

CORONAGRAPHIC IMAGING OF PRE-MAIN-SEQUENCE STARS WITH THE *HUBBLE SPACE TELESCOPE* SPACE TELESCOPE IMAGING SPECTROGRAPH. I. THE HERBIG Ae STARS^{1,2}

C. A. GRADY,^{3,4} B. E. WOODGATE,^{4,5} C. W. BOWERS,^{4,5} T. R. GULL,^{4,5} M. L. SITKO,^{6,7} W. J. CARPENTER,^{6,7} D. K. LYNCH,^{7,8}
 R. W. RUSSELL,^{7,8} R. B. PERRY,^{7,9} G. M. WILLIGER,¹⁰ A. ROBERGE,¹¹ JEAN-CLAUDE BOURET,¹² AND MEENA SAHU¹³

Received 2004 November 29; accepted 2005 March 29

ABSTRACT

STIS white-light coronagraphic imaging has been carried out for 14 nearby, lightly reddened Herbig Ae stars, providing data on the environments and disks associated with these stars. No disks are detected in our data when the Herbig Ae star is accompanied by a stellar companion at $r \leq 2''$. We find that the optical visibility of protoplanetary disks associated with Herbig Ae stars at $r \geq 50$ –70 AU from the star is correlated with the strength of the mid-IR PAH features, particularly 6.2 μm . These features, like the FUV fluorescent H_2 emission, trace the presence of material sufficiently far above the disk midplane that it is directly illuminated by the star's FUV radiation. In contrast, measures of the bulk properties of the disk, including ongoing accretion activity, mass, and the submillimeter slope of the SED, do not correlate with the surface brightness of the optical nebulosity. Modelers have interpreted the appearance of the IR SED and the presence of emission from warm silicate grains at 10 μm as a measure of geometrical shadowing by material in the disk near the dust sublimation radius of 0.5 AU. Geometrical shadowing sufficient to render a disk dark to distances as large as 500 AU from a star would require that the star be optically visible only if viewed essentially pole-on, in disagreement with our program star system inclinations. Rather than invoking shadowing to account for the optically dark disks, the correlation of the STIS detections with PAH emission features suggests a correlation with disk flaring and an anticorrelation with the degree of dust settling toward the midplane. If this correlation continues to lower levels, the STIS data suggest that improvements in coronagraph performance that suppress the residual scattered and diffracted stellar light by an additional factor of ≥ 10 should render the majority of disks associated with nearby Herbig Ae stars detectable.

Subject headings: infrared: stars — ISM: Herbig-Haro objects — ISM: jets and outflows — stars: pre-main-sequence

1. INTRODUCTION

Analysis of the optically visible Herbig Ae/Be stars studied by the *Infrared Space Observatory* (ISO) has revealed two general classes of object: stars with infrared excesses that can be fitted by simple power laws, and those that also require an additional component that can be fitted as a blackbody (Meeus et al. 2001; Acke & van den Ancker 2004). Meeus et al. (2001) initially suggested that the dichotomy might reflect the degree of shadowing of the inner disk, a model that has been further explored by Dullemond & Dominik (2004a, 2004b). They find that shadowing of Herbig Ae star disks can be caused both by a heated ring of dust near the dust sublimation temperature and typically located near 0.5 AU and by dust settling toward the

disk midplane. Dust settling is an expected consequence of grain growth and a precursor of planetesimal formation.

Recently, Acke et al. (2004) have analyzed submillimeter observations for the ISO sample of Herbig Ae stars and find that the slope of the submillimeter portion of the spectral energy distribution (SED) is correlated with the Meeus et al. (2001) group. At submillimeter wavelengths, the slope of the SED is sensitive to the average grain size in the disk, particularly its inner portions, and thus suggests that the Meeus et al. (2001) objects that are interpreted as shadowed at mid-IR wavelengths have larger average grain sizes than the unshadowed systems. However, as noted by Chiang et al. (2001), models for circumstellar disks incorporating a range of disk sizes and grain properties produce similar SEDs.

A natural solution to this degeneracy is to make use of high-contrast imaging data to better constrain the disk size and optical surface brightness and locate any previously unrecognized stellar companions. The coronagraphs on the *Hubble Space Telescope* (HST) enable us to take advantage of a comparatively stable

¹ Based on observations made with the NASA/ESA *Hubble Space Telescope*, which is operated by the Association of Universities for Research in Astronomy, Inc., under NASA contract NAS5-26555.

² Based on observations made with the NASA-CNES-CSA *Far Ultraviolet Spectroscopic Explorer*. FUSE is operated for NASA by The Johns Hopkins University under NASA contract NAS5-32985.

³ Eureka Scientific, 2452 Delmer Street Suite 100, Oakland, CA 94602-3017.

⁴ Exo-Planets and Stellar Astrophysics Laboratory, Exploration of the Universe Division, NASA Goddard Space Flight Center, Code 667, Greenbelt, MD 20771; cgrady@echelle.gsfc.nasa.gov.

⁵ Member of the Space Telescope Imaging Spectrograph Investigation Definition Team.

⁶ Department of Physics, University of Cincinnati, P.O. Box 210011, Cincinnati, OH 45221-0011.

⁷ Visiting Astronomer, NASA Infrared Telescope Facility, operated by the University of Hawaii under contract with the National Aeronautics and Space Administration.

⁸ The Aerospace Corporation, P.O. Box 92957, M2-266, Los Angeles, CA 90009.

⁹ Science Support Office, MS 160, NASA Langley Research Center, Hampton, VA 23681.

¹⁰ Department of Physics and Astronomy, Johns Hopkins University, 3400 North Charles Street, Baltimore, MD 21218; williger@pha.jhu.edu.

¹¹ Department of Terrestrial Magnetism, Carnegie Institution of Washington, 5241 Broad Branch Road, Washington, DC 20015-1305.

¹² Laboratoire d'Astrophysique de Marseille, BP 8, 13376 Marseille Cedex 12, France.

¹³ JWST Project, NASA Goddard Space Flight Center, Code 565, Greenbelt, MD 20771.

TABLE 1
THE PROGRAM STARS

Name	HD	Spectral Type	d (pc)	V	$B - V$	$E(B - V)$	i (deg)
KR Mus.....	100546	B9.5 IV–Ve (1)	103.6	6.698	0.009	...	45 (11)
AB Aur	31293	A2 Ve (2)	144	7.05	0.12	0.04	20 (12)
	95881	A1 IIIe (3)	118	8.2–8.4	0.11	...	...
MWC 275	163296	A3 Ve (4)	122	6.87	0.096	0.015	48 (13)
MWC 480	31648	A5 Ve (5)	131	7.73	0.17	0.02	38 (14)
HR 5999.....	144668	A5–7 III/IVe+sh (6)	200	6.9–8.3	0.29v	<0.09 (10)	70:
DX Cha.....	104237	A8/F0 Ve (7)	115	6.65	0.21	0.005	18 (7)
MWC 758	36112	A5 IVe (8)	200	8.29	0.25	...	25 (13)
V1026 Sco	142666	A8 Ve (3)	145:	8.81–9.7	0.52v	...	45–70 (15)
CQ Tau.....	36910	F5 IVe (5)	99	9.7–11.2	0.7v	...	63 (16)
	135344	F4 Ve (9)	140:	8.61	0.48	...	...

NOTE.—Reference numbers are given in parentheses.

REFERENCES.—(1) Deleuil et al. 2004; (2) Roberge et al. 2001; (3) Meeus et al. 1998; (4) Williger et al. 2004; (5) Mora et al. 2001; (6) Thé et al. 1985; (7) Grady et al. 2004; (8) Beskrovnaya et al. 1999; (9) Dunkin et al. 1997; (10) $E(B - V)$ for maximum light; (11) Grady et al. 2001; (12) Eisner et al. 2004; (13) Grady et al. 2000; Blake & Boogert 2004 give 60°; (14) Blake & Boogert 2004; (15) inclination range for UXORS from Natta & Whitney 2000; (16) Testi et al. 2001.

platform, with diffraction-limited imaging, and have produced the highest contrast images of protoplanetary disks around both pre-main-sequence (PMS) stars and debris disks (Grady et al. 1999, 2000, 2001, 2003, 2004; Heap et al. 2000; Augereau et al. 2001; Schneider et al. 2002; Clampin et al. 2003). While the circumstellar material associated with individual stars has been discussed for the Space Telescope Imaging Spectrograph (STIS) Herbig Ae stars (Grady et al. 1999, 2000, 2001, 2003), the goal of this survey is to discuss the full data set and to compare disk properties with observations at other wavelengths.

2. OBSERVATIONS AND DATA REDUCTION

2.1. The Program Stars

Over the course of 7 yr of operation, STIS has coronagraphically observed 11 Herbig Ae stars (Table 1) and three bright A star + debris disk systems. In contrast to coronagraphic observations obtained by the NICMOS GTO, which emphasized nearby objects and known debris disks (Schneider 2002), the STIS GTO coronagraphic imaging effort has been focused more on PMS A–F stars. The sample is primarily stellar magnitude and extinction limited, with a secondary goal of stellar proximity. Six of the program stars have resolved disks at millimeter wavelengths (Mannings & Sargent 1997, 2000; Mannings et al. 1997; Simon et al. 2000; Wilner et al. 2003; Corder et al. 2005). The majority of the program stars have $E(B - V) \leq 0.1$ and are located at $d \leq 210$ pc (van den Ancker et al. 1997, 1998) based on either *Hipparcos* parallax data or membership in nearby stellar associations such as Sco-Cen. At the time the program stars were selected, only one object, HR 5999 (HD 144668), was known to be a member of a close binary system (Stecklum et al. 1995); the other program stars were believed to be single stars. All of the program stars have conspicuous IR excesses and have been extensively studied with *IRAS* and *ISO*. The majority will be studied spectroscopically with *Spitzer*. Stellar spectral types are available for the program stars from the literature, while the *Far Ultraviolet Spectrographic Explorer* (*FUSE*) data allow us to identify those systems with a UV excess due to ongoing accretion. Near- and mid-IR interferometric observations are becoming available for many of our program stars. In tandem with model fitting of molecular emission lines, these data provide a direct measure of the disk inclination (Eisner et al. 2003, 2004; Leinert et al. 2004; Liu

et al. 2003; Blake & Boogert 2004), which can be compared with estimates based on the optical morphology of any large-scale nebulosity.

2.2. The STIS Coronagraph

HST STIS is equipped with a simple coronagraph, which in tandem with the unfiltered CCD provides wavelength coverage over 0.2–1.0 μm with an effective wavelength of 5875 Å for flat SEDs (Grady et al. 2003). The STIS coronagraph provides a sensitive probe of circumstellar nebulosity at distances 0".5–15" from an occulted star, reaching contrasts of 10^{-6} relative to the star by 2" from the source, and limiting contrasts near 10^{-8} by 4"–5" for $V = 6$ –9 stars (Grady et al. 2003).

The STIS coronagraph is not an optimal system for use with *HST*. For example, the STIS coronagraph incompletely apodizes the stellar diffraction spikes produced by scattering off the *HST* secondary support structure, with the result that the diffraction spikes are the brightest features in the point-spread function (PSF) of occulted objects. While normally not considered an advantage in coronagraph design, the diffraction spikes can be used to constrain the source magnitude and color at the epoch of the observations, as well as enabling us to determine the location of the occulted star relative to a PSF template object to within 0.05 pixels (0.5 mas). As a consequence of its extremely large bandpass and with an effective wavelength near $H\alpha$, the STIS coronagraph is equally sensitive to both reflection nebulosity and emission-line nebulosity. Optimal removal of the residual stellar light requires an excellent match between the SED of any PSF template source and the science target, as well as a good match in *HST* focus conditions. As discussed in Grady et al. (2003), these systematic effects become steadily more important as the surface brightness of any nebulosity decreases, and they ultimately limit the performance of STIS as a coronagraph, particularly within 2" of the occulted star.

2.3. STIS Observations and Data Reduction

STIS coronagraphic observations of 10 Herbig Ae stars were obtained under several STIS guaranteed time programs spanning 1998–2001 (Table 2). These data are supplemented by an archival observation of HD 135344 obtained under HST-GO-8674. The majority of the program stars were observed at wedge A1.0, a location along the vertical STIS coronagraphic wedge where

TABLE 2
HST JOURNAL OF OBSERVATIONS

Star	Program	ObsID	Aperture	P.A. (deg)	Date	T_{exp}	FOV (arcsec)	N_{read}
HD 100546	8474	O5KQ15010	WedgeA1.0	17.4	2000 May 11	600.0	25 × 50	8
	8474	O5KQ15020	WedgeA1.0	17.4	2000 May 11	600.0	25 × 50	8
	8474	O5KQ16010	WedgeA1.0	27.4	2000 May 11	600.0	25 × 50	8
	8474	O5KQ16020	WedgeA1.0	27.4	2000 May 11	600.0	25 × 50	8
AB Aur	8065	O57Z01020	WedgeA1.0	68.1	1999 Jan 23	576.0	25 × 50	8
	8065	O57Z01030	WedgeA1.0	68.1	1999 Jan 23	576.0	25 × 50	8
	8065	O57Z02030	WedgeA1.0	45.9	1999 Jan 24	480.0	25 × 50	8
HD 95881	8474	O5KQ12010	WedgeA1.0	−18.9	2000 Mar 19	864.0	25 × 50	8
	8474	O5KQ12020	WedgeA1.0	−18.9	2000 Mar 19	864.0	25 × 50	8
	8474	O5KQ11010	WedgeA1.0	−30.5	2000 Mar 19	720.0	25 × 50	8
	8474	O5KQ11020	WedgeA1.0	−30.5	2000 Mar 19	720.0	25 × 50	8
HD 163296	7565	O4XN01060	WedgeA1.0	38.1	1998 Sep 02	288.0	25 × 50	8
	7565	O4XN03060	WedgeA1.0	25.1	1998 Sep 02	288.0	25 × 50	8
	7565	O4XN02060	WedgeA1.0	51.1	1998 Sep 03	288.0	25 × 50	8
	8474	O5KQ09010	WedgeA1.0	28.1	2000 Jul 04	864.0	25 × 50	8
	8474	O5KQ09020	WedgeA1.0	28.1	2000 Jul 04	864.0	25 × 50	8
HD 31648	8474	O5KQ18010	WedgeA1.0	53.1	2000 Feb 04	1680.0	25 × 50	8
	8474	O5KQ17010	WedgeA1.0	38.1	2000 Feb 05	1680.0	25 × 50	8
HR 5999.....	8474	O5KQ01010	WedgeA1.0	−74.9	2000 Apr 24	864.0	25 × 50	8
	8474	O5KQ01020	WedgeA1.0	−74.9	2000 Apr 24	864.0	25 × 50	8
	8474	O5KQ02010	WedgeA1.0	−72.9	2000 Apr 26	864.0	25 × 50	8
	8474	O5KQ02020	WedgeA1.0	−72.9	2000 Apr 26	864.0	25 × 50	8
HD 104237	9241	o6bt01010	WedgeA1.0	139.1	2001 Oct 02	580.0	50 × 50	8
	9241	o6bt01020	WedgeA1.0	139.1	2001 Oct 02	580.0	50 × 50	8
	9241	o6bt03010	WedgeA1.0	159.1	2001 Oct 13	580.0	50 × 50	8
	9241	o6bt03020	WedgeA1.0	159.1	2001 Oct 13	580.0	50 × 50	8
HD 36112.....	8474	O5KQ03010	WedgeA1.0	34.1	2000 Jan 16	840.0	25 × 50	8
	8474	O5KQ03020	WedgeA1.0	34.1	2000 Jan 16	840.0	25 × 50	8
	8474	O5KQ04010	WedgeA1.0	49.1	2000 Jan 19	840.0	25 × 50	8
	8474	O5KQ04020	WedgeA1.0	49.1	2000 Jan 19	840.0	25 × 50	8
HD 142666	8474	O5KQ07010	WedgeA1.0	−112.9	2000 Apr 18	864.0	25 × 50	8
	8474	O5KQ07020	WedgeA1.0	−112.9	2000 Apr 18	864.0	25 × 50	8
	8474	O5KQ08010	WedgeA1.0	−97.9	2000 Apr 18	840.0	25 × 50	8
HD 135344	8674	o65410010	WedgeA1.0	−96.8	2001 Apr 08	1201.0	50 × 50	6
	8674	o65410020	WedgeA1.0	−96.8	2001 Apr 08	800.0	50 × 50	7
CQ Tauri	8037	O5DQ05010	WedgeA2.0	−138.2	1999 Oct 19	2250.0	50 × 50	5
	8037	O5DQ06010	WedgeA2.0	−117.2	1999 Oct 19	2250.0	50 × 50	5

