# An Edge-on Circumstellar Disk in the Young Binary System HK Tauri[1,2]

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[1]Using the NASA/ESA Hubble Space Telescope

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## ABSTRACT

Hubble Space Telescope images of HK Tauri reveal that the companion star in this 2.4″ (340 AU) pre-main sequence binary system is an entirely nebulous object at visual wavelengths. HK Tau/c appears as two elongated reflection nebulosities separated by a dark lane. Near-infrared adaptive optics observations made at the Canada-France-Hawaii Telescope show a similar morphology, and no directly visible star at $\lambda \leq 2.2$ $\mu$m. HK Tau/c is strikingly similar to scattered light models of an optically thick circumstellar disk seen close to edge-on, and to the HST images of HH 30 (Burrows *et al.* 1996). HK Tau/c is therefore the first disk to be clearly resolved around an individual star in a young binary system.

The disk properties have been constrained by fitting model reflection nebulae to the HST images. The disk has a radius of 105 AU, inclination of about 5°, scale height of 3.8 AU at $r = 50$ AU, and is flared. The absence of a point source in the near-IR requires $A_V > 50$ mag toward the unseen central star. The thickness of the dark lane establishes a disk mass near $10^{-4}$ $M_{\odot}$ ($\sim 0.1$ $M_{\rm Jupiter}$) of dust and gas, if the dust grains have interstellar properties and remain fully mixed vertically. With the observed disk radius equal to only 1/3 the projected separation of the binary, there is a strong possibility that tidal truncation of the circumsecondary disk has occurred in this system.

## 1. Introduction

The formation of circumstellar disks is now a generally accepted by-product of star formation processes (Shu *et al.* 1993). The Hubble Space Telescope (HST) and groundbased adaptive optics can now provide high resolution images of young star environs at a spatial resolution of 10 AU (Stapelfeldt *et al.* 1997; Roddier *et al.* 1996), making the internal structures of disks similar to the early solar system accessible to detailed study (Burrows *et al.* 1996). To build upon this initial work, we are conducting a T Tauri star snapshot survey using the HST. Our goal is to detect and characterize disks across a broad sample of young stars, including binaries, jet sources, and weak line T Tauri stars. One of the early and especially interesting results of our survey is reported in this *Letter*.

HK Tauri (HBC 48) is a pre-main sequence star located in the L1529/B18 molecular cloud at a distance of 140 pc (Kenyon, Dobrzycka, and Hartmann 1994). Optical [O I] emission lines indicate that HK Tau is the source of an unresolved jet (Hartigan, Edwards, and Ghandour 1995 (HEG95)), but no molecular outflow has been detected (Moriarty-Schieven *et al.* 1992). Spectral type and extinction estimates for the star range from K7 to M0.5, and $A_V$= 3-5 mag (Cohen and Kuhi 1979, hereafter CK; HEG95). Photometry of HK Tau has been compiled by Strom *et al.* 1989, and allows a photospheric luminosity of 0.7 $L_\odot$ to be derived. These parameters correspond to a mass of 0.5 $M_\odot$ and approximate age of $5 \times 10^5$ yrs, according to the pre-main sequence evolutionary tracks of D'Antona and Mazzitelli 1994.

A binary companion to HK Tau was discovered by CK, and was later detected in the infrared by Moneti and Zinnecker 1991. This object is known as HK Tau/c, and lies at a projected separation of 2.4″ (340 AU) at PA 175°. It is more than 3 mag fainter than the primary at $\lambda = 2.2$ $\mu$m. Recent resolved spectroscopy (Monin *et al.* 1998) has determined a spectral type of M2 and the presence of H$\alpha$ emission, establishing the companion as a T

Tauri star similar to the primary. The two stars almost certainly constitute a physical pair, as the areal density of young stars in the L1529 cloud (Gomez *et al.* 1993) determines a probability less than 0.1% that they could be a chance projection of two unrelated objects. O'Neal *et al.* 1990 discovered a variable 6 cm radio source associated with the companion, and suggested that HK Tau/c might be viewed through a large amount of extinction.

Circumstellar material in the HK Tau system is indicated by continuum excess emission extending from infrared to millimeter wavelengths. The 2 $\mu$m fluxes of the primary are almost twice those expected from the stellar photosphere alone (Strom *et al.* 1989). IRAS detected the system as PSC 04288+2417, and Beckwith *et al.* 1990 found a 1.3 mm flux density of 40 mJy. The latter two measurements do not resolve the binary, and thus interpretations of the spectral energy distribution (SED) have rested on the assumption that these excesses should be assigned to the primary. Circumprimary disk models have been fit to the HK Tau SED with good results (Beckwith and Sargent 1991), and suggest the presence of a disk with characteristic radius of 100 AU, mass near 0.01 $M_\odot$, and the possibility of an inner gap in the density distribution.

