ABSTRACT

Young stars with masses 2–8 times solar, the Herbig Ae and Be stars, often show a near-infrared excess too large to explain with a hydrostatically supported circumstellar disk of gas and dust. At the same time, the accretion flow carrying the circumstellar gas to the star is thought to be driven by magnetorotational turbulence, which, according to numerical MHD modeling, yields an extended low-density atmosphere supported by the magnetic fields. We demonstrate that the base of the atmosphere can be optically thick to the starlight and that the parts lying near 1 AU are tall enough to double the fraction of the stellar luminosity reprocessed into the near-infrared. We generate synthetic spectral energy distributions (SEDs) using Monte Carlo radiative transfer calculations with opacities for submicron silicate and carbonaceous grains. The synthetic SEDs closely follow the median Herbig SED constructed recently by Mulders & Dominik and, in particular, match the large near-infrared flux, provided the grains have a mass fraction close to interstellar near the disk’s inner rim.

Key words: protoplanetary disks – radiative transfer

Online-only material: color figures

1. INTRODUCTION

Young intermediate-mass stars with disks commonly show a large near-infrared excess at wavelengths of 2–4 μm. The luminosity in the excess is often a noticeable fraction of the stellar bolometric luminosity. Hydrostatic disk models fail to reproduce the near-infrared flux, emitting too little by a factor of 2 for some stars (Vinković et al. 2006). This is a puzzle because in the basic hydrostatic picture each star is allowed only a narrow range of fluxes, determined as follows (Dullemond & Monnier 2010): The 2 μm emission arises in material with temperatures near the silicate sublimation threshold of about 1500 K. Such temperatures occur at a certain distance from the star inside which the dust cannot survive, leaving the disk optically thin. The material at the sublimation front therefore faces the star directly, intercepting and reemitting at 2 μm a fraction of the stellar luminosity equal to the ratio of the disk thickness to the front’s radius.

The disk’s density scale height in hydrostatic balance is proportional to the sound speed divided by the orbital frequency, two quantities that are fixed—the sound speed by the sublimation temperature, and the orbital frequency by the radius where the sublimation temperature is reached. Varying the grain size and composition shifts the sublimation front somewhat, but the ratio of density scale height to sublimation radius changes little. For purposes of the near-infrared excess, the disk’s thickness is equal to the height of the surface where the starlight is absorbed and reprocessed. This starlight-absorbing surface lies a few density scale heights from the equatorial plane, growing logarithmically with the surface density as a consequence of the steep density profile of the hydrostatic disk atmosphere. In quite a few objects, the near-infrared excess cannot be accounted for even with extreme disk masses.

The puzzle only grows deeper when longer infrared wavelengths are considered. Matching the excess at 7 μm and the 13.5-to-7 μm flux ratio requires artificially scaling up the disk’s thickness near 1 AU by factors of as much as 3 compared with hydrostatic models, in the sample of 33 Herbig stars examined by Acke et al. (2009).

Two main ideas have been proposed to explain the large near-infrared excesses. The first is that the disk is thicker because it is hot. The extra heating might come from accretion. Herbig systems’ Hz equivalent widths, a measure of the accretion luminosity, correlate with the ratio of the K-band excess flux to that in the H band, suggesting a link between accretion and the inner disk shape (Manoj et al. 2006). However, as Manoj et al. were aware, the accretion power by itself cannot explain the observed near-infrared fluxes without mass flow rates exceeding \(10^{-6} \, M_\odot \, yr^{-1}\) (Hillenbrand et al. 1992; Lada & Adams 1992). Yet the flow rate must be less than \(10^{-7} \, M_\odot \, yr^{-1}\) for the gas inside the silicate sublimation radius to be optically thin (Hartmann et al. 1993) and compatible with the central holes detected in near-infrared interferometric observations of many Herbig stars. The holes have sizes generally consistent with the sublimation radius over a broad range of stellar luminosities, as reviewed by Dullemond & Monnier (2010).