the wedge occults $\pm 0''.5$, with the CCD charge transfer direction parallel to the wedge. CQ Tau was observed at wedgeA2.0, with a region $\pm 1''$ about the star occulted. The GTO observations were typically obtained at two spacecraft roll angles, separated by $5^\circ - 30^\circ$; HD 135344 was observed at only a single spacecraft roll angle. All observations were obtained, as described in Grady et al. (2003), as suites of short observations, in order to minimize saturation along the coronagraphic wedge, and with CCD GAIN = 4 to provide the maximum dynamic range. Our observing strategy evolved in the course of the program with a trend to longer integration times later in the program. Far-field limiting magnitudes range between 26.2 (288 s) and 28.0 for signal-to-noise ratio $S/N = 3$; after 600 s the images are read noise limited; the far-field limiting magnitudes for particular observations may be 0.5 mag brighter due to microphonics.

Five of our program stars have features in the STIS imagery that are detectable in the raw coronagraphic data, including nebulosity, diffraction spikes associated with nearby stars, and point-source cores. Bright nebulosity is seen at $r \geq 4''$ for AB Aur, as discussed in Grady et al. (1999). Herbig-Haro knots HH 409 A and C associated with HD 163296 are visible at $r \geq 8''$ in both the 1998 and 2000 coronagraphic observations (Grady et al. 2000; Devine et al. 2000). Diffraction spikes as-

sociated with stars within $2''$ of the primary are seen in HR 5999 and HD 104237 (Grady et al. 2004). Stellar PSF cores of nearby stars at projected offsets $\leq 2''$ from the primary star are also visible near HD 104237 and HD 36112.

Following CCD data reduction (Grady et al. 1999), additional steps are required to separate the residual *instrumentally* diffracted and scattered light from the signal due to circumstellar nebulosity and any nearby point sources (Grady et al. 2003). Lowrance et al. (1999) have used the technique of differencing observations obtained at two *HST* roll angles to locate point sources in the immediate vicinity of the program star. This technique also removes azimuthally symmetric PSF contributions and any azimuthally symmetric nebulosity, provided that the program star does not significantly change its magnitude and, more importantly, color from one observation to the next. Non-azimuthally symmetric contributions due to nebulosity, nearby point sources, and changes in the PSF from one observation to the next due to thermally driven changes in the *HST* focus and shape (termed “breathing”) will remain in the difference image. This technique is most effective for retrieving localized (surface area ≤ 1 arcsec²) nebulosity and point sources and can also be used to verify features that are detected by subtraction of a PSF template.

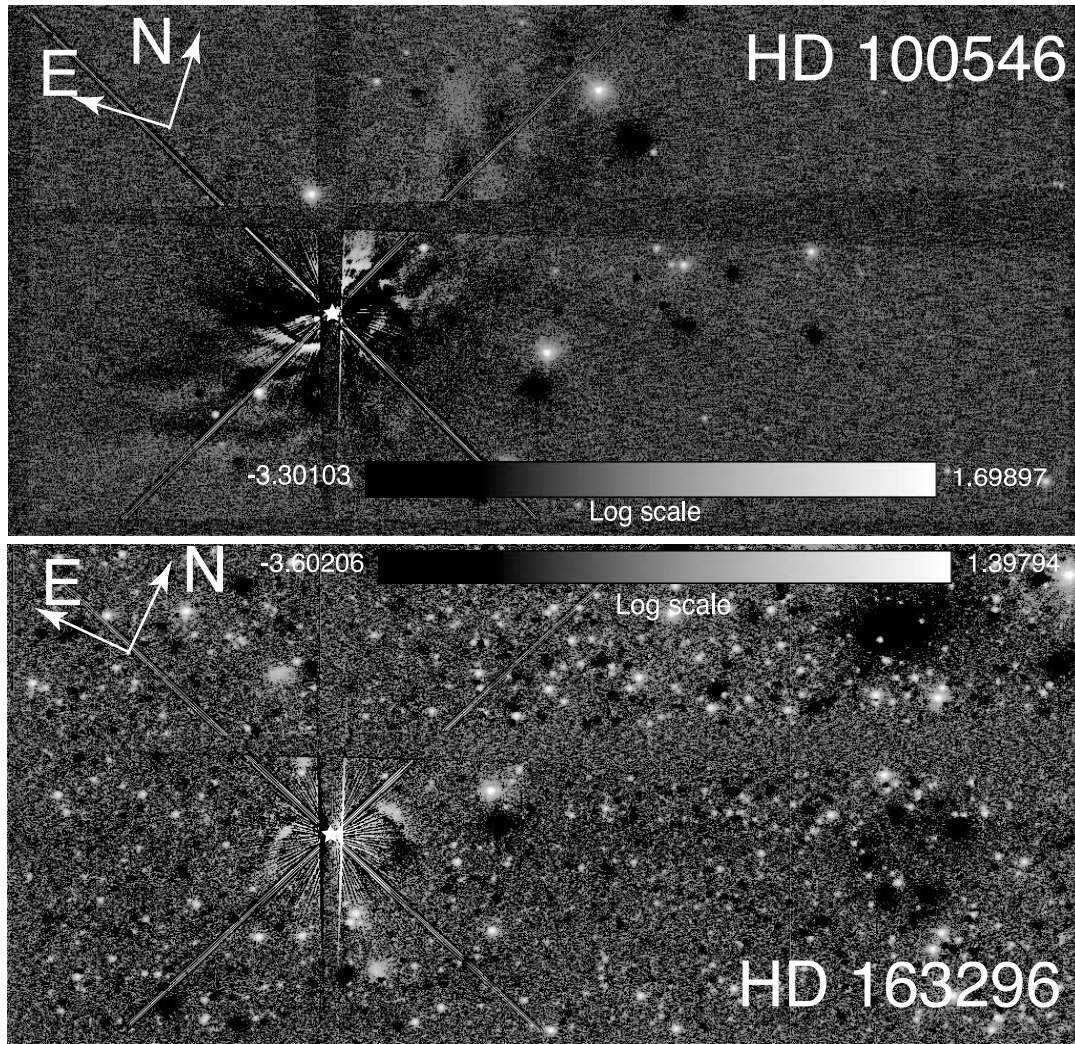


FIG. 1a

FIG. 1.—Roll-differenced imagery for Herbig Ae stars, shown with a logarithmic stretch. The position of stars and nebulosity in the image that has been subtracted are depicted as black features in the imagery. The dynamic range of the images has been limited to enhance the visibility of faint nebulosity but results in saturated emission at the locations of field stars. The location of the star is schematically indicated by a small star but is accurately determined from the crossing of the diffraction spikes. (a) HD 100546 and HD 163296. The entire $25'' \times 50''$ field of view is shown. (b) Same as (a), but for AB Aur and MWC 480. (c) Same as (a), but for CQ Tau and HD 142666. (d) Detail of $\pm 5''$ around the known binaries HR 5999 and HD 104237 and stars with point sources at $2''$, HD 36112 and CQ Tau. HR 5999 and CQ Tau are shown with PSF template star data subtracted, while HD 104237 and HD 36112 are shown as roll-differenced imagery. The locations of the occulted stars are shown schematically as stars, with the Herbig Ae star symbols larger. The size of the symbol is typically larger than the uncertainty in the stellar location as determined by the diffraction spike crossing.

The alternate technique, subtraction of a scaled and registered, color-matched PSF template star observation, produces difference images that retain any azimuthally symmetric nebulosity, as well as point sources. The principal limitation of this technique is that, due to STIS's extremely broad bandpass, it can be challenging to find a template star or linear combination of template star observations that are both good breathing and color matches to the science data. Our experience is that this technique is most effective in the presence of bright nebulosity and/or for debris disk systems where the SED of the occulted star matches the template star. Matching becomes progressively more difficult for stars with SEDs that are a poor match to the template objects, particularly those stars with detectable UV excesses longward of $2000 \text{ \AA}$.

2.3.1. Roll Differencing

Nine program stars have data obtained at spacecraft orientations with $\Delta\theta \geq 10^\circ$ that can be differenced to search for

localized nebulosity or nearby, faint point sources. This technique yields nebulosity detections for HD 100546, AB Aur, HD 163296, and CQ Tau (Figs. 1a–1c). For HD 100546 the difference image enhances the visibility of the smaller scale nebulosity and the spiral arcs noted by Grady et al. (2001) near the star, while, as expected, eliminating the large-scale, azimuthally symmetric nebulosity. For AB Aur, the difference image highlights the spiral bands and distant nebulosity discussed by Grady et al. (1999) and Fukagawa et al. (2004). For HD 163296 the difference image reveals the ansae discussed by Grady et al. (2000) and Fukagawa (2005) and the Herbig-Haro knots (Devine et al. 2000). The difference image for CQ Tau yields detection of a partial arc to the west of the star, extending up to $10''$ from the star, and smaller scale patchy nebulosity. In addition to the nebulosity detections, faint, nearby point sources are detected via the core of the PSF for HD 36112 and via partial diffraction spikes for CQ Tau (Fig. 1d).

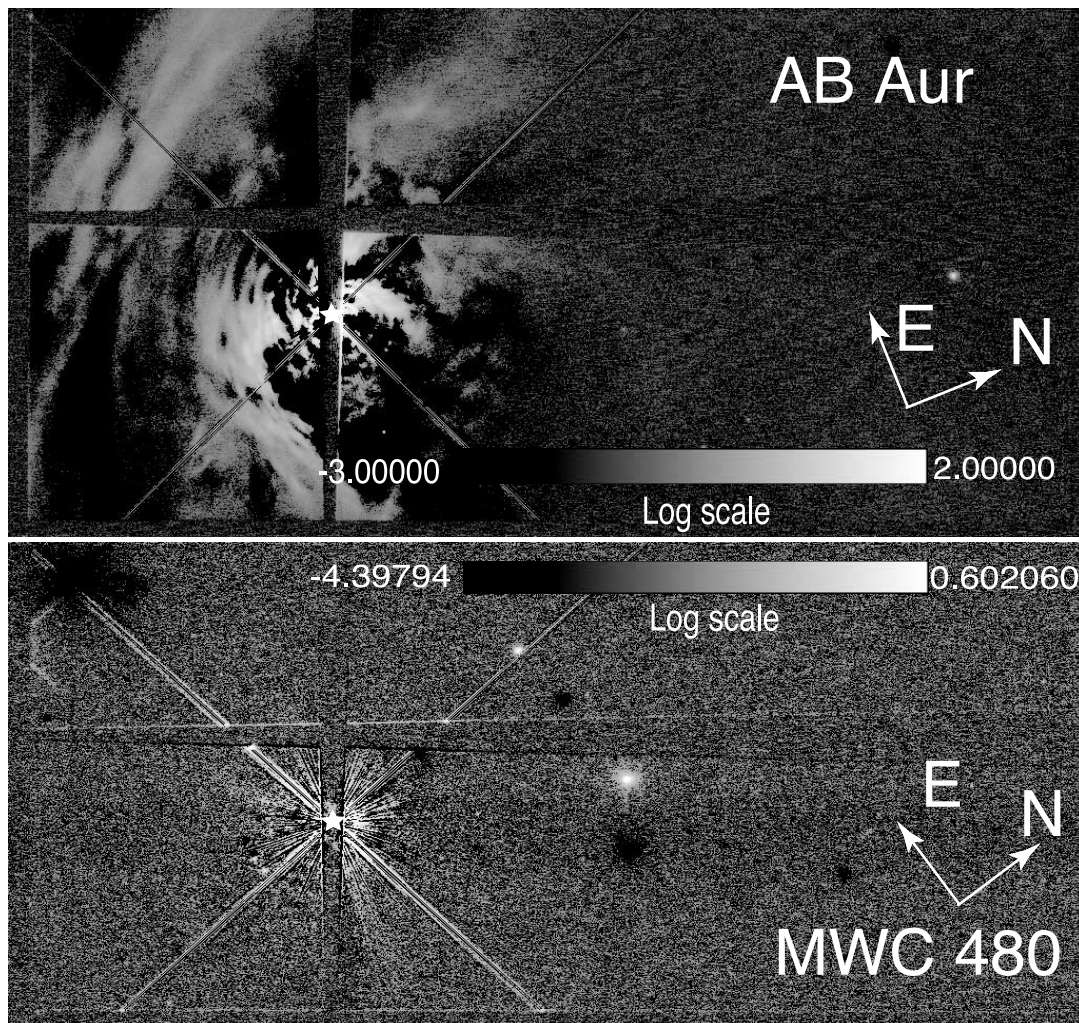


FIG. 1b

2.3.2. PSF Subtraction

In carrying out PSF subtraction for our program star data, we have made use of both the STIS PSF library (Grady et al. 2003) data and the program stars that appear to lack spatially extended nebulosity. The range of PSF template star $B - V$ that provides both a reasonable and the best fit to the Herbig Ae star PSF is shown in Table 3. The limiting performance for $V = 6.5-9.5$ single Herbig Ae stars is shown in Grady et al. (2003). The limiting contrast at $3''$, just beyond the region most affected by the PSF subtraction residuals, reaches $10^{-7 \pm 0.5}$ for our $V = 6.5-9.0$ single stars (Table 4). For close binaries, where the PSF of the secondary star must be compensated for prior to fitting the primary star PSF, the limiting contrast can be up to an order of magnitude worse.

