}$ in the middle row, $5 \times 10^{-7} M_\odot \text{ yr}^{-1}$ in the bottom row), and centrifugal radius is varied along the horizontal axis (10 AU in the left column, 100 AU in the middle column, 300 AU in the top column). Models have curved cavities in Figure 3 and conical cavities in Figure 4.

3.2.1. Variation in Morphology

For models with massive envelopes (top row in Figs. 3 and 4), the lower half of the reflection nebula is less bright than the upper half. This results from the fact that light from the lower half must travel through more matter to escape the envelope, as noted by Lazareff et al. (1990). As the optical depth in the envelope decreases, the lower half of the nebula obtains the same brightness as the upper half, as is seen in models with lower infall rates. Another interesting feature of the 60° grid is that the cavity walls are brighter than in the 85° grid. This can be seen by comparing the bottom panels of Figures 3 and 4 with the bottom panels of Figures 1 and 2. Also of interest is that the disk becomes lit up for the bottom three models of Figures 3 and 4.

To illustrate the appearance of young sources embedded in envelopes at other inclinations, we plot one of our models ($\dot{M} = 5 \times 10^{-6} M_\odot \text{ yr}^{-1}$, $r_c = 300$ AU) at 10 different inclinations between edge-on and pole-on (Fig. 5). The dynamic range of the images is 1.5×10^4 , typical of observations with CCD cameras, and the plotted intensity is scaled to the peak flux of the image. The diffuse emission *relative to peak flux* is much lower at inclinations less than $\sim 45^\circ$. Since the *total* diffuse emission is only a few percent of the stellar flux (Kenyon et al. 1993a, 1993b; Whitney et al. 1997), it is most easily detected in edge-on sources when the central star is blocked. Unless an observer is looking for faint extended diffuse emission associated with a bright source, they may not integrate long enough to detect the extended

FIG. 5.—Variation of images with cosine of the inclination angle starting from the top left and ending at bottom right ($\cos i = 0.1$ – 1.0 in steps of 0.1) for the envelope+disk model with $\dot{M} = 5 \times 10^{-6} M_{\odot} \text{ yr}^{-1}$ and $r_c = 300 \text{ AU}$. Intensity is displayed from the peak value to 7×10^{-4} times the peak. Additional disk and envelope parameters are listed in Table 2.

emission. Figure 5 shows that less than 30% of sources with large envelopes+disks are expected to reveal extended scattered light structures unless observed at high angular resolution and high dynamic range.

3.2.2. Variation in Color

Intuition tells us that since optical depth through the envelope and disk increases as source inclination becomes more edge-on, the colors of an edge-on source should be redder than those of a source oriented pole-on. In this subsection we show that the colors of a source, defined as the differences in aperture integrated magnitudes, change with inclination in a manner contrary to commonly perceived ideas: colors are reddest at intermediate inclinations ($i \sim 45^\circ$ – 70°) and become bluer again at edge-on inclinations. As discussed in § 3.1.1, the observed colors are also a function of envelope mass. Accurate classifications of evolutionary stage require understanding how these two effects combine to produce the observed source colors.

In Figure 6 we illustrate how the $(H_{160W} - K_{205W})$ colors change with inclination for sources with different infall rates (Fig. 6, *left panel*) and different cavity opening angles (Fig. 6, *right panel*). The magnitudes are converted from fluxes integrated in $3''.8$ radius apertures, using the zero-point fluxes (the flux of Vega) given in the *HST* Data Handbook for NICMOS. In all of the models, colors are reddest at inclinations between 45° and 70° . It is somewhat surprising that the edge-on sources are bluer than intermediate inclinations because the aperture is centered on the dark lane of the 300 AU disk. In fact, models with smaller disks have even bluer edge-on colors, as shown by Kenyon et al. (1993b). Kenyon et al. (1993b) and Whitney et al. (2003a) also showed that the colors become bluer with larger aperture size. To emphasize the importance of scattered light in the calculation, we plot the *extincted-only* colors of an envelope model ignoring the effects of scattering (*dot-dashed line*). Without the blue colors of scattered light, the colors quickly diverge from the other three models, becoming much redder as the inclination moves to edge-on.

The three envelope models (*dotted lines*) used in the left panel of Figure 6 are identical to those in the right column of Figure 1 ($r_c = 300 \text{ AU}$, curved outflow cavity). The infall rates of the models range from 10^{-5} to 5×10^{-6} to $5 \times 10^{-7} M_{\odot} \text{ yr}^{-1}$. With envelope masses ranging from 0.019 to $0.38 M_{\odot}$, all three lines represent young sources still embedded in their envelopes, with the solid line representing the youngest source and the dashed

line the most evolved. Note that models with smaller values of r_c or larger apertures would give bluer colors but with a similar shape. In the right panel of Figure 6, we take the model with an infall rate of $5 \times 10^{-6} M_{\odot} \text{ yr}^{-1}$ from the left panel of Figure 6 and vary the cavity opening angle from 10° (*dot-dashed line*), 25° (*dotted line*), and 35° (*dashed line*). Not surprisingly, the effects of varying cavity opening angle are similar to varying envelope infall rate.

Several patterns are immediately apparent in Figure 6: (1) as inclination angle moves from pole-on to edge-on, the $(H_{160W} - K_{205W})$ color becomes redder, peaks at some inclination, and then moves bluerward; (2) the inclination at which a source reaches its peak red ($H_{160W} - K_{205W}$) color is higher (i.e., closer to edge-on) for smaller infall rates (Fig. 6, *left panel*); and (3) the $(H_{160W} - K_{205W})$ colors at near-edge-on inclinations become redder as infall rate increases.