Alternatively, the extra heating might come from fast-moving electrons ejected from the grains by stellar ultraviolet photons. At the low gas densities found in the hydrostatic atmosphere, heat transfer from gas to dust is inefficient. The photoelectron-heated gas cannot easily cool and reaches temperatures up to several thousand kelvins (Thi et al. 2011). However, the low gas densities also mean that even submicron grains quickly settle out, so the hot material is likely to be transparent to the starlight.

The other main idea is an extra system component that is warm enough to emit significantly in the near-infrared, such as a spherical halo or envelope (Hartmann et al. 1993; Vinković et al. 2006), dusty disk wind (Vinković & Jurkić 2007; Bans & Königl 2012), or cloud of dust ejected by magnetic forces (Ke et al. 2012). A component covering a large solid angle might help
account for the common occurrence of variable circumstellar extinction among the Herbig Ae stars (Bibo & Thé 1991; Malfait et al. 1998; Natta et al. 2000) and especially the members of the UX Orionis class (Grinin et al. 1998, 2009). However, spherical structures by themselves appear incompatible with interferometric measurements (Tuthill et al. 2001; Eisner et al. 2004). Combining a spherical halo of modest optical depth with a hydrostatic disk yields a better fit than either component alone in several cases (Monnier et al. 2006; Verhoeff et al. 2011; Chen et al. 2012).

Here we focus on the expectation that the accretion stresses in the sufficiently ionized parts of the disks come from magnetic forces (Umebayashi & Nakano 1988; Balbus & Hawley 1991; Gammie 1996; Zhu et al. 2009; Armitage 2011). A magnetically supported atmosphere is a natural consequence, since shearing-box magnetohydrodynamic (MHD) calculations extending more than a few scale heights from the midplane show magnetic fields generated in magnetorotational turbulence and rising buoyantly to form an atmosphere in which magnetic pressure exceeds gas pressure (Miller & Stone 2000; Flaiag et al. 2010). The atmosphere is optically thin to its own continuum emission when its base is set by the penetration of the young star’s ionizing X-ray photons (Bai & Goodman 2009), but it is nevertheless optically thick to the starlight that illuminates the disks around low-mass T Tauri stars at grazing incidence (Hirose & Turner 2011).

In this contribution, we demonstrate that the magnetically supported atmosphere is optically thick to the starlight in Herbig disks too. The magnetic support can make the inner disk two to three times taller, so that it intercepts and reprocesses the near-infrared a correspondingly greater fraction of the stellar luminosity.

Our model star is described in Section 2, and the disk supported jointly by gas and magnetic pressure in Section 3. After choosing dust opacity curves (Section 4), we use a Monte Carlo radiative transfer approach (Section 5) to compute the disk’s shape and temperature, solving jointly for global radiative and vertical magnetohydrostatic equilibrium (Section 6). Synthetic observations are made using a ray-tracing method, described in Section 7. The results are set out in Section 8, and the summary and conclusions follow in Section 9.

2. STAR

Our star is a 2.4 $M_\odot$ Herbig Ae modeled on AB Aurigae. Its radius, 2.55 $R_\odot$, and temperature, 9550 K, yield a luminosity of 47.9 $L_\odot$ (van den Ancker et al. 1998). The star emits the spectrum of the solar-metallicity Kurucz model (Kurucz 1993) with the nearest gravity and effective temperature—$10^4$ cm s$^{-2}$ and 9500 K.

3. DISK

We assume the surface density $\Sigma$ falls inversely with radius $r$ until cut off exponentially at outer radius $r_o$:

$$\Sigma = \frac{M_d}{2\pi r_o^2} \left( \frac{r_o}{r} \right) \exp(-r/r_o). \quad (1)$$

This is a similarity solution with total mass $M_d$, obtained under a simple viscosity prescription (Hartmann et al. 1998). Equation (1) also is a fair match to the surface densities measured at separations of tens of AU using millimeter interferometry of the dust continuum emission from T Tauri stars (Andrews et al. 2010). We set the outer cutoff radius to $r_o = 250$ AU. In addition, we cut the disk short inside a radius $r_i$. This is meant to model not the stellar magnetosphere’s truncation of the gas but the sublimation front’s truncation of the optical depth. Directly solving for the position of the front can introduce convergence issues (Kama et al. 2009), which we wish to avoid. Inside $r_i$ we roll off the surface density by the factor $\exp[-((r - r_i)/\Delta r_i)^2]$. The inner cutoff radius and scale length are $r_i = 0.7$ and $\Delta r_i = 0.1$ AU.