Figure 2 shows the result of subtracting color-matched PSF template stars from HD 100546, AB Aur, HD 163296, and HD 135344. Figure 1d also shows PSF-subtracted and roll-differenced imagery for the known binaries in our sample, HR 5999 and HD 104237. Figure 3 shows the surface brightness of the nebulosity in swaths $0''.1$ wide perpendicular to the occulting wedge for AB Aur, HD 100546, HD 163296, and HD 142666, one of our nondetections. For HD 100546 and AB Aur the nebulosity is detected in the independently reduced data from both spacecraft orientations. For HD 163296, the nebulosity is detected for all three orientations for the first-epoch observation.

The second-epoch data were obtained when the star was close to the anti-Sun, a condition that was not otherwise matched by any of the STIS coronagraphic data and resulted in a PSF that differed significantly from all of the other STIS coronagraphic observations. For AB Aur, the nebulosity is within a factor of 2 of the raw image PSF and not only can be seen in the raw CCD data but also can be retrieved to the edge of the coronagraphic wedge for essentially any color PSF. HD 100546 has nebulosity that is a factor of 10 fainter than the PSF at $2''$ but only a factor of 2 below the PSF at the coronagraphic wedge: the presence of nebulosity can be detected with PSFs ranging from $-0.19 \leq B - V \leq 0.25$. The nebulosity associated with CQ Tau and HD 163296 is close to the STIS detection limit and can be retrieved only for a limited range of PSF colors: $B - V = 0.7 \pm 0.1$ for CQ Tau and $B - V = 0.10 \pm 0.10$ for HD 163296.

2.4. BASS Observations and Data Reduction

While the majority of our program stars have ISO SWS or ISOPHOT P40 mid-IR spectra permitting classification of the IR SED (Meeus et al. 2001), two of our program stars, HD 36112 and CQ Tau, lack such data. Mid-IR spectra of these stars were obtained at the NASA Infrared Telescope Facility (IRTF) on Mauna Kea, using the Aerospace Corporation's broadband array spectrograph system (BASS; see Lynch et al. 2000). CQ Tau was observed on 1996 October 14 (UT), while HD 36112

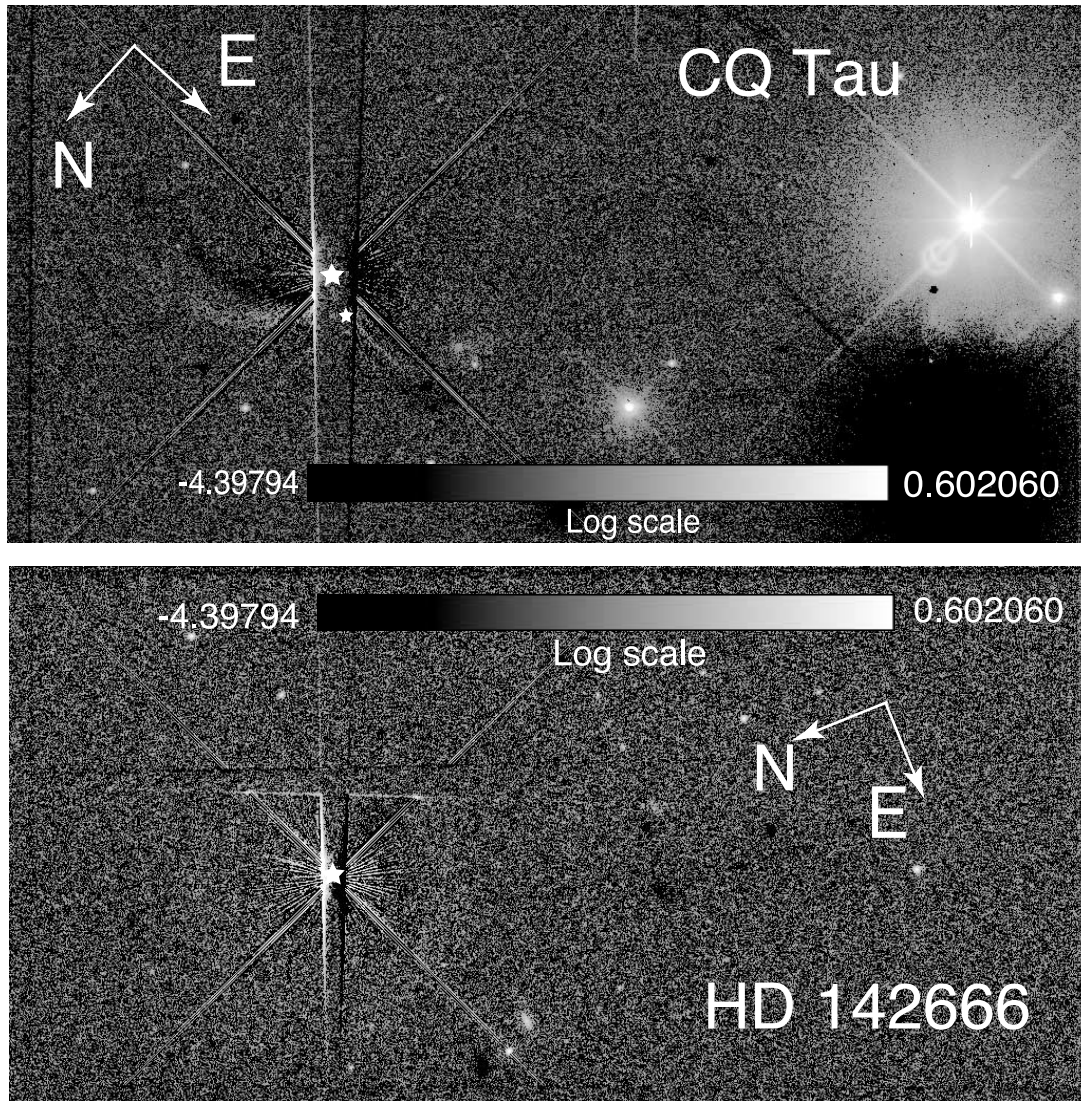


FIG. 1c

was observed on 2004 August 5 (UT). BASS uses a cold beam splitter to separate the light into two separate wavelength regimes. The short-wavelength beam includes light from 2.9–6 μm , while the long-wavelength beam covers 6–13.5 μm . Each beam is dispersed onto a 58-element blocked impurity band (BIB) linear array, thus allowing for simultaneous coverage of the spectrum from 2.9 to 13.5 μm . The spectral resolution $R = \lambda/\Delta\lambda$ is wavelength dependent, ranging from about 30 to 125 over each of the two wavelength regions. At the IRTF, the circular entrance aperture of the instrument subtends $3''.3$ on the sky. The observations were calibrated relative to α Tau, observed immediately before CQ Tau, and at approximately the same air mass (1.30 vs. 1.19). Figure 4 shows the BASS spectra together with local fits to the continuum under the 10 μm silicate emission feature.

3. RESULTS

3.1. UX Orionis Stars in the Sample

Three of our program stars are known large-amplitude light and color variables similar to UX Orionis (Grinin et al. 1991). These stars experience irregular drops in their optical light, in

tandem with polarization increases, which have been interpreted as the result of occultation of the star by material in the circumstellar disk. The short duration of some optical minima suggests that the occulting material is located near the star, in the inner portion of the disk. Natta & Whitney (2000) find that these stars must be observed in the inclination range $45^\circ \leq i \leq 70^\circ$ for material at the dust sublimation radius to occult the star. As a group, these stars are the highest inclination systems in our sample. HR 5999 was near $V = 7.05 \pm 0.05$ in both observations, while PSF subtraction of the HD 142666 data (HD 139470 as template) indicates $V = 8.65 \pm 0.03$. PSF subtraction of CQ Tau with HD 115617 as a template star yields $V = 9.85 \pm 0.06$. HR 5999 and HD 142666 were both near their recorded optical maximum light. For CQ Tau, the observed light level is comparable to the maximum observed by *Hipparcos* (Perryman et al. 1997) but a magnitude fainter than the historical maximum. The non-UXORs in the STIS survey were all observed at their expected optical light levels.

3.2. Binaries in the Sample

Compared to other coronagraphs, the large field of view of STIS imagery together with retention of the brightest features

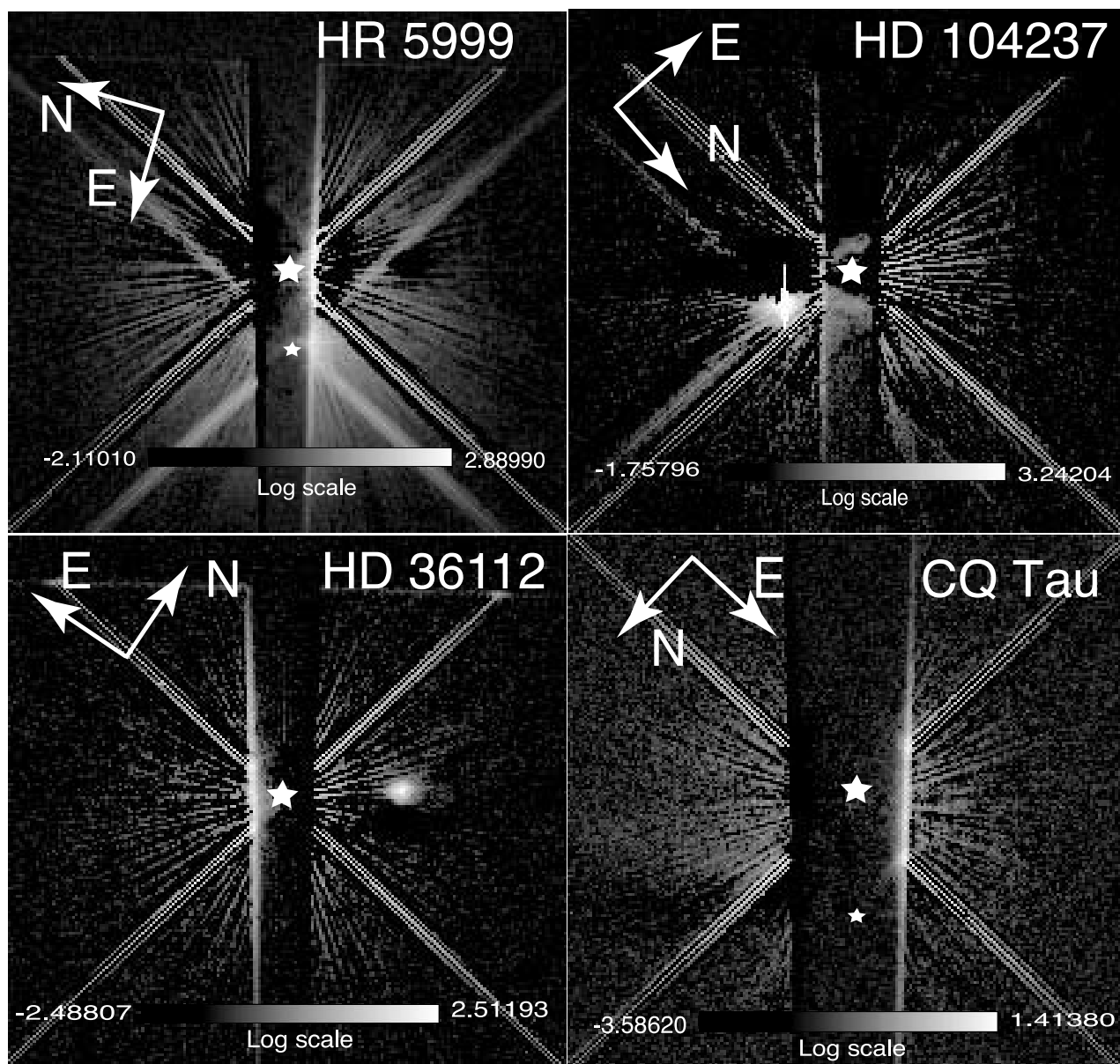


FIG. 1d

TABLE 3
BEST-FIT PSFs

Name	Type	$B - V$ Range	Best-Fit $B - V$
HD 100546	Detection	-0.19 to 0.25	≤ 0.06
HD 95881	Nondetection	0.06-0.21	0.11 ± 0.03
AB Aur	Detection	-0.19 to 0.7	0.11 ± 0.03
HD 163296	Detection	0.06-0.21	0.105 (ep0), 0.12 (ep1)
MWC 480	Nondetection	0.17-0.28	0.17 ± 0.03
HD 36112	Nondetection	0.21-0.28	0.25 ± 0.03
HR 5999	Nondetection	0.21-0.28	0.25 ± 0.03
Rst 3930	Nondetection	1.1-1.5	1.33
HD 104237	Nondetection	0.21-0.37	0.25
HD 142666	Nondetection	0.46-0.70	0.60
CQ Tau	Detection	0.71	0.71
HD 135344	Nondetection	0.46-0.7	HD 139470, $B - V = 0.58$

of the stellar PSF make it possible to search for stellar and/or substellar companions to our coronagraphically observed Herbig Ae stars (Grady et al. 2003). The program stars with point sources within $2''$ of the Herbig Ae/Fe star are shown in Figure 1d.

Rst 3930 (HR 5999 B).—Our sample contained one known binary star at the time the observations were planned: HR 5999, with its T Tauri companion Rst 3930 (Stecklum et al. 1995), offset $1''.67 \pm 0''.07$, at P.A. = 110° . Stecklum et al. (1995) find an offset of $1''.44$ at the same P.A. As a result of the known position angle, the HR 5999 observations were planned to have both stars occulted in both observations. While limiting the portion of the sky that was unocculted in both observations, occulting Rst 3930 enabled us to make full use of the STIS PSF library to characterize the magnitude and color of the secondary. For Rst 3930 we find that $V = 11.2 \pm 0.2$, when HR 2467 is used as the PSF template star. Acceptable fits to Rst 3930's PSF are found for $B - V = 1.33 \pm 0.2$, corresponding to a lightly reddened early to mid-K star. The early spectral type and

TABLE 4
STIS SURFACE BRIGHTNESS DATA

Star	$\log(S(r = 3''))$	Detection	Meeus Group	MM Data References	Comments
HD 100546	6.3 (0.1)	Yes	Meeus Ia	1	
HD 95881	<7.0 (0.3)	No	Meeus II		
AB Aur	5.8 (0.1)	Yes	Meeus Ia	2, 3	
HD 163296	6.7 (0.2)	Outer disk	Meeus II	2	
MWC 480	<7.0 (0.3)	No	Meeus II	4	
HD 36112	<7.2 (0.4)	No	Meeus Ia ^a	5	
HR 5999	<6.8 (0.3)	No	Meeus II		Likely small disk
HD 104237	<6.8 (0.4)	No	Meeus II	6	$r_{\text{outer}} \leq 0''.6$
HD 142666	<7.0 (0.2)	No	Meeus II		
CQ Tau	6.1 (0.2)	No	Meeus Ia ^a	5	Background 6.3
HD 135344	<7.0 (0.3)	No	Meeus Ib		

^a IR SED group from this study.