Each of these patterns can easily be understood as radiative transfer effects. The change in colors with inclination is due to

FIG. 6.—*Left:* $(H_{160W} - K_{205W})$ colors of three envelope models with varying infall rates from our grid as a function of inclination. The colors are calculated in $3''.8$ radius apertures. The three models (*dotted lines*) shown here correspond, from top to bottom, to those shown in the right column of Fig. 1. For reference, we show the extincted-only colors of an envelope model (*solid line*) with model parameters identical to those denoted by the middle dotted line ($\dot{M} = 5 \times 10^{-6} M_{\odot} \text{ yr}^{-1}$; $\cos i = 1$ is pole-on). *Right:* $(H_{160W} - K_{205W})$ colors of three envelope models with varying outflow cavity sizes. The model parameters (save the cavity size) are identical to the middle model in the right column of Fig. 1 ($\dot{M} = 5 \times 10^{-6} M_{\odot} \text{ yr}^{-1}$). The cavity sizes plotted are 10° (*dot-dashed line*), 25° (*dotted line*), and 35° (*dashed line*). Again, for reference, we show the extincted-only colors of an envelope model (*solid line*) with model parameters identical to those of the model represented by the dotted line.

the asymmetric distribution of matter around a young stellar object. At all inclinations, both diffuse scattered light and direct stellar light contribute to the flux. In pole-on sources, the light observed is dominated by direct star light, reddened by the small amount of dust in the outflow cavity. As noted in Kenyon et al. (1993b), roughly 2% of the light emitted by the central source in K is scattered; hence, greater than 4 mag of extinction are needed before the scattered light begins to dominate the observed flux. As inclination increases, the line of sight begins to intercept part of the dense envelope and less of the cavity, causing the central source to be more heavily extinguished and observed colors to be redder. Eventually, the extinction is high enough for the flux to be dominated by scattered light in H_{160W} . Meanwhile the flux at longer wavelengths, K_{205W} , continues to decrease, causing the $H_{160W} - K_{205W}$ colors to begin to shift blueward.

Knowledge of the envelope mass and inclination alone is not sufficient to predict near-IR colors. As noted in Kenyon et al. (1993b), increasing the cavity size results in bluer ($H_{160W} - K_{205W}$) colors at most inclinations because the scattered light is reddened less in its path (Fig. 6, *right panel*).

Taking the envelope mass infall rate as a proxy for the evolutionary state, we see in Figure 6 that it is not possible to directly correlate a single color (e.g., $H_{160W} - K_{205W}$) with the evolutionary state of a source. For example, in the left panel of Figure 6, the $H_{160W} - K_{205W}$ color of the source with the lowest infall rate at $\cos i \simeq 0.2$ (*lower dotted line*) is almost as red as the source with the middle infall rate (*middle dotted line*) in spite of the fact that their envelope masses differ by a factor of 10. Allowing cavity size to vary (Fig. 6, *right panel*) would create additional difficulties in directly correlating color with infall rate. Clearly, inferences of a young source's evolutionary stage require multiple source parameters to be fitted simultaneously. If a source is viewed at a high enough inclination for its flux to be dominated by scattered light, then this becomes feasible. The inclination can be estimated by the asymmetry of the scattered light nebulae, while the cavity opening angle can be obtained by the scattered light morphology. With these additional source parameters constrained and a reasonable set of envelope dust properties, the mass infall rate can be estimated.

3.3. Derivation of Extinction from Near-Infrared Colors

An important insight stemming from our models is that the line-of-sight extinction to the central source of an embedded object at near-edge-on inclination cannot be derived in the near-infrared by dereddening colors. This can be seen by comparing extinction at V band, A_V , derived from near-IR colors to that derived from longer wavelengths (e.g., Myers et al. 1987; Barsony & Kenyon 1992). This was usually attributed to excess disk emission in the near-IR, but one-dimensional radiative transfer models could not simultaneously fit the near-IR and far-IR (Adams et al. 1987; Kenyon et al. 1993a). However, two-dimensional models that include scattering can fit the near-IR flux (Kenyon et al. 1993b; Whitney et al. 2003a, 2003b). At these wavelengths, the observed flux in a given aperture includes contributions from both direct and scattered light. At high inclinations (near edge-on), scattered light dominates flux observed in the J_{110W} and H_{160W} bands, shifting $J_{110W} - K_{205W}$ and $H_{160W} - K_{205W}$ colors blueward and away from a standard reddening line (Kenyon et al. 1993b). In this case, deriving the extinction by dereddening the observed colors to the value expected for a T Tauri star in Taurus will underestimate the true extinction.

Figure 7 shows the deviation of the extinction derived from colors (hereafter the apparent extinction) from the true extinction

FIG. 7.—The $\log A_V$ vs. inclination for one of our envelope models with an infall rate of $5 \times 10^{-6} M_{\odot} \text{ yr}^{-1}$, $M_{\text{env}} = 0.17 M_{\odot}$, $r_c = 100 \text{ AU}$, and $M_{\text{disk}} = 0.01 M_{\odot}$. The dotted line plots $\log A_V$ calculated from colors (apparent extinction), while the solid line plots $\log A_V$ calculated from known density distribution of models (true extinction). The apparent extinction approximates the true extinction very closely at low inclinations but diverges significantly from the true extinction at high inclinations where the observed light is predominantly scattered. Note that the vertical axis is logarithmic.

using a model from our grid with an infall rate of $5 \times 10^{-6} M_{\odot} \text{ yr}^{-1}$, $M_{\text{env}} = 0.17 M_{\odot}$, $r_c = 100 \text{ AU}$, and $M_{\text{disk}} = 0.01 M_{\odot}$. The true extinction of the model is calculated by integrating the density distribution along the line of sight to the star to find the optical depth at V , τ_V , and then calculating A_V ($A_V = 1.086 \tau_V$). The apparent extinction is derived as follows: $A_V = [(H_{160W} - K_{205W}) - (H_{160W} - K_{205W})_0] [\kappa_V / (\kappa_H - \kappa_K)]$, where $H_{160W} - K_{205W}$ is the model color in the observed aperture, and $(H_{160W} - K_{205W})_0 = 0.45$, typical intrinsic colors for T Tauri stars in Taurus (Kenyon & Hartmann 1995). The opacities κ_h and κ_k are given in Table 1. The visual opacity κ_V is equal to $221 \text{ cm}^2 \text{ g}^{-1}$ in the KMH grain model.