## 2. Observations

HK Tauri was observed as a part of HST GO program 7387 on 1997 December 24 using the Wide Field and Planetary Camera 2. The F/28.3 Planetary Camera (PC1; $0.0455''$ pixel$^{-1}$) was used to make two exposures of 200 sec and 70 sec using the F606W and F814W filters, respectively. A third, deep image was made on the F/12.9 WF3 camera ($0.099''$ pixel$^{-1}$) using the F606W filter and a total exposure time of 600 sec. The F606W filter includes most of the spectral region of the Johnson V and R bandpasses, while the F814W filter is a close analog to Johnson I. All images were taken at a gain setting of 7 $e^-$ per DN, and in all images the primary star was deliberately saturated in order to maximize sensitivity to faint adjacent nebulosity. Processing steps included subtraction of detector bias, flat fielding, and the removal of cosmic rays by a local median about the affected pixels (PC1 images) or by anti-coincidence rejection (WF3 image). The photometric calibration of Holtzman *et al.* 1995 was adopted, and yields a measured $3\sigma$ limiting surface brightness of 25 mag arcsec$^{-2}$ for the WF3 image. Close to HK Tau itself, the limiting magnitude is lower due to noise in the wings of its point spread function.

Initial adaptive optics (AO) images of HK Tau obtained at the 3.6 m Canada-France-Hawaii telescope on 1996 September 25 clearly showed HK Tau/c to be an extended source. Follow-up observations at deeper exposure levels were obtained on 1998 January 13. PUEO, the telescope's AO Bonnette equipped with KIR, a NIR camera based on a $1024 \times 1024$ Rockwell HAWAII array, was used. The resulting plate scale is $0.035''$ pixel$^{-1}$. Reduced J, H, and K images were constructed by median stacking four offset 100 second exposures, after corrections for detector bias, dark current, flat field, and cosmic rays. The HK Tauri primary was saturated in all images. The 2 $\mu$m images are diffraction limited, with a FHWM= $0.14''$ measured on an unsaturated field star. At H and J bands the resolution achieved was slightly less ($0.16''$ and $0.18''$ respectively). UKIRT Faint Standards 4, 13, 17, and 24 (Casali and Hawarden 1992) were observed for photometric calibration.

## 3. Results

The HST F606W PC1 image of HK Tau is shown in Fig. 1 (plate X). HK Tau itself appears as a bright point source with prominent diffraction spikes and other artifacts of the HST point spread function (PSF). To the south, HK Tau/c shows a dramatically different appearance. At the position of the companion, no point source is seen; instead, there are two small elongated nebulosities. They lie parallel to each other at a position angle of 40°, and are separated by a dark, linear gap no more than $0.2''$ in width. The two nebulosities have an overall length of only 1.5″ (210 AU), as measured in the PC1 images at the F814W= 18 mag arcsec$^{-2}$ isophote. The NW nebulosity is brighter than its SE counterpart, by factors of 9.0 and 3.7 in integrated and peak brightness respectively. No color gradients are apparent in a comparison of the F606W and F814W images. Overall, the HK Tau/c nebula appears mirror symmetric about the dark lane bisector; however, there is a darkened region on the NE side of the faint nebula. At the HK Tau primary, a wisp of circumstellar nebulosity extends 0.5″ to the W in both the F606W and F814W images. No jet knots, circumbinary nebulosity, or other point sources are detected in the field within 30″ of the binary. Calibrated surface brightnesses for the HK Tau/c nebula in the F814W band are presented in Fig. 2.

A measurement of the photocenter of the HK Tau/c optical nebula yields a position 2.38″ from the primary at PA 172°. This is coincident with the infrared position of HK Tau/c reported by Moneti and Zinnecker 1991, to within their error bars. Aperture photometry of HK Tau/c yields integrated magnitudes of 17.54 and 15.90 in the F606W and F814W filters respectively. The estimated errors are ±0.02 mag. For the HK Tau primary, we follow the prescription for WFPC2 saturated star photometry given by Gilliland 1994, and obtain magnitudes of 14.94 and 12.93 (± 0.05) at F606W and F814W respectively. The values are consistent with existing groundbased measurements (Strom *et al.* 1989). However, HK Tau/c now appears 2-3 magnitudes brighter in the 5000-7000 Å spectral region than reported by CK in 1979.