REFERENCES.—(1) Wilner et al. 2003; (2) Mannings & Sargent 1997; (3) Corder et al. 2005; (4) Mannings et al. 1997; (5) Mannings & Sargent 2000; (6) Grady et al. 2004.

V magnitude are consistent with the optical photometry reported by Stecklum et al. (1995). The ease of PSF fitting to a single template star, compared to our experience with classical T Tauri stars (C. A. Grady et al. 2005, in preparation), suggests that Rst 3930 is not actively accreting and is a weak T Tauri star.

HD 104237 A and companions.—Prior to STIS observation, HD 104237 was believed to be the optically brightest “isolated” Herbig Ae star. The STIS observations revealed instead that the star is the highest mass member of a small T association, with two confirmed and one candidate T Tauri companions. Two of the companions have IR excesses at L' , and one has been detected at N (Grady et al. 2004). The nearest companion has an offset of $1''.36 \pm 0''.02$ from the Herbig Ae star at P.A. = 254.6° with $V = 15.1$. After subtraction of the PSF for the Herbig Ae primary, all of the associated stars have bright PSFs, with well-exposed diffraction spikes that can be traced between $2''$ and tens of arcseconds from the star and the horizontal bar characteristic of red sources as seen by the STIS CCD (Grady et al. 2004). They find that the nearest companion has a PSF appropriate to an unreddened mid-M star, placing this object just above the substellar limit.

3.3. Sources at Small Angular Distances from the Program Stars

Our experience with both Rst 3930 and the T Tauri companions to HD 104237 enables us to identify a suite of characteristics for plausible stellar or substellar companions to our $V = 6.5$ – 9.0 Herbig Ae and Fe stars. First, in our deep coronagraphic imagery, any plausible stellar companions will have conspicuous diffraction spikes in the raw coronagraphic data. Low-mass companions should appear red compared to the Herbig Ae/Fe stars. If unocculted, they should have the red horizontal bar characteristic of extremely red sources, as seen by STIS (Grady et al. 2004). If occulted, the diffraction spikes should drop slowly in intensity with distance from the star, similar to the late-type stars in the PSF template library or to the M stars in the M star parallel survey (Grady et al. 2004).

HD 36112.—A point source is visible in the raw coronagraphic data at $2''$ from the star and P.A. = 304° . After either PSF subtraction or roll differencing, the unsaturated core of the stellar PSF is retrieved. If we assume an A5 V SED, the star has $V = 17.95 \pm 0.1$, while for M2 V the star is fainter than $V = 20$. The absence of the red, horizontal bar suggests that the earlier spectral type is more appropriate and that the source is a background object.

CQ Tau.—*Hipparcos* found a periodic light curve for CQ Tau, prompting speculation that the star might be a binary (Grinin & Tambovtseva 2002). The STIS data show only a single diffraction spike pair, suggesting that any near-stellar companion must lie within $0''.05$ of the Herbig Fe star. At larger distances from CQ Tau, there are two sources of interest in the CQ Tau field. The first is an occulted source $1''.9$ from CQ Tau at P.A. = 46.3° that is marginally detected by a partial set of diffraction spikes. The source has $\Delta m_{\text{STIS}} = 7.25 \pm 0.3$, implying V no brighter than 17.1 for a star with spectral type of F5 V. At the distance and reddening toward CQ Tau, this could be either an object close to the substellar limit or a background object. The other object is at $30''.1$ and P.A. = 136.8° . It has the saturated PSF core and horizontal bar characteristic of T Tauri stars in these deep coronagraphic images. The extent of the bar suggests a mid-M spectral type, for an object with no foreground reddening. We derive $V = 16.86$ for an M2 V Kurucz model SED. Inspection of the POSS data indicates that this star has retained the same offset and position angle relative to CQ Tau since 1951 August, despite CQ Tau’s proper motion of -26 mas yr^{-1} in declination. This suggests that the red object is comoving with CQ Tau.

HD 135344.—The only other program star with a bright object at least partially in the field of view is HD 135344, which has one diffraction spike from CD $-36^\circ 10010$ visible in the coronagraphic data. At $V = 7.9$ and with a later spectral type than HD 135344, this is a foreground star.

The other sources typically have a few to many (HD 163296) objects in the STIS field, including galaxies. The point sources are typically sufficiently faint that they are most likely background sources. The faint source offsets from the Herbig Ae stars are typically $\geq 4''$. With two confirmed and one candidate binary/multiple stars in our sample, the overall binary fraction is $\frac{1}{4}$, which is low compared to unbiased surveys of PMS stars but high compared to samples selected for large millimeter disks, reflecting the heterogeneous nature of our sample.

3.4. Large-Scale ($r \geq 1000 \text{ AU}$) Nebulosity

The STIS images in this survey were all obtained prior to the STIS side 1 electronics failure and therefore have stable thermal control of the STIS CCD. This stability enables us not only to detect nebulosity that is smaller than the STIS field of view but also to search for larger scale nebulosity. Typical background levels in our sample are due to a mixture of sky background, zodiacal light, instrumental microphonics, and the detector dark

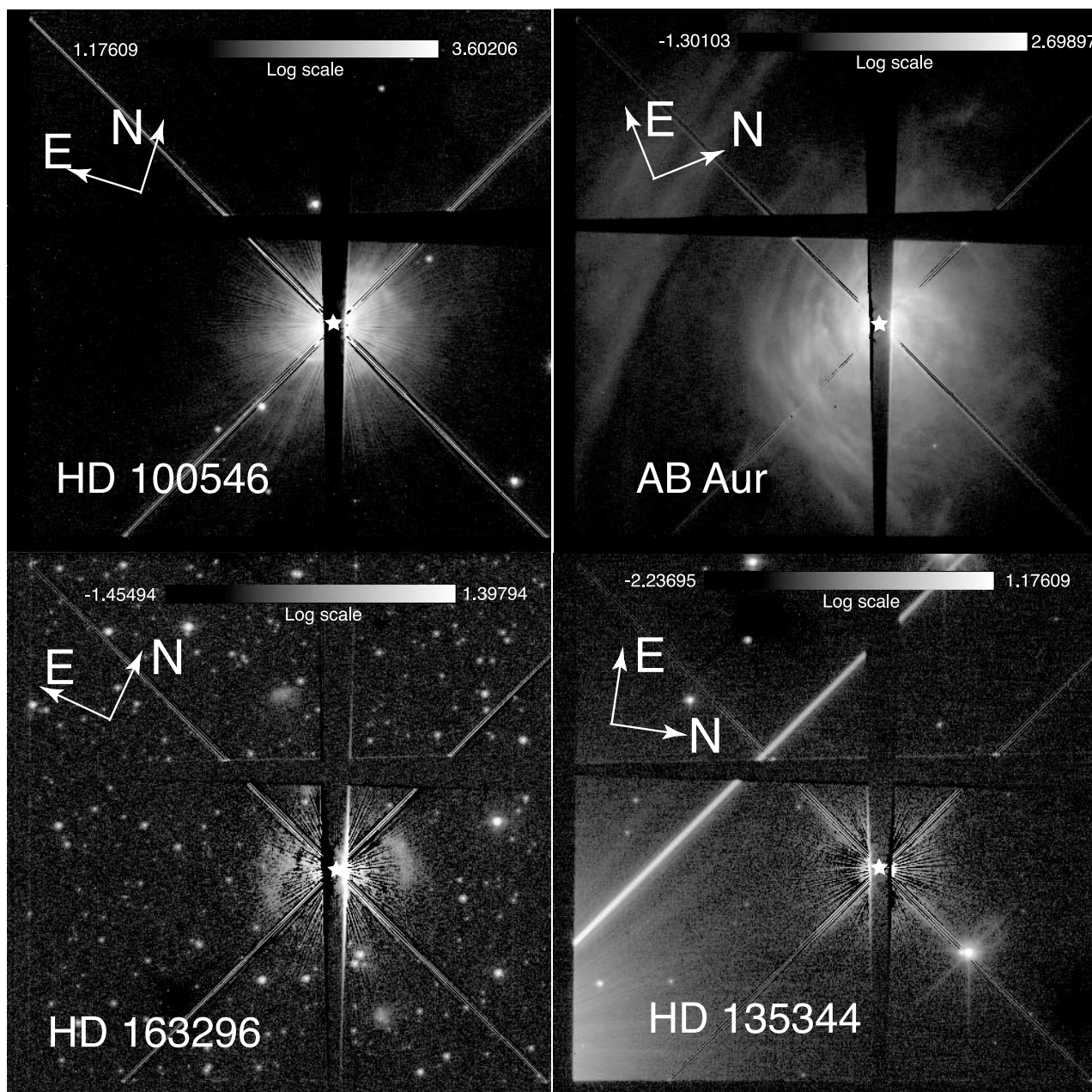


FIG. 2.—PSF-subtracted STIS imagery displayed with a logarithmic stretch. Background stars in the PSF template observations produce negative holes in the images. All stars are shown over a $25'' \times 25''$ field of view. The approximate stellar location is indicated by a star symbol; the actual stellar location is at the crossing of the diffraction spikes. The HD 100546 data are shown multiplied by an r^{-1} filter to reduce the contrast, rendering detail in the inner 270 AU and the outer envelope simultaneously visible. The PSF star for HD 100546 is HD 141653. The PSF star for AB Aur is HD 95881. For HD 163296 a composite PSF consisting of 50% of HD 141653 and 50% of HD 95881 was used. For HD 135344 the contemporary PSF data for HD 134970 were used.

count and contribute $\approx 0.09 \pm 0.025$ counts pixel $^{-1}$ s $^{-1}$. Two sources stand out in the sample with higher backgrounds: HR 5999, with a background level of 0.135 ± 0.02 , and AB Aur, with 0.148 ± 0.03 , both measured in portions of the STIS field far from the star and away from obvious features. The stars have some environmental similarities: both are members of widely separated common proper-motion pairs (AB Aur and SU Aur, HR 5999 and HR 6000) that are the brightest stars in their respective regions. Both occupy cavities in molecular clouds and are associated with reflection nebosity that is visible in the POSS plates. WFPC/2 parallel observations (WFPC/2 association ID U4K2FI01B) of AB Aur reveal that the cavity between AB Aur and SU Aur is filled with nebulous arcs and filaments with typical scales of tens of arcseconds. Inspection of

the lower resolution POSS data for HR 5999 reveals widespread nebosity, which the STIS data demonstrate has typical spatial scales $\geq 25''$ – $50''$.

Nebulous arcs are seen in the imagery for AB Aur, CQ Tau, and HD 100546. For AB Aur, the arc is present on the east side of the star and is visible in the POSS data. The closest approach of this arc to the star is $12''$. It is separated from material nearer the star by a $3''$ band. CQ Tau appears to have a smaller scale and much lower surface brightness arc extending more than $10''$ from the star with closest approach $1''$ to the north of the star. As noted by Grady et al. (2001), HD 100546 appears to be encountering a band of nebosity running roughly north-northwest through south-southeast, with arcsecond-scale clumps within a few arcseconds of HD 100546. In addition, there is a

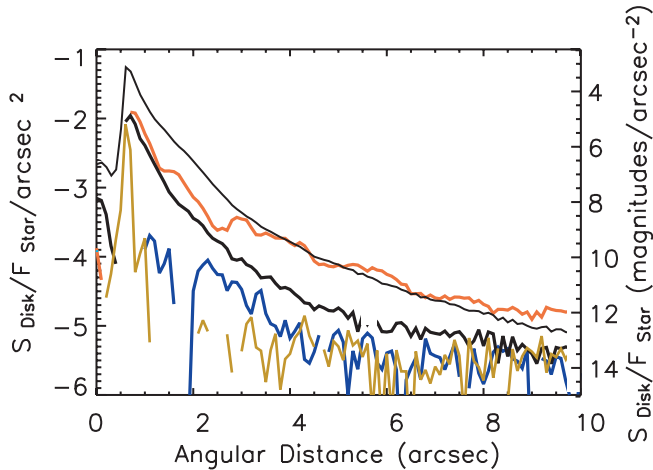


FIG. 3.—Surface brightness of the circumstellar nebulosity in $0''.1$ wide swaths crossing the star. The region to the left of the coronagraphic wedge in the detector format is shown. The raw coronagraphic surface brightness profile for HD 100546 is shown (thin black line). Surface brightness profiles following subtraction of color-matched PSF template stars are shown for AB Aur (red line), HD 100546 (thick black line), HD 163296 (blue line), and HD 36112 (gold line; null detection).

faint double band wrapping around the west side of the star, with closest approach to the star at $6''$, in the direction of the star's proper motion.

HD 163296 is accompanied by a chain of arcsecond-scale, low-excitation Herbig-Haro knots at P.A. = $42^\circ.5$ and $222^\circ.5$ (see Fig. 2 in Grady et al. 2000). Low-resolution, spatially resolved spectroscopy, obtained with STIS and discussed in Devine et al. (2000), demonstrates that the knots lack continuum emission at the level detectable in single-orbit *HST* integrations and therefore do not contain appreciable amounts of reflection nebosity. Ultraviolet narrowband coronagraphic imagery with the Goddard Fabry-Perot at Apache Point Observatory demonstrates that the knots seen in the STIS data are accompanied by additional knots extending at least $28''$ from the star (Swartz et al. 2005).

3.5. Nebulosity at 500–1000 AU

AB Aur.—This star has the brightest nebosity among the Herbig Ae stars, with bright material extending beyond $10''$

from the star. As noted by Grady et al. (1999), the nebosity includes structure down to the resolution limit of *HST* in the form of centrosymmetric bands and small clumps. Similar bands have been detected at *H* band with Subaru (Fukagawa et al. 2004), indicating that the bulk of the nebosity seen by STIS is reflection nebosity. The scale of the optical nebosity is larger than the CO disk reported by Mannings & Sargent (1997). The lack of obvious angular asymmetry favors a face-on ($i \leq 25^\circ$) inclination, in agreement with model fits to the near-IR visibility function (Eisner et al. 2004) and the *M*-band CO profiles (Blake & Boogert 2004). For a face-on system, like AB Aur, the STIS data do not allow us to distinguish between a highly vertically extended structure, such as the walls of an outflow cavity, and a flattened structure more intimately associated with a circumstellar disk: both can produce an r^{-2} radial surface brightness profile. However, the detection of spiral features in the millimeter (Corder et al. 2005) and the similarity between that structure and features seen at *H* (Fukagawa et al. 2004) favor a disk association. A double band of nebosity delimits the centrosymmetric material at $6''.18$ (890 AU) and has its closest approach to the star to the south, in the direction of AB Aur's proper motion.