The true extinction is very small at inclinations near pole-on due to the cavity cleared out by the outflow. At these inclinations, the light is dominated by direct light from the central object rather than scattered light; hence, deriving the extinction from colors provides a reasonable estimate of the true extinction. The true extinction diverges from the apparent extinction at high inclinations, where nearly all light observed has been scattered by the disk or envelope.

The results presented in Figure 7 are slightly model dependent. For example, increasing the size of the outflow cavity will make the true extinction comparable to the extinction derived from colors for a larger range of inclinations. In addition, the colors are aperture dependent, as discussed in Kenyon et al. (1993b) and Whitney et al. (2003a). Regardless, the general point remains valid: deriving the line-of-sight extinction to the central source of a young stellar object by dereddening near-IR colors underestimates the true extinction whenever the source's inclination is high enough that the observed light is predominantly scattered.

3.4. Disk-only Models Viewed Edge-on

In the previous sections we have investigated models of young sources embedded in envelopes of gas and dust (along with disks)

FIG. 8.—Grid of disk-only models viewed at 85° inclination. Disk radius is varied horizontally (100, 300, and 1000 AU). Disk mass is varied vertically, $0.001 M_\odot$ in the bottom row, $0.01 M_\odot$ in the middle row, and $0.1 M_\odot$ in the top row. The dust grains of the disk-only models are larger than grains used to model envelopes (see Table 3). Each model is $3181.36 \text{ AU} \times 3181.36 \text{ AU}$ and is displayed from 0.01 to $300 \mu\text{Jy arcsec}^{-2}$.

and outflow cavities). Here we present models of more evolved sources that have no surrounding envelopes and discuss observable differences between the two evolutionary stages.

In Figure 8 we display a grid of our models containing flared disks without envelopes viewed at 85° inclination. Larger dust grains are employed in these models to account for grain growth expected in this phase of evolution (see Table 1 for properties).

The radius of the disk is varied along the horizontal axis (*left to right*: 100, 300, and 1000 AU), and disk mass is varied vertically (*bottom to top*: 0.001, 0.01, and $0.1 M_\odot$). The parameter space sampled in the grid was chosen to illustrate a range of physical properties exhibited in disk-only sources.

Several differences stand out when compared to the models with infalling envelopes. The absence of matter falling onto the disk creates a substantially lower optical depth, resulting in images that do not have the red colors seen in the envelope+disk models with high infall rates. With all of the matter distributed in the disk, scattered light is not visible at large radii ($\sim 10^3 \text{ AU}$) above the central source as it is in the models with an envelope. Likewise, scattered light is not as extended horizontally in the disk-only models. Thus, disk-only sources likely subtend a smaller solid angle than sources still embedded in envelopes, assuming that both are observed with the same sensitivity, resolution, and wavelengths.

A common interpretation of observed sources is that of disks with bipolar outflows but no envelopes. We present two edge-on models in Figure 9 to illustrate the resulting source colors of such a configuration. The outflow cavity is filled with KMH dust (see Table 2 for properties), causing scattered light to be extended vertically to similar distances as in models with an infalling envelope (Figs. 1 and 2). However, the colors are again not nearly as red as the models with a disk surrounded by an envelope of matter with a high infall rate. In addition, no shadowing by the

FIG. 9.—Star-disk system with an outflow cavity and no infalling envelope. *Left*: $r_{\text{disk}} = 100 \text{ AU}$; *right*: $r_{\text{disk}} = 300 \text{ AU}$. Both models are $3181.36 \text{ AU} \times 3181.36 \text{ AU}$ and are displayed from 0.01 to $300 \mu\text{Jy arcsec}^{-2}$.

disk is observed because there is no envelope to provide a screen against which any shadowing may be seen.

4. *HST* NICMOS DATA OF YOUNG STELLAR OBJECTS IN TAURUS

Padgett et al. (1999) have presented *HST* NICMOS images of six young stellar objects in the Taurus star-forming region. Three of the six sources (IRAS 04016+2610, IRAS 04248+2612, IRAS 04302+2247) are Class I objects identified by *IRAS*, and the other three (CoKu Tau/1, Haro 6-5B, DG Tau B) are low-luminosity stars associated with Herbig-Haro outflows. The observations comprise images in the J_{110W} , H_{160W} , F187W, and K_{205W} filters (i.e., $1.1\text{--}2 \mu\text{m}$) with the NIC2 detector, with a spatial resolution (after PSF subtraction) of $\sim 15 \text{ AU}$.

These six objects are ideal case studies for our modeling purposes because all six objects exhibit bipolar scattered light nebulae and are crossed by dark lanes, most likely arising from circumstellar disks seen nearly edge-on. These systems thus allow us to probe such details as circumstellar disk structure (size, flaring, etc.) and circumstellar envelope structure (bipolar cavities, density profile, etc.).

The NICMOS data were obtained from the *HST* archive and were rereduced using the IRAF STSDAS package with the most recent set of reference files available. We created bad pixel masks using the data quality frames associated with each image, manually masking transient bad pixels and the bad column 128 (Bergeron & Skinner 1997). For the NICMOS data, the subsets of each image association were registered and combined using the IRAF STSDAS pipeline `calnircb` task.

In order to subtract the PSF from each of the recalibrated *HST* images, we rebinned the images by a factor of 2 and deconvolved them using PSFs computed with Tiny Tim version 4.4 (Krist 1997), which were also oversampled by a factor of 2. The deconvolution was performed within IRAF using the STSDAS `lucy` task, which uses a Richardson-Lucy-based algorithm. The deconvolution process is an iterative one, and we stopped the process after five iterations in the J_{110W} filter, 10 iterations in H_{160W} , 15 iterations in F187W, and 20 iterations in K_{205W} .