The adaptive optics H-band image of HK Tau/c is shown in Fig. 3 (plate X+1). The major feature is the bright NW nebula extending along the same PA as seen in the HST image. It appears somewhat smaller at 1.6 $\mu$m, with an overall length of 1.3″. However, the bright nebula's FWHM along PA 40° is close to 0.4″ in both the optical images and the near-IR J and H band images, and is 0.35″ at K band. Both the fainter SE nebula and the dust lane can be seen in the AO images, although they appear somewhat blended with the bright nebula by resolution effects. Rather than a local minimum in the nebula light, the dark lane manifests itself as a plateau in the surface brightness profile SE of the bright nebula. Overall, the AO images indicate only a slight change in the nebula's appearance between 0.5-2.2 $\mu$m.

Integrated brightnesses for HK Tau/c were measured from the AO images, and values of J= 13.50, H= 12.49, and K= 12.05 $\pm$ 0.10 mag were obtained. These are quite close to the epoch 1990 values quoted by Moneti and Zinnecker 1991. There is no evidence for a near-infrared point source within the HK Tau/c nebulosity. To determine the limiting magnitude for a star within the nebula, a template PSF was constructed from a K= 15.5 field star in the AO images. This was shifted to the center of the nebula, where the minimum scale factor for which a PSF could be identified against the nebula background was determined. This results in a limiting magnitude of K= 17.5 for the central star.

The extinction toward HK Tau/c cannot be determined from photometry of the nebula. However, the star's intrinsic brightness can be estimated using its spectral type and evolutionary tracks. If the companion is coeval with the HK Tau primary, then its $\log(T_{eff}) = 3.55$ implies a luminosity of 0.3 $L_\odot$ and mass of 0.3 $M_\odot$ (D'Antona and Mazzitelli 1994). This would make the binary mass ratio about 2:1. At the distance of Taurus, these stellar properties imply an intrinsic K= 9.3, $A_K = 8.2$, and $A_I \sim 50$ mag. As HK Tau/c is likely to have its own intrinsic near-infrared excess, this extinction should be considered a lower limit.

The HK Tau/c nebula appears strikingly similar to what one would expect from an optically thick circumstellar disk seen nearly edge-on. Such a disk is so dense that starlight cannot penetrate to its mid-plane; it appears only as a central absorption lane flanked by reflected light at its upper and lower surfaces. HK Tau/c is now the fifth young star in which an edge-on disk has been imaged at high resolution, following HH 30 (Burrows *et al.* 1996;

hereafter B96), Orion 114-426 (McCaughrean *et al.* 1998), IRAS 04302+2247 (Padgett *et al.* 1997), and Haro 6-5B (Krist *et al.* 1998). It provides further confirmation that young stars with edge-on disks appear as unusually faint near-infrared sources (Stapelfeldt *et al.* 1997). HK Tau/c is an especially interesting case because (1) its disk is the smallest among the edge-on systems by a factor of two; (2) it shows the narrowest dust lane; (3) and it is the first such object to be found in a binary system.

## 4. Disk Models for HK Tau/c

In the case of HH 30, B96 demonstrated that structural parameters for an optically thick, nearly edge-on disk can be derived through a detailed comparison of scattered light models with high resolution images. The disk inclination, mass, and scale height can be well determined in such an analysis, while the radial density profile can be constrained somewhat, and the variation of scale height with radius can be constrained only slightly. These results have now been independently confirmed by Wood *et al.* 1998. We now apply the same method and software of B96 to determine the best-fit disk model for an HST image of HK Tau/c.

For the disk density distribution, we assume a parameterized surface density $\Sigma(\mathrm{r}) = \Sigma_0 (\mathrm{r}/\mathrm{r}_0)^p$; a gaussian vertical profile $\rho(\mathrm{z}) = \rho_0 \exp(-\mathrm{z}^2/\mathrm{H}(\mathrm{r})^2)$ valid for a vertically isothermal, hydrostatic, non-self-gravitating disk; and a parameterized scale height $\mathrm{H}(\mathrm{r}) = \mathrm{H}_0(\mathrm{r}/\mathrm{r}_0)^\beta$. Combining these leads to the following general density expression