At $r \geq 500$ AU, HD 100546 has nebosity that is distributed azimuthally symmetrically about the star, with an r^{-2} surface brightness profile (Grady et al. 2001 and figures therein). This outer nebosity is a factor of 10 fainter than the material around AB Aur and may be optically thin, judging by the background sources visible through the nebosity. Like AB Aur, HD 100546 is accompanied by a double arc that has its closest approach to the star at $10''$ on the west side of the disk, also in the direction of the star's proper motion.

3.6. Nebulosity within 500 AU of the Star

The disks of AB Aur and HD 100546 are discussed in Grady et al. (1999, 2001). Grady et al. (2000) reported the detection of a ring of material around HD 163296 but could not assess the residual light levels close to the star that early in the coronagraphic survey. With a more complete set of PSF template stars (Grady et al. 2003), we find that the ring of material is retrieved in the difference images and with PSF subtraction for the first-epoch data, when the breathing match to the PSF library was better. The second-epoch data, while optimized for study of the HH knots, were obtained with the star near the anti-Sun and do

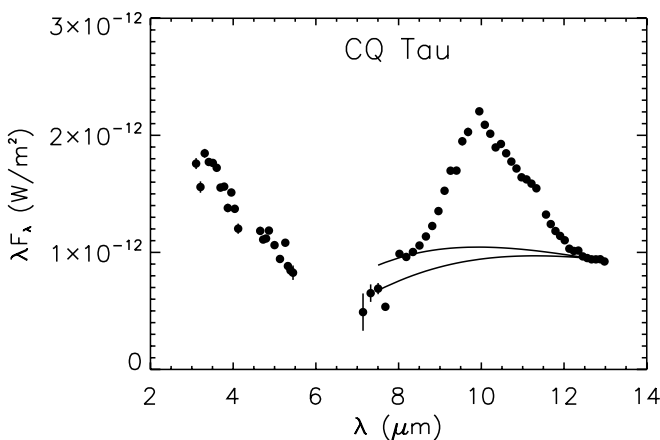


FIG. 4a

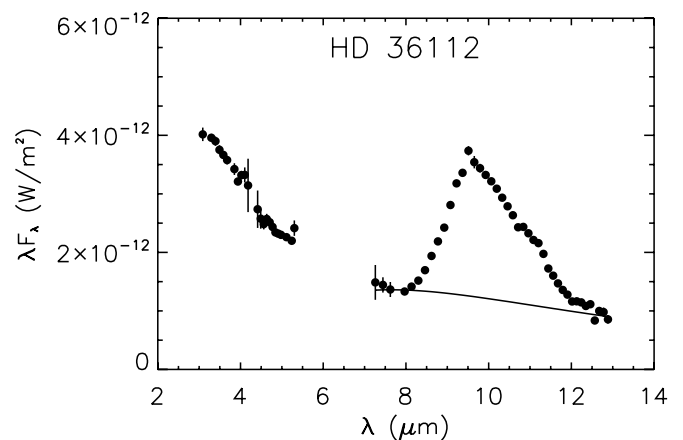


FIG. 4b

FIG. 4.—BASS spectra of (a) CQ Tau and (b) HD 36112 together with local fits to the continuum under the $10 \mu\text{m}$ silicate profile. Also shown is the underlying continuum used for determining the band/continuum ratio. For CQ Tau, in both cases the flux at $12.5 \mu\text{m}$ was used for the continuum on the long-wavelength side of the silicate band. Between 7 and $8 \mu\text{m}$, incomplete removal of the telluric extinction is often problematic. For that reason, we have normalized the fit to two possible flux levels: the flux at $8 \mu\text{m}$ (upper solid line) and $7.5 \mu\text{m}$ (lower solid line). The uncertainty has little effect on the derived band/continuum ratio, however (see Fig. 6).

not have a good fit to any of the PSF template data. When compared with a nondetection such as HD 142666, the HD 163296 residual image exceeds the PSF residual level only exterior to $2''.5$ from the star. Similarly, we find that changing the choice of PSF template greatly affects the residuals near the star. We conclude that while the scattered light ring appears to be robustly detected (Grady et al. 2000), the inner disk is consistent with a nondetection. L. Testi (2003, private communication) reports that the ring is seen in the millimeter, indicating that it is a real density feature and is not simply visible due to an absence of shadowing. A similar pattern of bright(er) outer ring and dark inner disk is seen for DM Tau (C. A. Grady et al. 2005, in preparation).

3.7. Disk Properties

Binaries.—No nebulosity is detectable beyond the coronagraphic wedge in the STIS data for either HD 104237 or HR 5999. A firm upper limit to the size of the disk in HD 104237 is provided by the detection of counterjet material in Ly α (Grady et al. 2004), of $r \leq 0''.6$. The SED of HR 5999 is similar to HD 104237, suggesting that the disk in that system may also be geometrically small.

Known large disks.—Six of our program stars have sufficiently large and bright disks at millimeter wavelengths that interferometric observations have been obtained (Mannings et al. 1997; Mannings & Sargent 1997, 2000; Simon et al. 2000; Wilner et al. 2003), implying circumstellar material at $r \geq 2''$ from the star. The optical surface brightness of the nebulosity around these stars spans at least 2 orders of magnitude at $r = 2''$ – $3''$ from the star.

AB Aur.—AB Aur has the brightest nebulosity in our survey, detectable in the raw coronagraphic data beyond $4''$ and after subtraction with virtually any PSF template star down to the coronagraphic wedge. The disk was resolved in both the millimeter continuum and CO by Mannings & Sargent (1997) and has subsequently been detected at H band by Fukagawa et al. (2004). The nebulosity is typically within a factor of 2 of the PSF level. At $3''$, the nebulosity has $\log(S/F_*) = 5.8 \pm 0.2$ in counts s^{-1} per 0.1 arcsec^2 per total stellar flux. The $S \propto r^{-2}$ trend continues into the wedge (Fig. 3), which *excludes the nebulosity arising from a geometrically flat disk with surface density radially decreasing away from the star*, which would have $S \propto r^{-3.5}$ or steeper.

HD 100546.—At the coronagraphic wedge, the HD 100546 disk is as bright as AB Aur's nebulosity. At larger distances, the nebulosity, which exhibits the elliptical symmetry of a disk viewed at 45° inclination, drops as $r^{-3.1}$ out to 500 AU. Grady et al. (2001) noted spiral structure in the midregions of the disk, which is detectable at low contrast to the overall nebulosity. Compared to other coronagraphic detections, the HD 100546 nebulosity appears very washed out, a feature that is also seen in the ACS narrower band data (D. Ardila 2004, private communication). Reflection nebulosity extending 100–200 AU from the star is seen near Ly α , together with fluorescent H $_2$ emission (Grady et al. 2005). Using TIMMI2 at the ESO 3.6 m, van Boekel et al. (2004a) have resolved the bright polycyclic aromatic hydrocarbon (PAH) emission features seen in ISO data (Meeus et al. 2001) and find that they extend over 100–150 AU from the star. The $8.7 \mu\text{m}$ emission is resolved by the VLT and has the same morphology as the disk seen by STIS, while the star has the low interferometric visibility at $10 \mu\text{m}$ expected for resolved nebulosity (Leinert et al. 2004). Bouwman et al. (2003) find evidence for a 10 AU scale cavity in the inner disk from analysis of the IR SED. Grady et al. (2005) marginally resolve the cavity and find that it is not centered on

the star but is offset 5 AU to the southeast (semiminor axis for the disk).

HD 163296.—This star has the faintest disk of any of the coronagraphically detected disks seen by STIS, only 3% of the PSF level at $3''$ from the star. Roll differencing and PSF subtraction of the first-epoch data reveal two ansae with an outer radius of 450 AU, in good agreement with the size and position angle of the millimeter disk (Mannings & Sargent 1997; L. Testi 2003, private communication). With a good color match in PSF subtraction, the peak S/N of the ansae is 5 per STIS pixel. The second-epoch data, obtained when HD 163296 was near the anti-Sun, have breathing residuals that are very different from the PSF template library data or the first-epoch observations and result in a disk nondetection. At $r \leq 2''$, the disk surface brightness in both epochs is at or below the PSF residuals. The outer radius of the disk is 450 AU both from the STIS imagery and from the closest approach of the counterjet knots to the star at Ly α , and it is unusually sharp compared to AB Aur, HD 100546, or HD 141569 A (Mouillet et al. 2001; Clampin et al. 2003): the closest comparison is to HR 4796 A (G. Schneider 2005, private communication). The STIS image, while presenting literally hundreds of point sources, does not exhibit any obvious low-mass companions with conspicuous diffraction spikes, similar to those seen in association with HD 104237 (Grady et al. 2004) or HR 5999. If the disk were truncated by a previous close passage of a low-mass star, we infer that the perturbing object now lies outside the coronagraphic field, or farther than $25''$ – $50''$ from HD 163296.

In contrast to HD 100546, AB Aur, or T Tauri disks like TW Hya (Roberge et al. 2005), the inner disk of HD 163296 is fainter than the ansae, with surface brightness limit at $r \leq 2''$ indistinguishable from the other large-disk nondetections, such as MWC 480 (Fig. 1b). An optical nondetection might be due either to an absence of material near the star or to the inner disk being either dominated by larger grains and/or geometrically flatter than the outer disk. The presence of accretion onto the star, demonstrated by the presence of a far-ultraviolet (FUV) excess light continuum at *FUSE* wavelengths (Lecavelier des Etangs et al. 2003) and into the STIS spectral range, an Ly α bright bipolar jet (Devine et al. 2000) that produces a chain of HH knots that can be traced $28''$ from the star, and X-ray-bright knots (Swartz et al. 2005), excludes the presence of a cleared central cavity within $10''$ of HD 163296. We conclude that the inner portion of the HD 163296 disk is present but optically dark.

The remaining known large disk systems, MWC 480 (HD 31648), MWC 758 (HD 36112), and CQ Tau (HD 36910), have disk surface brightnesses that are below the PSF subtraction residuals of 10^{-7} relative to the total stellar flux per pixel $3''$ from the star.

3.8. Searching for Correlations with Bulk Disk Properties

Due to a wealth of mid-IR through millimeter observations, we can compare the optical disk surface brightness data with several bulk measures of the disk properties. The first, and simplest, measure is the integrated disk mass. The debris disks studied by STIS have dust masses of down to a few times $10^{-5} M_\odot$, while the Herbig Ae stars generally have disk masses estimated to be a few hundredths of a solar mass. With the exception of AB Aur and the inner $1''$ of the HD 100546 disk, the STIS Herbig Ae nebulosity detections are *fainter than all of the optically bright debris disks imaged by STIS*, HD 141569 A (Mouillet et al. 2001), HR 4796 A (G. Schneider et al. 2005, in preparation), and β Pic (Heap et al. 2000), at the same angular distances from the

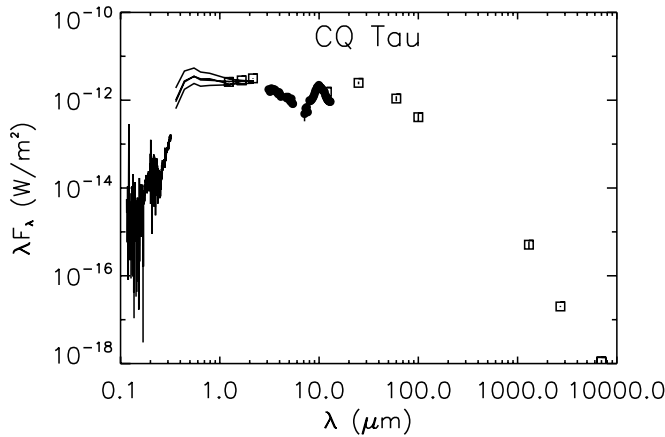


FIG. 5a

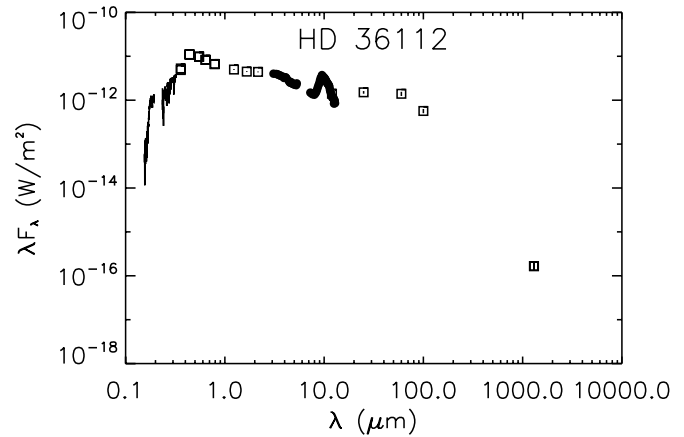


FIG. 5b

FIG. 5.—SEDs for CQ Tau and HD 36112 demonstrating the presence of Meeus et al. (2001) group I SEDs. (a) CQ Tau: SED from 0.16 μm to 7 mm. From shortest to longest wavelengths: merged *IUE* spectra (solid line); export *UBVRJHK* photometry (Oudmaijer et al. 2001; Eiroa et al. 2001) from four nights (1998 October 5, 26, 27; 1999 January 31; solid lines); Two Micron All Sky Survey (2MASS) *JHK* photometry (open squares); BASS spectroscopy (filled circles); *IRAS* photometry (12, 25, 60, and 100 μm ; open squares); and millimeter fluxes (Mannings & Sargent 1997; Testi et al. 2001; open squares). (b) SED for HD 36112 from 0.16 μm to 1.3 mm. *IUE* spectra SWP 53939 and LWP 30023 are shown in the UV. The *UBVRJ* data are from de Winter et al. (2001). *JHK* is from 2MASS. At longer wavelengths, *IRAS* photometry and the 1.3 mm flux from Mannings & Sargent (1997) are shown. Both stars have SEDs that would be classified as group I.

star. Thus, the Herbig Ae disk optical surface brightnesses do not correlate with the total disk mass, as inferred from single-dish millimeter observations.