5. APPLICATION OF MODELS TO OBSERVATIONS

In this section we apply our models to interpret *HST* NICMOS observations of young stellar objects in Taurus. We use the grid of models presented above to interpret these data and to place constraints on relevant disk and envelope parameters. Parameters used in our best-fit models are presented in Table 4.

Comparing the colors and morphology of the observations to our grid of models (Figs. 1–4 and 8), we obtain preliminary

TABLE 4
MODEL PARAMETERS FOR FITS TO NICMOS SOURCES

Model	$\dot{M}_6$ ($10^{-6} M_\odot \text{ yr}^{-1}$)	r_c (AU)	M_{disk} ($M_\odot$)	i (deg)	θ_{cav} (deg)	ρ_{cav} ($10^{-19} \text{ g cm}^{-3}$)	Luminosity ($L_\odot$)	A_V Cavity
IRAS 04302+2247.....	2.5	300	0.07	85	25	$3.5 r^{0.0}$	0.44	5.2
DG Tau B	5.0	300	0.04	73	30	$1.0 r^{-0.5}$	0.2	6.1×10^{-3}
IRAS 04016+2610.....	10.0	300	0.01	65	25	$1.5 r^{0.0}$	3.70	3.0
IRAS 04248+2612.....	1.0	50	0.01	76	20	$6.0 r^{0.0}$	0.37	8.9
CoKu Tau/1	0.2	50	0.01	64	20	$1.0 r^{-0.5}$	0.3	6.1×10^{-3}
Haro 6-5B	...	275	0.02	74	...	...	0.50	...

NOTES.—Parameter i is the inclination of the polar angle with respect to line of sight. Parameter θ_{cav} is the cavity opening angle. IRAS 04302+2247, IRAS 04248+2612, and CoKu Tau/1 have curved cavities with $z = a\varpi^{1.5}$ (see § 2.3). IRAS 04016+2610 and DG Tau B have streamline-shaped cavities. The streamline hole size of DG Tau B is 50 AU. The disk of our IRAS 04302+2247 model has flaring parameters, $\beta = 1.2$ and $\alpha = 2.165$. The IRAS 04248+2612 model has a 25 AU hole in the center of the disk. Parameters not mentioned above are the same as in Table 1. The infall rate, $\dot{M}$, assumes a stellar mass of $0.5 M_\odot$ and can be scaled by $(M_*/0.5 M_\odot)^{1/2}$ if the central mass is known.

estimates of the centrifugal radius of the disk, the inclination, and the mass infall rate. We next create a new set of models varying infall rate by $\pm 25\%$, 50% , 100% , and 200% , inclination by $\pm 5\%$, 10% , 15% , 20% , . . . , and centrifugal radius by $\pm 10\%$, 15% , 20% , Examining each of these by eye, we define the range of infall rates, inclinations, and centrifugal radii that produce reasonable fits to the data. We estimate the percentage errors in our fits to be approximately 50% for $\dot{M}$, since it is affected by uncertainties in the grain model and stellar mass, 30% for r_c and luminosity, 15% for i , 10% for θ_{cav} , and 50% for ρ_{cav} and $A_{V,\text{cav}}$. The models are not very sensitive to disk mass; thus, the errors in the disk masses derived from our fits are at least a factor of 2. We do not claim to do better by modeling near-IR images alone. Modeling of the complete SED in conjunction with the images would better estimate source luminosity, stellar temperature, and therefore stellar mass and disk mass, which would then better constrain the other parameters in the images; for example, the uncertainty in the stellar temperature alone causes an uncertainty in the near-IR colors that affect the derived envelope infall rate, and the derived infall rate also has a modest dependence on stellar mass (eq. [1]).

The source luminosities are initially estimated from Padgett et al. (1999) or Kenyon & Hartmann (1995). We then further adjust the luminosity to fit the image intensity values, as needed.

5.1. IRAS 04302+2247

Of the six *HST* NICMOS sources, IRAS 04302+2247, shown in Figure 10, exhibits the most striking example of an obscuring

FIG. 10.—IRAS 04302+2247 *HST* NICMOS image and corresponding model. The image sizes for Figs. 10–15 are $11''.4 \times 11''.4$, assuming a distance for the models of 140 pc. North is up and east is to the left in Figs. 10–15. The model infall rate is $\dot{M} = 2.5 \times 10^{-6} M_\odot \text{ yr}^{-1}$. Additional model parameters are described in Table 4. The range of intensities displayed is $0.01\text{--}47 \mu\text{Jy arcsec}^{-2}$.

dust lane. The dust lane exhibits very little curvature (indeed, it is nearly rectangular) except at the edges where it begins to fan out. The horizontal extent of the observed dust lane is ~ 700 AU; the vertical extent decreases with increasing wavelength, from 250 AU at K_{205W} to 340 AU at J_{110W} (Padgett et al. 1999). This object's integrated colors in a $3''.8$ aperture ($J_{110W} - H_{160W} = 3.11$, $H_{160W} - K_{205W} = 1.01$) are similar to some of the models shown in Figure 6, not surprisingly since the left panel of Figure 6 shows $r_c = 300$ AU models. The colors agree reasonably well with those calculated from the Padgett et al. (1999) measured fluxes. When integrated in larger apertures, the colors of this source are fairly blue compared to other Taurus Class I sources (Kenyon et al. 1993a, 1993b) because more scattered light is added to the beam. The large extinction lane and moderately blue colors do not, however, require this source to be nearing the end of its envelope-dominated stage; rather, our models suggest that a substantial amount of gas and dust must be present in the envelope to match the observed colors and morphology.