$$\rho(r,z) = \frac{(2-p)}{2\pi^{3/2}} \frac{M_d R_o^{-2} H_0^{-1}}{\left(1-\left(\frac{R_i}{R_o}\right)^{(2-p)}\right)} \left(\frac{r}{r_0}\right)^\alpha \exp(-z^2/H(r)^2) \qquad (1)$$

where $\mathrm{M}_d$ is the disk mass, $\mathrm{R}_i$ and $\mathrm{R}_o$ are the disk inner and outer radii, $\alpha \equiv p - \beta$, and $\mathrm{r}_0$ is a reference radius chosen to be 50 AU. We adopt $\mathrm{R}_o$ = 105 AU, half the observed length of the parallel nebulae in the HST images, and $R_i = 0.5$ AU. Scattering within this density distribution is dictated by the properties of dust grains, for which we adopt opacity $\kappa = 120$ cm$^2$ gm$^{-1}$ and albedo= 0.5 at $\lambda = 0.8$ $\mu$m (Whitney 1995). A Henyey-Greenstein phase function was used, with an asymmetry parameter $g$ to be solved for. Model nebulae are calculated in a single scattering approximation. Full details on the scattering model's implementation, validation, and sensitivity to input parameters can be found in B96.

There are clear asymmetries in the HK Tau/c nebula which our axisymmetric model cannot account for. The most prominent one is on the NE end of the faint nebula, where at intermediate brightness levels there is a 0.3″ (40 AU) long region that is asymmetrically faint relative to the other parts of HK Tau/c (see Fig. 2). To exclude this region, the model fitting was restricted to only the SW half of the nebula. A second, more subtle asymmetry is the slight NE displacement of brightest isophotes from the disk axis defined by the bisector of the outer isophotes. We assume that the primary is a negligible source of illumination for the disk of HK Tau/c, which is in accord with our luminosity estimates. Fitting was performed on the HST F814W image, with the parameters $\alpha, \beta$, $H_0$, $M_d$, $g$, and inclination $i$ solved for by $\chi^2$ minimization.

EDITOR: PLACE TABLE 1 HERE.

The results of five different model runs are shown in Table 1. A best-fit model image is shown along with the data in Fig. 4 (plate X+1). Each run produced a best-fit $g$ near 0.65, indicating forward scattering grains for HK Tau/c as also seen for HH 30 (B96). Models A and B represent the best fits to the HST image, but obtain different values for $\beta$ that depend on the initial guess. This is a recurrence of the $\alpha, \beta$ degeneracy noted by B96. Both of these models provide too little extinction to obscure the star at near-IR wavelengths. Models C, D, and E are therefore forced to produce an extinction $A_I = 50$

mag, in accordance with the estimates of section (3). Models C and D show how models A and B are affected by this new constraint. A bow-tie disk ($\beta = 1$; model E), however, is a somewhat poorer fit to HK Tau/c; we interpret this as a constraint that $\beta > 1$. We adopt models C and D for the discussion below.

## 5. Discussion

### 5.1. The Disk and Its Binary Environment

A key question about young binary systems is the extent to which the circumstellar material of each star has been modified by perturbations from its companion. Indirect evidence for tidal truncation has been observed as a deficit of disk mass, as traced by mm continuum flux, in young binaries in the separation range of 1-100 AU (Jensen, Mathieu, and Fuller 1996; Osterloh and Beckwith 1995). Dynamical models for the evolution of disks in young binary systems indicate that tidal truncation should limit circumstellar disk radii to the range of 15-45% of the semi-major axis $a$, depending on the specific orbital parameters (Artymowicz and Lubow 1994). The HK Tau system provides a new, direct opportunity to test these ideas.

The projected binary separation in this system is only a factor of three larger than the observed radius of the circumsecondary disk. Ideally we would like to compare the disk radius to an orbital semi-major axis, but the orbital elements for HK Tau are currently unknown and may require several decades to establish astrometrically (e.g. Ghez *et al.* 1995). A statistical analysis of the projected separation distribution vs. time for elliptical orbits, assuming random inclinations and apsidal orientations to the line of sight, indicates that for $0.0 \leq e \leq 0.5$, a binary with $a$= 800 AU will appear at a projected separation of 340 AU or larger 90% of the time. This phase space argument suggests that $a$ need not be larger than 800 AU to have a good chance of producing the current projected separation. Considering this as an upper bound to $a$ at a 90% confidence level, the disk outer radius of 105 AU is thus likely to be $\geq 0.12a$ - very close to the size range where tidal evolution is predicted to be important (Artymowicz and Lubow 1994). Larger eccentricities up to 0.98 increase the 90% upper bound to $a=$ 1100 AU, but at the expense of rapidly reducing the periastron distance to the disk radius - also suggesting significant star-disk tidal interaction. Combined with the small disk radius for HK Tau/c in comparison with the other edge-on disks, these considerations indicate a strong possibility that HK Tau/c disk has been tidally truncated.