3.8.1. Mid-IR Spectral Groups

Several recent studies have explored the IR–millimeter SEDs of Herbig Ae stars, including a number of our program stars. Meeus et al. (2001) grouped the 2.5–200 μm SEDs into two broad bins: (1) those stars with IR excesses consistent with a dust disk passively reprocessing the stellar light, which produces a power-law distribution (group II), and (2) those that have an additional component that can be modeled as a black-body (group I). For the Herbig Ae stars, the power-law + black-body group has been interpreted as systems where the gas and dust are well mixed, producing flared disks in hydrostatic equilibrium. The power-law SED systems can be interpreted as either the result of geometrical shadowing of the inner few tens of AU of the disk by heated material located near 0.3–0.5 AU, at the point that the dust in the inner disk sublimates, or systems

where grain growth and subsequent settling have occurred (Dullemond & Dominik 2004a, 2004b).

Six of our program stars were classified in the Meeus et al. (2001) study, while Acke & van den Ancker (2004) identified MWC 480, HD 95881, and HR 5999 as having group II SEDs. The remaining program stars, CQ Tau and HD 36112, lack *ISOPHOT* or *SWS* data but were observed with the BASS. The SEDs for both stars from the vacuum UV through the millimeter are shown in Figure 5, and expanded scale plots of the continuum normalized 10 μm silicate emission profiles are shown in Figure 6. Both stars would be classified as group Ia (black-body + power law with 10 μm silicate emission) by the criteria of Meeus et al. (2001). We find no correlation between disk surface brightness, as seen by STIS (Fig. 7a) or in the near-IR, as seen in the literature, and the Meeus et al. (2001) SED group: HD 135344, HD 36112, and CQ Tau are all disk nondetections with group I SEDs, while HD 169142 (Kuhn et al. 2001) is a detection. The situation is similar among the group II sources: HD 163296 is detected in our data, HD 150193 is seen in the

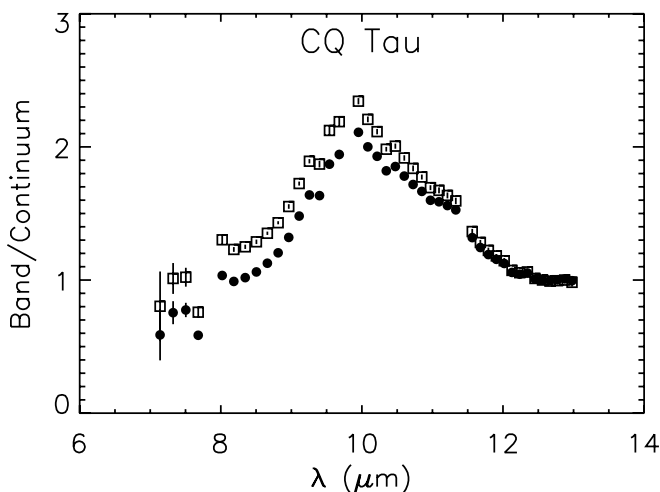


FIG. 6a

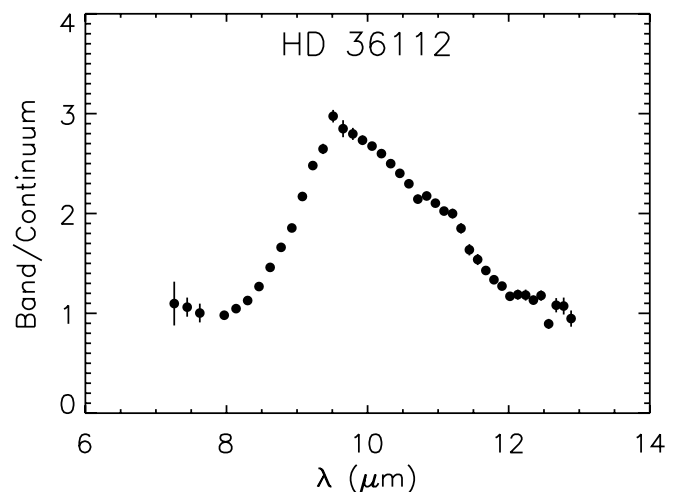


FIG. 6b

FIG. 6.—BASS spectra normalized to a local continuum at 7.5–8.5 μm and near 12.5 μm . The continuum is locally fitted as a blackbody curve. The BASS data reveal strong silicate emission at 10 μm , indicating that these stars fall into Meeus et al. (2001) group Ia.

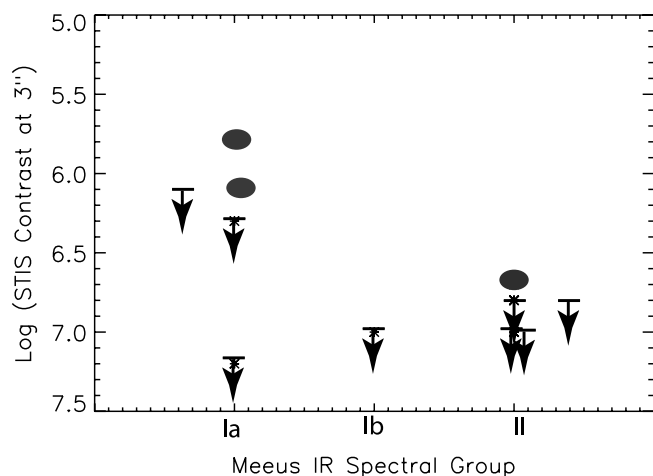


FIG. 7a

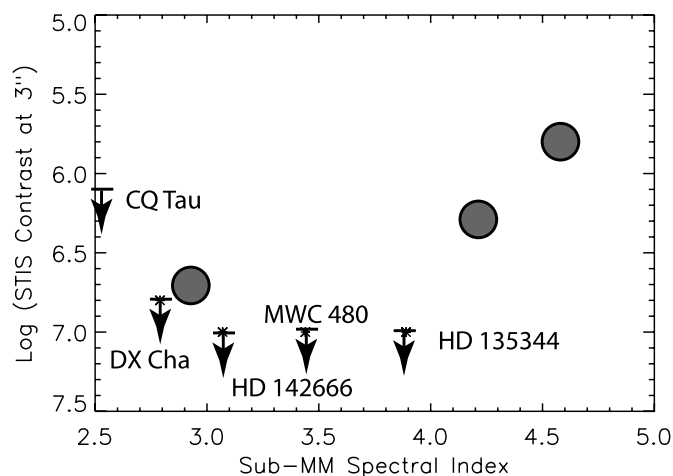


FIG. 7b

FIG. 7.—(a) Distribution of coronagraphic disk detections and nondetections among the Meeus mid-IR SED groups. (b) Distribution of coronagraphic disk detections as a function of submillimeter spectral index. The STIS data are taken from Table 4, and the submillimeter measurements from Acke et al. (2004).

near-IR (Fukagawa et al. 2003), while MWC 480 is a non-detection. We note that both of our binary stars, plus HD 144432, which Pérez et al. (2004) have identified as a binary, are classified as group II SEDs. This suggests that group II is heterogeneous and may include both large, potentially geometrically flat disks and stars with small disks that may have been tidally truncated.

3.8.2. Far-IR to Millimeter Spectral Indices

Acke et al. (2004) find a trend of larger submillimeter spectral indices in the group I sources than for the group II sources but a large dispersion within each group. Since the submillimeter slope of the SED is a measure of average grain properties in the disk, including both grain size and temperature (Beckwith & Sargent 1991), Acke et al. (2004) interpret this as indicating that the group II disks have larger average grain sizes. Generally, light is most efficiently scattered by dust grains that are comparable in size to the wavelength of the light (i.e., Bohren & Huffman 1983 under Mie theory), so one might expect a correlation between submillimeter spectral index, n , and disk surface brightness as seen by STIS. While the overlap between the Acke et al. (2004) sample and our program stars is not large, it is sufficient to test this hypothesis. While our bright nebulousity detections are associated with stars with large submillimeter spectral indices, e.g., smaller grains (HD 100546 and AB Aur; Fig. 7b), there is no correlation between optical or near-IR disk detection and submillimeter spectral index below $n = 4.0$. In the STIS data, HD 163296 is detected with n near 2.9, while MWC 480 is a nondetection at $n = 3.44$, and HD 135344 is a nondetection with $n = 3.89$. The situation worsens with the inclusion of the ground-based coronagraphic detections: HD 169142 has a bright near-IR disk (Kuhn et al. 2001) detected at $n = 3.56$, and HD 150193 is detected at n near 2.9 (Fukagawa et al. 2003). The lack of a correlation with the disk mass (§ 3.8) or with the average grain properties in the disk suggests that the optical and near-IR scattered light detections *do not trace the bulk of the disk material for Herbig Ae stars*. This is in marked contrast to the debris disks, where all of the known A star debris disks with $L_{\text{IR}}/L_{\text{bol}} \geq 10^{-3}$ are bright optical detections.

3.9. Correlations with Inner Disk Surface Properties

Next we consider how well the optical surface brightness of Herbig Ae star protoplanetary disks correlates with the inner disk properties, beginning with material accreting onto the star

and continuing out to emission lines that are formed at AU-scale distances from the star.

3.9.1. Presence of Ongoing Accretion

T Tauri stars that are accreting material from their protoplanetary disks exhibit a number of distinctive features in their optical/UV spectra, including the presence of bipolar microjets or associated chains of Herbig-Haro knots, excess light at short wavelengths that is produced in the accretion shock (Gullbring et al. 2000; Calvet et al. 2004), and distinctive emission-line profiles in a wide range of ionization stages. While T Tauri stars exhibit detectable UV excesses due to accretion onto the star beginning at U band, detecting such excesses against the photospheres of hotter A and early B stars requires data at shorter wavelengths. Ten of our program stars have been observed from 912 through 1180 Å by *FUSE* through 2004 August. The *FUSE* spectral range includes wavelengths where distinctive photospheric features (C I transitions and the C I edge) can be detected for our hotter program stars. However, for stars later than A2 at the V magnitudes of our program stars, no photospheric signal should be detected by *FUSE*: detection of a continuum constitutes a direct detection of a UV/FUV excess for such stars. The *FUSE* spectral range also includes transitions of C III (977 and 1176 Å) and O VI (1032 and 1038 Å). While normally seen in the chromospheres and transition regions of late-type stars, these features have been detected in association with several Herbig Ae stars (Roberge et al. 2001; Lecavelier des Etangs et al. 2003; Deleuil et al. 2004). The O VI emission profiles are particularly broad and, in some cases, are known to exhibit enhanced variability on their long-wavelength side, providing a direct detection of infalling material. The full *FUSE* data set is reviewed in Williger et al. (2004). When corrected for distance and extinction, the *FUSE* Herbig Ae stars with STIS data exhibit O VI fluxes in a narrow range, which is a factor of 10–100 above that seen in nonaccreting young stars (Fig. 8a). FUV excesses are seen in all of our program stars with *FUSE* data with the exception of HD 100546: an FUV excess at the level seen in HD 135344 cannot be excluded. Two of these stars have bipolar microjets that have been detected in $\text{Ly}\alpha$ (HD 163296, Devine et al. 2000; HD 104237 A, Grady et al. 2004), while AB Aur has an associated chain of HH knots and UV integrated light spectral signatures of a jet (Williger et al. 2004) and MWC 480 is driving a parsec-scale chain of HH knots (Stecklum et al. 2005). Lower levels of activity

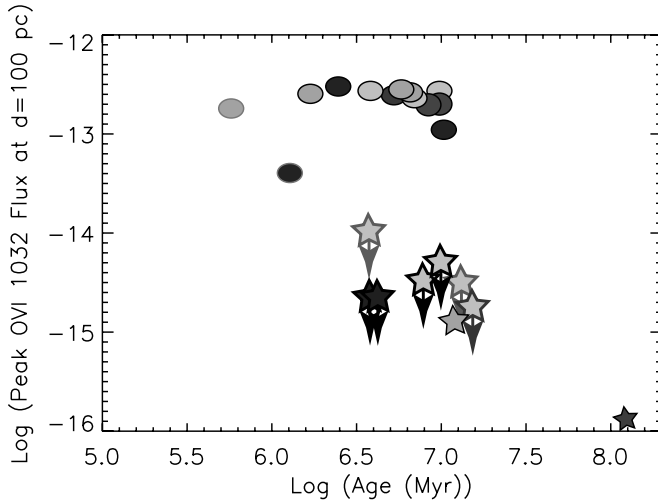


FIG. 8a

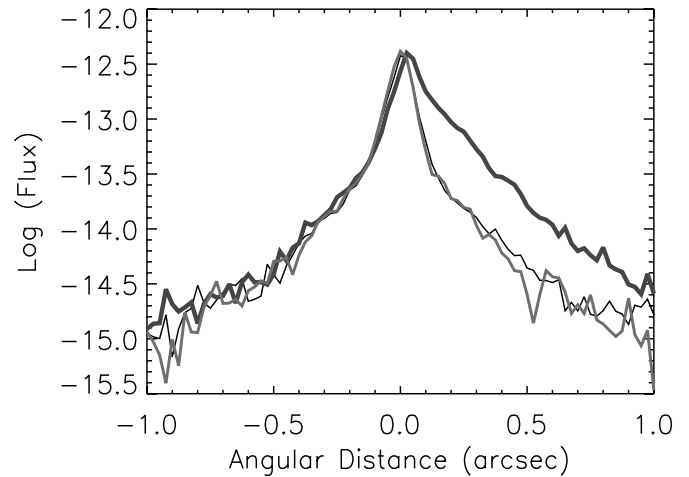


FIG. 8b

FIG. 8.—(a) Peak fluxes in transition region species such as O VI λ 1023 show only a limited range for the Herbig Ae stars observed by *FUSE*, which lies above the scaled flux for β Pic and upper limits for coeval, nonaccreting young A stars. Age estimates for individual objects are uncertain by typically several million years, while the flux uncertainties are smaller than the plot symbols. (b) Spatial profiles near 1230 Å for HD 104237 (black line), HD 163296 (light gray line), and HD 100546 (dark gray line) along the system semiminor axis, at wavelengths where reflection nebosity and strong H₂ emission are seen in the HD 100546 spectrum. From 10 to 70 AU, the disk of HD 100546 is a factor of 5–6 times brighter than those of the group II Herbig Ae stars.

appear to be present in HD 100546, which is not driving a jet (Grady et al. 2005), and HD 135344, which shows O VI and C III profiles typical of chromospheric and transition regions. The presence or absence of ongoing accretion does not appear to affect the visibility of the disk at $r \geq 50$ –70 AU from the star.