Kenyon & Hartmann (1995) estimate a bolometric luminosity of $0.34 L_\odot$ for this source. We required a source luminosity of $0.44 L_\odot$ to fit the intensity of the near-IR images. Whitney et al. (2003b) showed that the observationally derived bolometric luminosity is inclination dependent with more edge-on sources having a lower bolometric luminosity than the true luminosity, by 50% in the example model they showed (with curved bipolar cavity). Our requirement of a luminosity 30% higher than the bolometric luminosity measured by Kenyon & Hartmann (1995) is consistent with this.

Following the procedure discussed at the beginning of this section, we create a new grid of models to find the range of parameters that produce reasonable fits to the observed near-IR image. To match the observed colors and vertical extent of the nebulosity, we require the presence of a large, relatively massive envelope [$M_{\text{env}} \sim 0.12(R_{\text{env}}/5000 \text{ AU})^{3/2} M_\odot$] with a mass infall rate of $2.5 \times 10^{-6} M_\odot \text{ yr}^{-1}$. For this source, we require a centrifugal radius ~ 300 AU with modestly more flaring than the models in our grid ($\beta = 1.2$ and $\alpha = 2.165$). These flaring parameters are well within the range expected for T Tauri disks (Kenyon & Hartmann 1995). To match the brightness of the scattered light within the cavity walls requires more dust in the cavity than the models in our grid. The model presented in Figure 10 has A_V of ~ 5 along the polar axis from the star to R_{env} . Even with more dust in the cavity, the scattered light within the cavity walls is not as bright relative to the rest of the image as the *HST* image. The discrepancy could be explained if dust properties in IRAS 04302+2247 differ from those used in our models or if dust in the cavity is clumpy.

FIG. 11.—DG Tau B *HST* NICMOS image and corresponding model. Model parameters are described in Table 4. The range of intensities displayed is $0.07\text{--}208 \mu\text{Jy arcsec}^{-2}$.

Our grid of models indicates that a circumstellar disk alone cannot reproduce the observed colors and morphology of the reflection nebula. This is most easily seen by contrasting this object to our disk-only models (Fig. 8) and the disk+outflow models (Fig. 9). While the disk-only models do show a dark dust lane, the upper and lower edges of the disk appear brightly illuminated due to light from the central source scattering in the lower density regions of the flared disk. Furthermore, both the disk-only and disk+outflow models exhibit colors that are bluer than those observed in this source. For disk-only models and disk+outflow models displayed in Figures 8 and 9, the $(J_{110W} - H_{160W})$ colors vary from 0.68 to 1.37 and the $(H_{160W} - K_{205W})$ colors vary from 0.34 to 1.04 (both integrated over a $3''.8$ aperture). The addition of an envelope serves both to attenuate the scattered light from the disk and to redden the overall colors of the source. There is also some hint of cavity edges, which of course requires the presence of an envelope.

The point here is that the intuitive picture of IRAS 04302+2247 as a “TTS-like” object, with an edge-on disk and clumpy bipolar material, is likely not correct. Rather, our models suggest that IRAS 04302+2247 should be regarded as an object in a relatively early stage of evolution, still surrounded by a massive, infalling envelope.

We note that our derived mass infall rate is a factor of ~ 30 greater than those presented by Wolf et al. (2003). Wolf et al. (2003) only included the dust mass in their calculation of envelope mass (S. Wolf 2005, private communication). Multiplying their result by the same gas-to-dust ratio that we assume, 100, our envelope infall rates are lower than theirs by a factor of 3. However, their envelope outer radius was only 450 AU, an order of magnitude smaller than ours, so it is not surprising that they required a higher infall rate to fit the near-IR images.

5.2. DG Tau B

Our models indicate that DG Tau B, shown in Figure 11, is morphologically and evolutionarily similar to IRAS 04302+2247. The NICMOS images prominently show a dark dust lane that divides the source. The integrated colors, too, are similar to IRAS 04302. DG Tau B also shows bipolar material that appears in scattered light from the central source.

DG Tau B does show some interesting differences, however, compared to IRAS 04302+2247. In particular, the system inclination appears to be somewhat less edge-on than in IRAS 04302+2247. This is evident by virtue of the fact that the central source is visible (in the K_{205W} image only) and that the upper and lower bipolar reflection nebulae are distributed and illuminated much less symmetrically than is the case for IRAS 04302+2247.

FIG. 12.—IRAS 04016+2610 *HST* NICMOS image and corresponding model. Model parameters are described in Table 4. The range of intensities displayed is $0.15\text{--}150 \mu\text{Jy arcsec}^{-2}$.

Furthermore, the shape of the cavity in lower reflection nebulae of DG Tau B appears morphologically different from those in IRAS 04302+2247. The cavity in DG Tau B has linear edges, forming a distinct V shape, in contrast to the curved cavities in IRAS 04302+2247.

Our model presented in Figure 11 reproduces many of the features mentioned above. The model has an inclination of $\sim 73^\circ$ and a circumstellar disk with $r_c \sim 300$ AU. More importantly, as with IRAS 04302+2247, a massive infalling envelope with an infall rate of $\sim 5 \times 10^{-6} M_\odot \text{yr}^{-1}$ is required to explain the NICMOS observations. As with IRAS 04302+2247, models that lack a massive envelope do not correctly predict the highly reddened colors observed; further, the illumination of the dark dust lane is strikingly different. Kenyon & Hartmann (1995) place a lower limit of $>0.02 L_\odot$ on the bolometric luminosity of this source. Since this source is near an optically bright T Tauri star (DG Tau), it is likely that the *IRAS* flux was originally assigned to that source. We find that matching the observed intensity requires a luminosity of at least $0.2 L_\odot$.

Our best model also requires a conical cavity to reproduce the observations. While our models do not shed much light on the nature of the cavity beyond its morphology, they do indicate that these sources do possess multiple cavity morphologies that are distinct from one another. A curved cavity like that used in our IRAS 04302+2247 model does not closely resemble the observed cavity in DG Tau B. The cavity is evacuated to match the lack of scattered light within the cavity walls in the *HST* NICMOS image (see Table 4 for density distribution).