It is interesting to consider the relative alignment of the binary orbit and the disk plane, as this will affect the character of any perturbations induced by the primary (Larwood *et al.* 1996). If the primary star were located in the disk plane, the current physical separation must then exceed the projected separation by a factor of cotan($i$). The physical separation required, 3800 AU, is so large that the binary would statistically appear at the current projected separation of 340 AU or less only 10% of the time. This suggests that bound stellar orbits are unlikely to be coplanar with the disk. If $a$ was actually 800 AU, the primary would be located on the order of $\tan^{-1}(340/800) = 20°$ above the disk plane.

### 5.2. Disk Vertical Structure

Although the exponent $\beta$ in the radial scale height law is is not uniquely determined by our analysis, the normalization $H_0$ is. Models C and D show that the scale height is closely constrained to 3.8 AU at $r=$ 50 AU. The disk of HK Tau/c is thus significantly flatter than that of HH 30 (H/R of 0.08 vs. 0.12 at $r=$ 50 AU; B96). Under the assumption of vertical pressure support and provided that the dust and gas remain fully mixed, the scale height can be directly related to the local gas temperature according to $H(r) = \sqrt{kT(r)r^3/GMm}$.

If the central star's mass is 0.3 $M_\odot$ as estimated above, then a dynamical temperature of only 8 K is implied. This is unexpectedly cold; the equilibrium temperature of a unit emissivity, unshielded dust grain at 50 AU from a 0.3 $L_\odot$ star should be more like 30 K. A larger stellar mass would tend to resolve this discrepancy, but is not suggested by the companion's spectral type and presumed age (D'Antona and Mazzitelli 1994). If the low inferred temperature is real, then it might be explained via shielding by the opaque inner disk, and/or via unusual dust properties. Alternatively, the low dynamical temperature could be an artifact of the settling of reflecting dust to the disk midplane - a theoretically expected first stage of planet formation.

### 5.3. Disk Mass

As discussed by B96, the mass of an edge-on disk is directly coupled to the width of its central absorption lane. Models C and D indicate that the HK Tau/c disk has a mass near $10^{-4}$ $M_\odot$ of dust and gas. The accuracy of this estimate depends on the assumed dust opacity, and on the applicability of equation (1) throughout the HK Tau/c nebula. Optical depth effects are already accounted for by the model fitting in the derivation of this mass; however, it remains a minimum mass because larger particles, if present, are not accounted for. The mm continuum flux density of HK Tau suggests a combined circumstellar mass two orders of magnitude larger than that determined here for HK Tau/c (Beckwith and Sargent 1991). A much smaller difference was found for HH 30, where the mm continuum also indicated a disk mass larger than inferred from the modeling the HST image (B96). The most likely explanation for the divergent mass estimates here is that the primary star, and not HK Tau/c, is the source of the mm continuum flux from the system. This is quite plausible, as the HST and AO observations do not exclude a circumprimary disk viewed at a less favorable inclination. Evidence for circumprimary material includes the star's near-IR excess, its forbidden line emission, and the wisp of nebulosity in the HST image. If the primary dominates the mm continuum flux, then this would support the very low circumsecondary disk mass inferred from the nebula geometry, and confirm the presence of two circumstellar disks in the system. It should be possible to verify this scenario using exisiting millimeter interferometers.

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Fig. 1.— Logarithmic greyscale F606W/PC1 image of the HK Tau system. N is up and E is to the left. The field of view is 5.2″x3.6″.

Fig. 2.— Surface brightness map of the F814W/PC1 image of HK Tau/c. The outermost contour level corresponds to 18.3 mag arcsec$^{-2}$, the peak contour level is 13.3 mag arcsec$^{-2}$, and the contour interval is 0.5 mag arcsec$^{-2}$.