3.9.2. Material at AU-Scale Distances from the Star

Many Herbig Ae stars have mid-IR emission features due to small, warm silicate grains (Meeus et al. 2001). The emission is believed to originate in the upper layers of the disk (van Boekel et al. 2003; Bouwman et al. 2001; Meeus et al. 2001) and thus provides a probe of conditions at the disk surface within 10 AU of the star (Leinert et al. 2004). The feature is most conspicuous for submicron grains and becomes undetectable for grains much larger than $a \approx 3 \mu\text{m}$ (e.g., Lynch & Mazuk 2000). Van Boekel et al. (2003) find a correlation between the strength of the 10 μm silicate feature and its shape among the Meeus et al. (2001) group II sources. While the two group II disk detections (HD 163296 and HD 150193) are among the disks with the stronger silicate features and hence smaller grains in the disk surface layers, other disks that are not detected in the optical or near-IR, such as HD 31648 (Augereau et al. 2001), HD 36112, and CQ Tau (Fig. 6), have silicate emission profiles similar to, or stronger than, the detected sources (Sitko et al. 1999). Moreover, some disks are detected (HD 169142; Kuhn et al. 2001) that lack silicate emission. This suggests that the warm silicate emission (or its absence) is not a robust predictor of the appearance of the disk beyond 50 AU.

FUV reflection nebosity and fluorescent H₂ emission.—Three of our program stars have STIS G140M long-slit spectra at Ly α : HD 100546, HD 163296, and HD 104237. While initially used to search for the presence or absence of microjets, the 50 Å coverage of the spectra can sample both reflection nebosity visible in the FUV and transitions of neutral atomic and molecular gas. The H₂ transitions are of particular interest, since in order to fluoresce, pumping by FUV photons is required (Herczeg et al. 2002, 2004). Far from bright OB stars, the diffuse interstellar radiation field is insufficient to excite these transitions at levels detectable in single-orbit STIS integrations, so their presence implies that the molecular gas has a direct line

of sight to the Herbig Ae star. Geometrically flat disks and those with constant opening angle should produce no detectable H₂ emission other than from the inner edge of the dust and gas disk, since material at that location will shadow the outer disk out to arbitrarily large radii. Both reflection nebosity and fluorescent H₂ emission are seen along the disk semiminor and semimajor axes for HD 100546 (Grady et al. 2005).

Figure 8b shows radial flux profiles in a swath near 1230 Å along the system minor axis of each system. Both HD 104237 and HD 163296 have radial profiles indistinguishable from that of the O subdwarf GD 71. For HD 100546, the flux peak is offset to the northeast of the star: the bandpass chosen to highlight both the reflection nebosity and some of the stronger H₂ transitions noted by Grady et al. (2005) has some contamination from the stellar photosphere, reducing the spatial offset from that seen at line center in Ly α . From 0".1 to 0".7 (10–70 AU) from HD 100546 the nebosity is a factor of 5–6 times brighter than the stellar PSF and the two Meeus group II Herbig Ae star disks. A difference in the Ly α flux alone cannot account for this difference: HD 104237, one of the disk nondetections at these wavelengths, has a variable Ly α peak flux ranging between 64 and 100 times brighter than the peak flux seen in HD 100546. PSF wings elevated over the GD 71 profile by 25% are marginally detected in the wings of Ly α at wavelengths where the jets in both systems do not contribute significantly. This may represent detection of a wide-angle wind, as suggested in Devine et al. (2000), the H I liberated from the photodissociation of OH, if Acke & van den Ancker (2004) are correct, or the result of photodissociation of H₂. While the difference in the surface brightness of the reflection nebosity near the two group II Herbig Ae stars might be a simple consequence of average grain size at the disk surface, the absence of H₂ emission indicates that the group II sources have less material at high altitude above the disk midplane.

3.10. Correlation with Outer Disk Surface Properties

Silicate emission and other thermally excited solid-state bands are not the only tracers of material in the outer disk. Forty percent of the Meeus et al. (2001) Herbig Ae stars have detectable PAH emission in their *ISO* integrated light spectra. Like

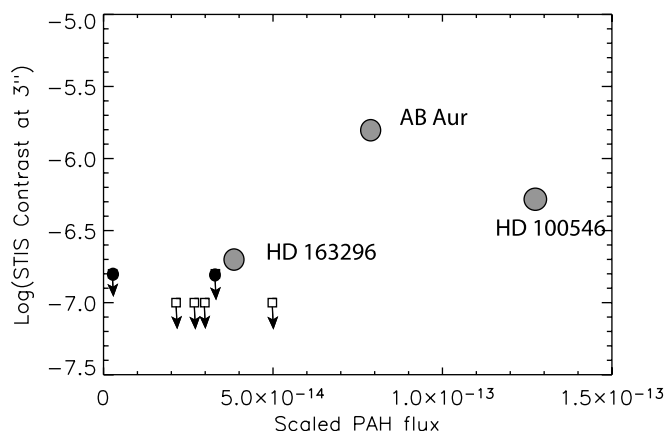


FIG. 9.—In contrast to the millimeter data and appearance of the IR SED, the optical disk surface brightness shows a general correlation with the strength of the PAH emission at $6.2\ \mu\text{m}$, scaled to a common distance of 100 pc.

the H_2 emission, the mid-IR PAH features are transiently excited by absorption of FUV photons and sample material with a direct line of sight to the FUV source. All of our program stars lie far from other strong FUV sources, so the PAH emission must be excited by the Herbig Ae star itself. Detection of spatially resolved PAH emission, therefore, probes portions of the surface of a circumstellar disk that are *unshadowed* by material closer to the star. In the *ISO* sample, the PAH emission, particularly the $6.2\ \mu\text{m}$ feature, is most conspicuous in the disks with large submillimeter spectral indices, from Meeus group I. These objects include our bright nebosity systems, AB Aur and HD 100546. The PAH emission from HD 100546 extends over 100–150 AU from the star (van Boekel et al. 2004a), covering the region producing the fluorescent H_2 emission seen in the STIS spectra. Habart et al. (2004) have modeled the PAH emission from Herbig Ae stars and find that 6.2 and $11.2\ \mu\text{m}$ features should be most extended for ionized PAHs containing 100 carbon atoms.

Comparison of the STIS relative surface brightnesses at $3''$ from the star with the *ISO* sample (Meeus et al. 2001; Acke & van den Ancker 2004) shows that the optical visibility of the large disks correlates with the strength of the $6.2\ \mu\text{m}$ (Fig. 9) and to a lesser extent with the $7.7\ \mu\text{m}$ PAH features. In both cases, PAH nondetections include smaller disks (e.g., HD 104237, Grady et al. 2004; HD 150193, Kuhn et al. 2001), as well as larger disks with shallow submillimeter spectral indices. Acke et al. (2005) report a correlation of $[\text{O I}] \lambda 6300$ flux and PAH emission. While $[\text{O I}]$ emission can be produced in outflows from T Tauri stars (Hartigan et al. 2004), Acke & van den Ancker (2004) interpret the emission as arising from the photodissociation of water. The similar behavior of tracers of grains (reflection nebosity, PAHs), icy material ($[\text{O I}]$), and the fluorescent H_2 emission indicates that Herbig Ae disk surfaces have a wide range of scale heights and/or flare angles at any given distance from the star.

4. DISCUSSION

Eleven Herbig Ae stars have been coronagraphically observed with the white-light coronagraph on *HST* STIS. We find the following:

1. An absence of nebosity at $r \geq 0''.5$ associated with the two confirmed binary/multiple stars in the sample, HR 5999 and HD 104237. For HD 104237, direct detection of counterjet material in $\text{Ly}\alpha$ (Grady et al. 2004) demonstrates that the disks of the Herbig Ae stars in these comparatively close binary sys-

tems are geometrically small, with $r_{\text{outer}} \leq 0''.6$. The small disk size naturally accounts for the weak far-IR and submillimeter emission associated with these stars.

2. For disks that are spatially resolved in the millimeter, we find that the optical surface brightness of the disks spans at least 2 orders of magnitude at any given radius from the star. Some of the most conspicuous protoplanetary disks in the millimeter are among the optical nondetections (e.g., MWC 480). In the optical, the three bright A star debris disk systems, HD 141569 A, HR 4796 A, and β Pic, have optical disk surface brightnesses that are in the upper half of the range spanned by the Herbig Ae protoplanetary disks.

3. We find no correlation between the Herbig Ae disk surface brightness in the optical and measures of the bulk disk properties including disk mass and average grain size. This is in marked contrast to the debris disks, where the optical brightness does appear to correlate with inferred disk mass and fractional IR luminosity. An immediate conclusion is that the disks associated with Herbig Ae stars, unlike the debris disks, are optically thick. The optical data, as well as the more limited near-infrared data, sample the upper reaches of the disks and *do not probe the bulk of the disk material*. This finding has implications for the classes of models that can be used to account for structure observed in the disks: models tracing the density in the disk should not be used to interpret the scattered light features seen in Herbig Ae disks without supporting data (e.g., millimeter data) that directly map the disk density. Such data, with spatial resolution that can be directly compared with the *HST* images, will become available for all of our program stars once ALMA is operational.

4. We find a correlation between disk surface brightness and the strength of molecular gas transitions and the mid-IR PAH features that are photoexcited by FUV photons. These features will be excited in the environments of our program stars only when the small grains and/or molecular gas are directly illuminated by the star and its FUV radiation and thus trace the presence of material that is sufficiently far above the disk midplane that it is unshadowed by the inner disk. The correlation between the integrated strength of these features, the optical surface brightness of the disk, the limited FUV reflection nebosity and H_2 emission data, and the $[\text{O I}] \lambda 6300$ emission (Acke et al. 2005) suggests that the pattern of disk detection and nondetection is a measure of the degree of flaring of the outer disk.

4.1. Implications for Dust Settling and Transport Mechanisms

Many of the large disks that are optically faint have IR SEDs consistent with disks with sufficiently low accretion rates that the disk emission is due to heating by the star alone (e.g., the disks passively reprocess the stellar light; Chiang et al. 2001). For such disks, as noted by van Boekel et al. (2003), dust grains should gravitationally settle toward the disk midplane over time, with large grains vanishing first and settling out in $t \leq 1$ Myr, while $0.1\ \mu\text{m}$ grains remain aloft through most of the PMS lifetime of the star. Habart et al. (2004) note that the emission associated with PAHs is a good tracer of the presence of very small particles in the upper layers of circumstellar disks. Under gravitational settling alone, we would expect a pattern of the older disks being primarily visible via their smallest grains, with a trend to detection of light scattering of micron-sized grains in the younger systems. While the age estimates of Herbig Ae stars are frequently uncertain by several million years, the disks around the older stars in this scenario should be preferentially detected in the PAH features and not via reflection nebosity. At present, there are no disks that have been detected only in the PAH features: reflection nebosity is typically present. Moreover, the

presence of a correlation between PAH emission and the optical surface brightness of the disks suggests that this simple settling scenario is not operating at $r \geq 50\text{--}70$ AU from the star. Van Boekel et al. (2003) reached similar conclusions for the inner 10–20 AU of the disk from the silicate data.

Is it reasonable to propose a simple disk stratification? VLA¹⁴ observations of some of our program stars (CQ Tau, Testi et al. 2003; HD 163296, Natta et al. 2004) confirm the presence of very large grains within 100 AU of the star. Once grains grow and begin to settle toward the midplane, the remaining small grains will experience an increase in the UV flux from the star reaching them. The correlation between disk surface brightness and photodissociation region species such as the [O I] and PAH emission suggests that the remaining small grains may photo-dissociate rapidly, resulting in a disk that is geometrically thinner rather than producing a disk with large-scale vertical stratification. If settling is present, in a sufficiently large sample, there should be some disk detections where the inner, higher density portions of the disk have settled and become dark, while the outer, lower density portions of the disk remain flared and well mixed. The available coronagraphic and FUV data suggest that HD 163296 may be one such system. HD 163296 is not alone: the classical T Tauri star, DM Tau, also has STIS coronagraphic imagery showing a faint ring with dark inner disk (C. A. Grady et al. 2005, in preparation). DM Tau has an estimated age of 5 Myr (Simon et al. 2000), and HD 163296 has been variously estimated as being 2–6 Myr (van den Ancker et al. 1998), while membership in Sco-Cen suggests $t \approx 5$ Myr.

The STIS data reveal protoplanetary disks as three-dimensional structures with significant structure within the disks. The combination of imagery and spectroscopy sampling cosmochemical tracers indicates that the range in disk surface brightness may be due to environment (disk truncation for the close binaries) and changes in the degree of flaring of the disk over time and as a function of radius from the star. Much of the latter process may be tied to grain growth, an expected precursor to planetesimal formation. The STIS data indicate that the preliminary phases of this process are not limited to regions on the scale of the planetary zone in the solar system but may extend much farther from the star. Early planetary system formation scenarios had suggested that after the protoplanetary disk forms, the infalling envelope dissipates, the disk flattens, and then the planets form. The STIS coronagraphic data suggest that reality may be more complex: If HD 100546 is indeed a zero-age main-sequence star (van den Ancker et al. 1997), the fact that it has retained a 1000 AU envelope through the entire PMS lifetime of the star and that the binary/multiple stars apparently lack such envelopes by 0.7–5 Myr suggests that retention of the outer envelope and large disks may owe more to the star-forming environment than to the activity of the star itself. Similarly, the detection of what appears to be a central cavity in the HD 100546 disk (Bouwman et al. 2003; Grady et al. 2005) suggests that the disk flattening may not be a prerequisite for planet formation.

4.2. Implications for Future Missions

HST STIS has demonstrated that the optical surface brightness of protoplanetary disks spans at least 2 orders of magnitude at any radius within 3'' of the star. The optically detected A star

debris disks lie in the upper half of this range: fainter debris disks are likely to have a similar or larger range in surface brightness. If the trend of PAH emission correlating with disk surface brightness extends to optically fainter disks, the STIS data suggest that with a factor of 10 improvement in coronagraph contrast over that achieved by the *HST* coronagraphs, the majority of large Herbig Ae disks may be directly detectable at $r \geq 50\text{--}70$ AU. The more limited long-slit spectroscopic data indicate that the nebulosity within 0''.5 may follow the same trend as the outer disk surface brightness, with nebulosity spanning a dynamic range of at least a factor of 20 at 0''.3 (30–40 AU for our program stars). Of particular interest are disks like those of HD 163296 that have a hybrid character: an outer, relatively bright ring of reflection nebulosity, with the inner disk much darker. Probing such disks will require the next generation of coronagraphs capable of limiting contrasts in excess of 10^8 within 2'' of the star.

HD 100546 and all of the A star debris disks imaged to date have central clearing of the disk and/or other dynamical signatures (rings, clumps, warps) suggesting that planetary mass bodies may have already formed by 10–12 Myr. If the AU Mic disk is representative of disks around lower mass stars (Kalas et al. 2004; Liu et al. 2004; Liu 2004), this conclusion is not limited to intermediate-mass stars but may extend throughout the stellar mass range that will be probed in more detail by *TPF Coronagraph*. The available data indicate that *young* planetary systems retain significant amounts of circumstellar nebulosity that will provide a bright, potentially structured background for planet detection. In addition to the ability to suppress the stellar diffracted and scattered light to a level needed for planet detection, the STIS experience suggests that the *TPF Coronagraph* must have a high intrascene dynamic range.