As noted by Padgett et al. (1999), the shape of the cavity is a function of wavelength, appearing more V shaped at shorter wavelengths and more curved at longer wavelengths. Our grid of models explains this naturally as a radiative transfer effect: longer wavelength light propagates farther into cavity walls than shorter wavelength light.

5.3. IRAS 04016+2610

The colors and SED of IRAS 04016+2610 (Fig. 12) indicate a young embedded state with $L_{\text{bol}} = 3.7 L_\odot$ (Kenyon & Hartmann 1995). While the NICMOS images reveal a very complicated circumstellar environment, our models suggest an envelope-dominated status for this object.

Unlike the relatively symmetric reflection nebulae observed in IRAS 04302+2247 and DG Tau B, IRAS 04016+2610 shows a much more complicated structure, perhaps due to the impact of multiple outflows on the infalling envelope (Gómez et al. 1997; Lucas et al. 2000; Wood et al. 2001). Submillimeter observations

FIG. 13.—IRAS 04248+2612 *HST* NICMOS image and corresponding model. Model parameters are described in Table 4. The range of intensities displayed is $0.01\text{--}316 \mu\text{Jy arcsec}^{-2}$.

find two peaks of emission suggestive of a close (~ 20 AU) binary (Hogerheijde & Sandell 2000). As noted by Padgett et al. (1999), the $J_{110\text{W}}$ and $H_{160\text{W}}$ images show evidence for an absorbing dust lane just north of the central star.

Of the six sources in our sample, IRAS 04016+2610 is the reddest, which, in the context of our models, suggests a massive envelope. Owing to the visible central star in the $K_{205\text{W}}$ NICMOS image, we infer that this object is not observed edge-on. Varying the inclination by $\pm 5\%$, 10% from our grid's 60° inclination models, we find best agreement between the model and observed near-IR image with an inclination angle of $\sim 65^\circ$. With this inclination, matching the observed red colors requires an envelope infall rate of $\dot{M} = 1.0 \times 10^{-5} M_\odot \text{ yr}^{-1}$ integrating the resulting envelope density distribution results in an envelope mass of $0.37(R_{\text{env}}/5000 \text{ AU})^{3/2} M_\odot$ indicative of a young embedded source. A luminosity of $3.7 L_\odot$ fits the intensity of the images and is in agreement with the L_{bol} estimate of Kenyon & Hartmann (1995). Interestingly, the luminosity correction factor suggested by Whitney et al. (2003b) is only about 10% at this viewing angle, in agreement with our similarities between L and L_{bol} .

Previous modeling of this source in Eisner et al. (2005) also suggests the presence of a massive infalling envelope and an embedded disk. Their best-fit model for this system has an infall rate of $6 \times 10^{-6} M_\odot \text{ yr}^{-1}$, a centrifugal radius of 100 AU, and an inclination of 53° ; each parameter value is broadly consistent with our analysis of the source. The three-dimensional nature of this source makes it more difficult to model, so our parameter estimates are less certain for this source than others. Since Eisner et al. (2005) modeled the SED as well as I -band images, their parameter estimates are probably more accurate.

As with DG Tau B, the morphology of the reflection nebula is a function of wavelength. At $1 \mu\text{m}$, the nebulosity is V shaped, with roughly straight edges. But at $1.6 \mu\text{m}$, the edges defining the cavity are considerably more curved. Our models reproduce this wavelength-dependent behavior, providing additional evidence for our picture of this source as being surrounded by a massive envelope with bipolar cavities.

5.4. IRAS 04248+2612

This source differs substantially from those discussed above in its integrated colors. Being characterized by a bluer SED, one might infer that IRAS 04248+2612 has a lower mass envelope and so is a somewhat more evolved object. The upper and lower halves of the reflection nebula are of equal brightness, which suggests a near-edge-on orientation. Our IRAS 04248+2612 model (Fig. 13), equipped with an inclination of $\sim 76^\circ$, shows

FIG. 14.—CoKu Tau/1 *HST* NICMOS image and corresponding model. Model parameters are described in Table 4. The range of intensities displayed is $0.13\text{--}3981 \mu\text{Jy arcsec}^{-2}$.

that this source requires the presence of a low-mass envelope [$M_{\text{env}} \sim 0.076(R_{\text{env}}/5000 \text{ AU})^{3/2} M_\odot$] with mass infall rate $1.0 \times 10^{-6} M_\odot \text{ yr}^{-1}$, supporting the assumption that this source has nearly dispersed its envelope. We find that the luminosity of $0.37 L_\odot$ quoted by Kenyon & Hartmann (1995) reproduces the images well. In this case, the correction factor of Whitney et al. (2003b) would lead to an overestimate.

The evolutionary stage classification is supported by the presence of the disk shadow in IRAS 04248+2612. As discussed in § 3.1.2, the shadow appears most striking in models with low-mass envelopes.

An interesting feature of this source is that, despite having a nearly edge-on disk, the central binary is quite visible. Perhaps we can understand this in terms of the binary (with a projected separation of ~ 25 AU) having dynamically cleared an inner hole in the circumbinary disk. Such a hole reduces the extinction through the disk, allowing the central source to become visible if the envelope is thin enough. To reproduce this effect, we equip our models for this source with a 25 AU hole in the center of the disk.

Note that while this source's colors are indicative of a somewhat more evolved evolutionary state, our models do clearly show that a low-mass envelope is required to successfully model the observed scattered light morphology. In particular, a model with no envelope cannot reproduce the observed disk shadow, which only results in our models when the shadow of the disk can project onto the screen of an infalling envelope.