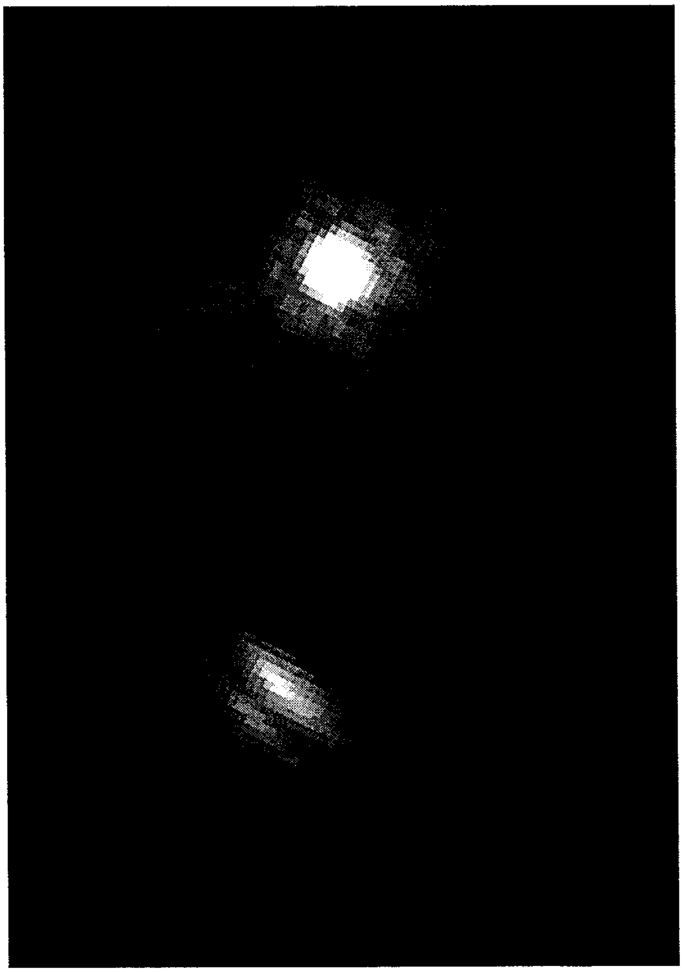
Fig. 3.— Logarithmic greyscale 1.6 $\mu$m adaptive optics image of HK Tau/c. N is up and E is to the left. The field of view is 2.25″x2.25″.

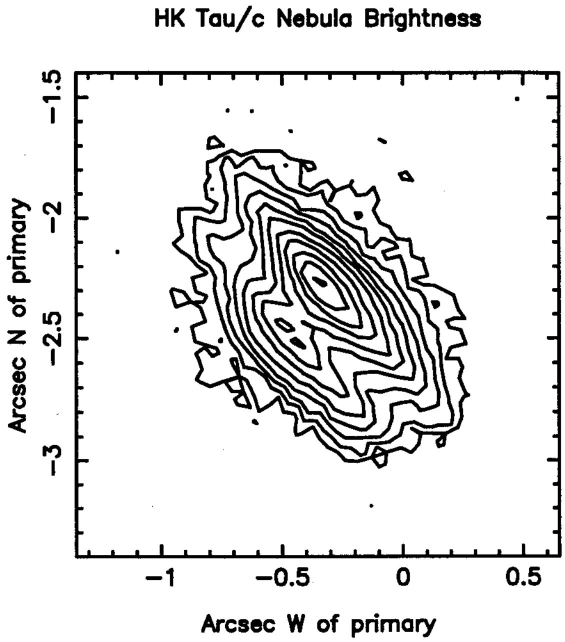
Fig. 4.— Comparison of the best-fit model C reflection nebula (left) with the HST F814W image (right). The field of view is 1.6″x1.0″.

Table 1. Results of Disk Model Fitting for HK Tau/c

| | Model A | Model B | Model C | Model D | Model E |
|---|---|---|---|---|---|
| alpha | -0.82 | -2.31 | -1.41 | -2.78 | -1.16 |
| beta | 1.12 | 1.34 | 1.10 | 1.32 | [1.0] |
| $H_0$ (AU) | 4.02 | 3.74 | 3.88 | 3.81 | 3.77 |
| inclination (deg) | 5.7 | 6.2 | 5.4 | 6.0 | 4.8 |
| mass ($M_\odot$) | 6.1x$10^{-5}$ | 8.8x$10^{-5}$ | 5.9x$10^{-5}$ | 1.2x$10^{-4}$ | 5.6x$10^{-5}$ |
| extinction (mag) | 12.4 | 17.9 | [50] | [50] | [50] |
| $\chi^2$ | 10.2 | 10.2 | 10.6 | 10.5 | 11.2 |

[1]Brackets indicate quantities held fixed during the fitting process




HK Tau/c Nebula Brightness
Arcsec N of primary
−1.5
−2
−2.5
−3
−1
−0.5
0
0.5
Arcsec W of primary