Our study of the Herbig Ae star disks has greatly benefited from access to multiwavelength spectroscopic data. Such data are needed to firmly establish whether disk material is reaching the star and to provide the chemical diagnostics that can allow one to separate structural differences in the disks from illumination effects. At present, for the Herbig Ae stars we are largely limited to integrated light spectroscopy of the disks, particularly in the mid-IR. Such data do not allow one to distinguish between a geometrically small disk and a larger disk that is geometrically flat without access to other data, such as detection of emission from a counterjet, which constrains the disk outer radius. What is really needed is the ability to image the disks in selected transitions with a spatial resolution comparable to that of the optical imagery. Herbig Ae stars and their inner disks are bright objects in the mid-IR (Meeus et al. 2001). Even at 10 μm , the thermal emission is largely confined to the inner disk (Leinert et al. 2004); the outer disk will be detected via scattered light and by photoexcited emission features. Direct imaging of the outer disks will require not only a large IR-optimized aperture but also use of a cooled coronagraph and detectors that can accommodate large dynamic range scenes. Going beyond morphological studies, the first systematic chemical assays of circumstellar disks in the mid-IR will require either coronagraphic long-slit spectroscopy or a suitable filter complement.

Van Boekel et al. (2003) have noted that the presence of silicate features indicating the presence of small grains in the disks of stars with ages of several million years suggests either the presence of turbulence in the disk or the presence of large-scale transportation mechanisms that can preferentially enrich the upper margins of the outer disk. More recently, detection of radial gradients in the silicate emission profiles (van Boekel et al. 2004b) implies that some form of radial mixing or

¹⁴ The National Radio Astronomy Observatory is a facility of the National Science Foundation operated under cooperative agreement by Associated Universities, Inc.

transport mechanism must have been operating in these disks. Such mixing mechanisms can potentially account for the presence of partially crystalline silicates and organics beyond the “snow line,” with subsequent incorporation into icy planetesimals. The organics, in particular, are preferentially synthesized in the warm, dense conditions appropriate to the inner AU of the protoplanetary disk (Hill & Nuth 2003). Information on the geometry of the wind and whether it is distinct from the spatial distribution of features associated with photodissociation of other materials in the upper layers of the disk is needed to determine whether the transport mechanism operates within the disk or is associated with a wide-angle wind. While some of the atomic gas species have transitions in the optical, including H I and O I, the bulk of wind features are located in the vacuum UV, and other PDR species such as the H₂ transitions that are pumped by Ly α occur at $\lambda \leq 1700$ Å. Our STIS experience has shown that while these features are conspicuous in the FUV integrated light spectra of T Tauri stars (Valenti et al. 2000; Herczeg et al. 2002; Bergin et al. 2004), they are swamped by the stellar photosphere and light from the accretion shock in integrated light spectra of Herbig Ae stars. Direct detection of these species, together with other photodissociation species such as OH, requires high spatial resolution, high dynamic range, and potentially coronagraphic, spectral imagery. If the *TPF*

Coronagraph optics permit, such a capability would greatly enhance disk studies with that platform.

This study made use of *HST* observations obtained as part of HST-GTO-7065, HST-GTO-8065, HST-GTO-8474, HST-GTO-9241, HST-GTO-8891, and HST-GO-8674. PSF template star data were acquired under HST-GO-9136. This study made use of *FUSE* data obtained under *FUSE* programs C126, D065, and E510. Support for the STIS IDT was provided by NASA Guaranteed Time Observer (GTO) funding to the STIS Science Team in response to NASA A/O OSSA-4-84 through the *Hubble Space Telescope* Project at Goddard Space Flight Center. C. A. G. was supported through NASA PO 70789-G, HST-GO-9136, NASA PR NNG04EA16P, and NASA PR 4200048153 to Eureka Scientific. M. L. S. was supported under NASA NAG5-13242 and NAG5-9475 to the University of Cincinnati. D. K. L. and R. W. R. were supported by the Aerospace Corporation’s Independent Research and Development Program. Data analysis facilities were provided by the Laboratory for Astronomy and Solar Physics, at NASA’s GSFC. Special thanks to Karl Stapelfeldt and the anonymous referee for useful comments while the paper was still in manuscript.

REFERENCES

- Acke, B., & van den Ancker, M. E. 2004, *A&A*, 426, 151
- Acke, B., van den Ancker, M. E., & Dullemond, C. P. 2005, *A&A*, in press (astro-ph/0502504)
- Acke, B., van den Ancker, M. E., Dullemond, C. P., van Boekel, R., & Waters, L. B. F. M. 2004, *A&A*, 422, 621
- Augereau, J.-C., Lagrange, A.-M., Mouillet, D., & Ménard, F. 2001, *A&A*, 365, 78
- Beckwith, S. V. W., & Sargent, A. I. 1991, *ApJ*, 381, 250
- Bergin, E. A., et al. 2004, *ApJ*, 614, L133
- Beskrovnaya, N. G., et al. 1999, *A&A*, 343, 163
- Blake, G. A., & Boogert, A. C. A. 2004, *ApJ*, 606, L73
- Bohren, C. F., & Huffman, D. R. 1983, *Absorption and Scattering of Light by Small Particles* (New York: Wiley)
- Bouwman, J., de Koter, A., Dominik, C., & Waters, L. B. F. M. 2003, *A&A*, 401, 577
- Bouwman, J., Meeus, G., de Koter, A., Hony, S., Dominik, C., & Waters, L. B. F. M. 2001, *A&A*, 375, 950
- Calvet, N., Muzerolle, J., Briceño, C., Hernández, J., Hartman, L., Saucedo, J. L., & Gordon, K. D. 2004, *AJ*, 128, 1294
- Chiang, E. I., Jøung, M. K., Creech-Eakman, M. J., Qi, C., Kessler, J. E., Blake, G. A., & van Dishoeck, E. F. 2001, *ApJ*, 547, 1077
- Clampin, M., et al. 2003, *AJ*, 126, 385
- Corder, S., Eisner, J., & Sargent, A. 2005, *ApJ*, 622, L133
- Deleuil, M., Lecavelier des Etangs, A., Bouret, J.-C., Roberge, A., Vidal-Madjar, A., Martin, C., Feldman, P. D., & Ferlet, R. 2004, *A&A*, 418, 577
- Devine, D., et al. 2000, *ApJ*, 542, L115
- de Winter, D., van den Ancker, M. E., Mair, A., Thé, P. S., Tjin A Djie, H. R. E., Redondo, I., Eiroa, C., & Molster, F. J. 2001, *A&A*, 380, 609
- Dullemond, C. P., & Dominik, C. 2004a, *A&A*, 417, 159
- . 2004b, *A&A*, 421, 1075
- Dunkin, S., Barlow, M. J., & Ryan, S. G. 1997, *MNRAS*, 290, 165
- Eiroa, C., et al. 2001, *A&A*, 365, 110
- Eisner, J. A., Lane, B. F., Akeson, R. L., Hillenbrand, L. A., & Sargent, A. I. 2003, *ApJ*, 588, 360
- Eisner, J. A., Lane, B. F., Hillenbrand, L. A., Akeson, R. L., & Sargent, A. I. 2004, *ApJ*, 613, 1049
- Fukagawa, M. 2005, Ph.D. thesis, Univ. Tokyo
- Fukagawa, M., Tamura, M., Itoh, Y., Hayashi, S. S., & Oasa, Y. 2003, *ApJ*, 590, L49
- Fukagawa, M., et al. 2004, *ApJ*, 605, L53
- Grady, C. A., Woodgate, B. E., Bruhweiler, F. C., Boggess, A., Plait, P., Lindler, D. J., Clampin, M., & Kalas, P. 1999, *ApJ*, 523, L151
- Grady, C. A., Woodgate, B. E., Heap, S. R., Bowers, C., Nuth, J. A., III, Herczeg, G., & Hill, H. G. M. 2005, *ApJ*, 620, 470
- Grady, C. A., et al. 2000, *ApJ*, 544, 895
- . 2001, *AJ*, 122, 3396
- . 2003, *PASP*, 115, 1036
- Grady, C. A., et al. 2004, *ApJ*, 608, 809
- Grinin, V. P., Kiseleva, N. N., Chernova, G. P., Minikulov, N. Kh., & Voshchinnikov, N. V. 1991, *Ap&SS*, 186, 283
- Grinin, V. P., & Tarnobtseva, L. V. 2002, *Astron. Lett.*, 28, 601
- Gullbring, E., Calvet, N., Muzerolle, J., & Hartmann, L. 2000, *ApJ*, 544, 927
- Habart, E., Natta, A., & Krügel, E. 2004, *A&A*, 427, 179
- Hartigan, P., Edwards, S., & Pierson, R. 2004, *ApJ*, 609, 261
- Heap, S. R., Lindler, D. J., Lanz, T. M., Cornett, R. H., Hubeny, I., Maran, S. P., & Woodgate, B. 2000, *ApJ*, 539, 435
- Herczeg, G. J., Linksy, J. L., Valenti, J. A., Johns-Krull, C. M., & Wood, B. E. 2002, *ApJ*, 572, 310
- Herczeg, G. J., Wood, B. E., Linksy, J. L., Valenti, J. A., & Johns-Krull, C. M. 2004, *ApJ*, 607, 369
- Hill, H. G. M., & Nuth, J. A. 2003, *Astrobiology*, 3, 291
- Kalas, P., Liu, M. C., & Mathews, B. C. 2004, *Science*, 303, 1990
- Kuhn, J. R., Potter, D., & Parise, B. 2001, *ApJ*, 553, L189
- Lecavelier des Etangs, A., et al. 2003, *A&A*, 407, 935
- Leinert, Ch., et al. 2004, *A&A*, 423, 537
- Liu, M. C. 2004, *Science*, 305, 1442
- Liu, M. C., Mathews, B. C., Williams, J. P., & Kalas, P. G. 2004, *ApJ*, 608, 526
- Liu, W. M., Hinz, P. M., Meyer, M. R., Mamajek, E. E., Hoffmann, W. F., & Hora, J. L. 2003, *ApJ*, 598, L111
- Lowrance, P., et al. 1999, *ApJ*, 512, L69
- Lynch, D. K., & Mazuk, S. 2000, in *ASP Conf. Ser. 196, Thermal Emission Spectroscopy and Analysis of Dust, Disks, and Regoliths*, ed. M. L. Sitko, A. Sprague, & D. K. Lynch (San Francisco: ASP), 127
- Lynch, D. K., Russell, R. W., & Sitko, M. L. 2000, *Icarus*, 144, 187
- Mannings, V., Koerner, D. W., & Sargent, A. I. 1997, *Nature*, 388, 555
- Mannings, V., & Sargent, A. I. 1997, *ApJ*, 490, 792
- . 2000, *ApJ*, 529, 391
- Meeus, G., Waelkens, C., & Malfait, K. 1998, *A&A*, 329, 131
- Meeus, G., Waters, L. B. F. M., Bouwman, J., van den Ancker, M. E., Waelkens, C., & Malfait, K. 2001, *A&A*, 365, 476
- Mora, A., et al. 2001, *A&A*, 378, 116
- Mouillet, D., Lagrange, A. M., Augereau, J. C., & Ménard, F. 2001, *A&A*, 372, L61
- Natta, A., Testi, L., Neri, R., Shepherd, D. S., & Wilner, D. J. 2004, *A&A*, 416, 179
- Natta, A., & Whitney, B. A. 2000, *A&A*, 364, 633
- Oudmaijer, R. D., et al. 2001, *A&A*, 379, 564
- Pérez, M. R., van den Ancker, M. E., de Winter, D., & Bopp, B. W. 2004, *A&A*, 416, 647
- Perryman, M. A. C., et al. 1997, *A&A*, 323, L49
- Roberge, A., Weinberger, A. J., & Malumuth, E. 2005, *ApJ*, 622, 1171
- Roberge, A., et al. 2001, *ApJ*, 551, L97
- Schneider, G. 2002, in *The 2002 HST Calibration Workshop: Hubble after the Installation of the ACS and the NICMOS Cooling System*, ed. S. Arribas, A. Koekemoer, & B. Whitmore (Baltimore: STScI), 250

- Schneider, G., et al. 2002, Domains of Observability in the Near-Infrared with *HST*/NICMOS and (Adaptive Optics Augmented) Large Ground-based Telescopes, <http://www.stsci.edu/hst/proposing/docs/nicmos-ao-whitepaper.html>
- Simon, M., Dutrey, A., & Guilloteau, S. 2000, *ApJ*, 545, 1034
- Sitko, M. L., Grady, C. A., Lynch, D. K., Russell, R. W., & Hanner, M. S. 1999, *ApJ*, 510, 408
- Stecklum, B., Eckart, A., Henning, T., & Loewe, M. 1995, *A&A*, 296, 463
- Stecklum, B., Grady, C. A., & Muensinger, H. 2005, in preparation
- Swartz, D. A., Drake, J. J., Eisner, R. F., Ghosh, K. K., Grady, C. A., Wassell, E., Woodgate, B. E., & Kimble, R. A. 2005, *ApJ*, 628, 811
- Testi, L., Natta, A., Shepherd, D. S., & Wilner, D. J. 2001, *ApJ*, 554, 1087
- . 2003, *A&A*, 403, 323
- Thé, P.-S., Tjin A Djie, H. R. E., Brown, A., Linksy, J. L., & Catala, C. 1985, *Irish Astron. J.*, 17, 79
- Valenti, J. A., Johns-Krull, C. M., & Linsky, J. L. 2000, *ApJS*, 129, 399
- van Boekel, R., Waters, L. B. F. M., Dominik, C., Bouwman, J., de Koter, A., Dullemond, C. P., & Paresce, F. 2003, *A&A*, 400, L21
- van Boekel, R., Waters, L. B. F. M., Dominik, C., Dullemond, C. P., Tielens, A. G. G. M., & de Koter, A. 2004a, *A&A*, 418, 177
- van Boekel, R., et al. 2004b, *Nature*, 432, 479
- van den Ancker, M. E., et al. 1997, *A&A*, 324, L33
- . 1998, *A&A*, 330, 145
- Williger, G. M., Grady, C. A., Woodgate, B. E., Bouret, J.-C., Roberge, A., & Sahu, M. 2004, *AAS*, 205, 1611
- Wilner, D. J., Bourke, T. L., Wright, C. M., Jorgensen, J. K., van Dishoeck, E. F., & Wong, T. 2003, *ApJ*, 596, 597