5.5. CoKu Tau/1

Compared to IRAS 04248+2612, CoKu Tau/1 (Fig. 14) exhibits similar integrated colors, but a distinctly different bipolar morphology. Indeed, the bipolar morphologies appear as “inverses” of one another, with CoKu Tau/1 showing clearly demarcated bipolar cavities and relatively little emission inside those cavities, whereas the emission from IRAS 04248+2612 does not appear very “cavity-like” at all. From our grid of models we believe that this difference can be accounted for in terms of different system inclinations.

Matching the observed colors and morphology clearly requires an intermediate inclination of $\sim 64^\circ$ and the presence of an infalling envelope with infall rate of $\sim 2 \times 10^{-7} M_\odot \text{ yr}^{-1}$, corresponding to a relatively low mass envelope [$0.007(R_{\text{env}}/5000 \text{ AU})^{3/2} M_\odot$]. This suggests that, like IRAS 04248+2612, CoKu Tau/1 is nearing the end of its embedded phase. Kenyon & Hartmann (1995) assigned a luminosity of $>0.29 L_\odot$ for this source. We find that a luminosity of $0.3 L_\odot$ produces the correct intensity levels in the

FIG. 15.—Haro 6-5B *HST* NICMOS image and corresponding model. Model parameters are described in Table 4. The range of intensities displayed is 0.05–517 $\mu\text{Jy arcsec}^{-2}$.

images. White & Hillenbrand (2004) suggest that CoKu Tau/1 is a Class II source. Given the very low mass of our envelope, the distinction between our model fits and the White & Hillenbrand (2004) class may be a matter of semantics.

5.6. Haro 6-5B

The observations of Haro 6-5B indicate that it is more evolved compared to the other objects in our sample. In many of the other objects, an extended circumstellar envelope manifests itself as an extended scattered light nebosity that is relatively red in color due to reddening of the scattered light through the ~ 5000 AU envelope. In Haro 6-5B, however, we see little evidence for extended emission that might be associated with an envelope. Instead, the observations very much resemble our models in which only a (flared) circumstellar disk is present (Fig. 8). High-resolution millimeter observations suggest a disk radius of 309 AU, a disk mass of $0.021 M_{\odot}$, and an inclination of 67° (Yokogawa et al. 2001).

Our model for Haro 6-5B (Fig. 15) includes a flared disk with $r_{\text{disk}} = 275$ AU at $i = 74^{\circ}$. At this inclination, the central source can be seen over the edge of the disk, and the asymmetry in the upper and lower halves of the disk corroborates this inclination angle as well. We require a bolometric luminosity of $\geq 0.5 L_{\odot}$ to match the observed brightness of the scattered light of this source. The disk mass of the best-fit model is $0.02 M_{\odot}$; this mass produces the best agreement between the vertical extent of the model and observed extinction lane. This is in good agreement with the millimeter observations, suggesting that our large grain model for disks may not be too unreasonable.

Another line of evidence supporting our interpretation of no significant envelope is the blue color of the illuminated material (designated R1 by Mundt et al. 1991) $10''$ to the northeast. This indicates that the material is seen in singly scattered light from the source, with little or no intervening material to redden that scattered light. White & Hillenbrand (2004) assign a Class II evolutionary state, consistent with our results.

While the morphology of Haro 6-5B clearly indicates that it is in a disk-dominated stage, the colors of the nebula surrounding the disk are redder than those in our disk-only models (Fig. 8). This could be explained if Haro 6-5B is significantly embedded in its host molecular cloud; 10 mag of extinction (at V) are required to reproduce the observed colors. Alternatively, the dust grains in Haro 6-5B may be larger than those employed in our disk-only models, which would also shift the near-IR colors redward.

6. SUMMARY

We have created a grid of synthetic images of envelope and disk-only sources to illustrate the effects of varying physical properties (e.g., centrifugal radius, outflow cavity shape, source inclination, and evolutionary stage) on the color and morphology of the near-infrared scattered light. Using our grid, we infer the evolutionary stage, envelope mass, and disk size of the six young stellar objects observed at high resolution with *HST* NICMOS (Padgett et al. 1999). The primary conclusions of this study are as follows:

1. Accurate modeling of source colors generally requires including the effects of both a disk and an infalling envelope. Five of the six young stellar objects observed by Padgett et al. (1999) require the presence of a disk and an infalling envelope for our models to match their colors. Although some of the sources may look like disks with outflows and no envelopes, they are all (except Haro 6-5B) surrounded by envelopes (although some are low mass).

2. Sources embedded in envelopes of gas and dust may exhibit several morphological signatures, including (a) a large (≈ 1000 AU) disk shadow caused by a much smaller (≈ 100 AU) flared disk and (b) varying cavity wall morphologies with changing wavelength. The disk shadow is most striking in sources nearing the edge of their embedded stage since it is most distinct in the presence of a low-mass envelope [$M_{\text{env}} \sim (0.01-0.1)(R_{\text{env}}/5000 \text{ AU})^{3/2} M_{\odot}$]; it is apparent in IRAS 04248+2612 and CoKu Tau/1 and is also present in our grid. In both of the models and in IRAS 04016+2610, the cavity walls appear V shaped at shorter wavelengths and curved at longer wavelengths. Not all embedded sources will exhibit such characteristics, but the synthesis of observed colors and morphology should provide the means necessary to accurately classify the evolutionary stage.

3. The disk shadows seen in the midplane regions in IRAS 04248+2612 and CoKu Tau/1 may be mistaken as large flared disks; however, our grid of models shows that these are large shadows created by a small flared disk (§ 3.1.2). This phenomenon was also studied by Hodapp et al. (2004) and Pontoppidan & Dullemond (2005).

4. The colors of a given source are a function of both envelope mass and inclination. For a given inclination and cavity size, the greater the envelope mass, the redder the source. However, sources with near-edge-on inclinations have bluer near-infrared colors than sources with intermediate inclinations. It is thus imperative that the inclination be considered when determining the evolutionary state of a source. Inferences based on color alone may be oversimplistic.

5. The colors of edge-on protostars cannot be used to derive extinction A_V through the envelope and disk unless scattering is included in the computation (i.e., by solving the radiative transfer equation).

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REFERENCES

- Adams, F. C., Lada, C. J., & Shu, F. H. 1987, *ApJ*, 312, 788
- Barsony, M., & Kenyon, S. J. 1992, *ApJ*, 384, L53
- Bergeron, L. E., & Skinner, C. J. 1997, in *The 1997 HST Calibration Workshop with a New Generation of Instruments*, ed. S. Casertano et al. (Baltimore: STSci), 240
- Burrows, C. J., et al. 1996, *ApJ*, 473, 437
- Cassen, P., & Moosman, A. 1981, *Icarus*, 48, 353
- Chiang, E. I., & Goldreich, P. 1997, *ApJ*, 490, 368
- Cotera, A., et al. 2001, *ApJ*, 556, 958
- D'Alessio, P., Calvet, N., & Hartmann, L. 2001, *ApJ*, 553, 321
- D'Alessio, P., Cantó, J., Calvet, N., & Lizano, S. 1998, *ApJ*, 500, 411
- Eisner, J. A., Hillenbrand, L. A., Carpenter, J. M., & Wolf, S. 2005, *ApJ*, 623, 952
- Gómez, M., Whitney, B. A., & Kenyon, S. J. 1997, *AJ*, 114, 265
- Hartmann, L. 1998, *Accretion Processes in Star Formation* (Cambridge: Cambridge Univ. Press)
- . 2002, *ApJ*, 578, 914
- Hodapp, K. W., Walker, C. H., Reipurth, B., Wood, K., Bally, J., Whitney, B. A., & Connelley, M. 2004, *ApJ*, 601, L79
- Hogerheijde, M. R., & Sandell, G. 2000, *ApJ*, 534, 880
- Kenyon, S. J., Calvet, N., & Hartmann, L. 1993a, *ApJ*, 414, 676
- Kenyon, S. J., & Hartmann, L. 1995, *ApJS*, 101, 117
- Kenyon, S. J., Whitney, B., Gómez, M., & Hartmann, L. 1993b, *ApJ*, 414, 773
- Kim, S.-H., Martin, P. G., & Hendry, P. D. 1994, *ApJ*, 422, 164 (KMH)
- Krist, J. E. 1997, in *The 1997 HST Calibration Workshop with a New Generation of Instruments*, ed. S. Casertano et al. (Baltimore: STSci), 271
- Lada, C. J. 1987, in *IAU Symp. 115, Star Forming Regions*, ed. M. Peimbert & J. Jugaka (Dordrecht: Kluwer), 1
- Lazareff, B., Monin, J., & Pudritz, R. E. 1990, *ApJ*, 358, 170
- Lucas, P. W., Blundell, K. M., & Roche, P. F. 2000, *MNRAS*, 318, 526
- Martin, P. G., & Whittet, D. C. B. 1990, *ApJ*, 357, 113
- Mundt, R., Ray, T. P., & Raga, A. C. 1991, *A&A*, 252, 740
- Myers, P. C., Fuller, G. A., Mathieu, R. D., Becoming, C. A., Benson, P. J., Schild, R. E., & Emerson, J. P. 1987, *ApJ*, 319, 340
- Padgett, D. L., Brandner, W., Stapelfeldt, K. R., Strom, S. E., Terebey, S., & Koerner, D. 1999, *AJ*, 117, 1490
- Pontoppidan, K. M., & Dullemond, C. P. 2005, *A&A*, 435, 595
- Pringle, J. E. 1981, *ARA&A*, 19, 137
- Shakura, N. I., & Sunyaev, R. A. 1973, *A&A*, 24, 337
- Shu, F. H. 1977, *ApJ*, 214, 488
- Shu, F. H., Adams, F. C., & Lizano, S. 1987, *ARA&A*, 25, 23
- Terebey, S., Shu, F. H., & Cassen, P. 1984, *ApJ*, 286, 529
- Ulrich, R. K. 1976, *ApJ*, 210, 377
- Walker, C., Wood, K., Lada, C. J., Robitaille, T., Bjorkman, J. E., & Whitney, B. 2004, *MNRAS*, 351, 607
- White, R. J., & Hillenbrand, L. A. 2004, *ApJ*, 616, 998
- Whitney, B. A., & Hartmann, L. 1992, *ApJ*, 395, 529
- . 1993, *ApJ*, 402, 605
- Whitney, B. A., Kenyon, S. J., & Gómez, M. 1997, *ApJ*, 485, 703
- Whitney, B. A., Wood, K., Bjorkman, J. E., & Cohen, M. 2003a, *ApJ*, 598, 1079
- Whitney, B. A., Wood, K., Bjorkman, J. E., & Wolff, M. J. 2003b, *ApJ*, 591, 1049
- Whittet, D. C. B., Gerakines, P. A., Hough, J. H., & Shenoy, S. S. 2001, *ApJ*, 547, 872
- Whitworth, A. P., & Ward-Thompson, D. 2001, *ApJ*, 547, 317
- Wolf, S., Padgett, D. L., & Stapelfeldt, K. R. 2003, *ApJ*, 588, 373
- Wood, K., Kenyon, S. J., Whitney, B. A., & Turnbull, M. 1998, *ApJ*, 497, 404
- Wood, K., Smith, D., Whitney, B., Stassun, K., Kenyon, S. J., Wolff, M. J., & Bjorkman, K. S. 2001, *ApJ*, 561, 299
- Wood, K., Wolff, M. J., Bjorkman, J. E., & Whitney, B. 2002, *ApJ*, 564, 887
- Yokogawa, S., Kitamura, Y., Momose, M., Asaki, Y., Tamura, M., Ida, S., & Kawabe, R. 2001, *ApJ*, 552, L59