With these choices, the disk is optically thin inside about 0.4 AU, which is near the expected sublimation radius for our model star. We check after the fact that the temperature at unit radial optical depth is close to the sublimation threshold. Solving in detail for the shape of the sublimation front is unlikely to significantly reduce the fraction of the starlight intercepted by the disk within 1 AU, but it could change how the reprocessed luminosity is distributed across near-infrared wavelengths.

The surface density profile, shown in Figure 1, along with the temperatures found as described below, yields a Toomre $Q$-parameter that is smallest near 160 AU, where it exceeds 7 in all models, indicating stability against self-gravity.

The vertical profile of density in each disk annulus is obtained as follows: First, we fit the mean density profile in the fiducial radiation MHD calculation from Hirose & Turner (2011) with the sum of a gas-pressure-supported isothermal interior and a magnetically supported atmosphere (Figure 2). The interior has a Gaussian density profile in the height $\Delta z$, while the atmosphere is exponential:

$$\frac{\rho(z)}{\rho_0} = \exp\left(-\frac{z^2}{2H^2}\right) + \frac{1}{78.6} \exp\left(-\frac{z}{1.57H}\right), \quad (2)$$

where $\rho_0$ is the Gaussian’s midplane density, $H = c_s(z = 0)/\Omega$ is the density scale height, $\Omega$ is the Keplerian orbital frequency, and $c_s(z = 0)$ is the midplane isothermal sound speed, computed using the gas mean molecular weight, 2.3.

In the Monte Carlo radiative transfer calculations, we use $H$ to rescale the MHD results that Hirose & Turner (2011) obtained at 1 AU from a 0.5 $M_\odot$, T Tauri star. To be conservative, we round
down the exponential scale length and normalization, making the magnetically supported atmosphere a little more compact and less massive. We adopt the density profile

\[ \rho(z) = \rho_{\text{HSE}}(z) + N\rho_0 \exp\left(-\frac{z}{A H}\right), \]

(3)

where \( \rho_{\text{HSE}} \) is the profile obtained by solving for vertical hydrostatic balance while fixing the variation of the temperature with mass column to the profile found in the previous Monte Carlo transfer iteration. The parameters are \( N = 1/80 \), which normalizes the exponential relative to the Gaussian, and \( A = 1.5 \), the exponential scale height in units of \( H \). The hydrostatic component’s midplane density \( \rho_0 = \rho_{\text{HSE}}(0) \) is chosen using simple root finding by bisection, so that the total profile has the desired surface density.

We now consider three configurations: (1) the entire disk is supported in the traditional fashion by gas pressure alone, (2) gas and magnetic pressures contribute throughout according to Equation (3), and (3) magnetic pressure adds to gas pressure only in annuli with a narrow range of radii just outside the silicate sublimation front, where the high temperatures ensure good magnetic coupling through collisional ionization of the alkali metals. The three configurations are listed in Table 1. The magnetically supported “bump” in the third configuration is merged smoothly with the surrounding gas-pressure-supported disk by giving the exponential atmosphere’s scale height a Gaussian radial variation about the maximum value \( A(r_b) = 1.5 \). The Gaussian’s FWHM is equal to the radius \( r_b \) of the bump’s peak.

| Table 1 Disk Configurations’ Support against Vertical Gravity |
|-------------|---------------|-----------------|
| Name        | Gas Support   | Magnetic Support |
| Gas         | Yes           | None            |
| Magnetic    | Yes           | Throughout      |
| Magnetic bump | Yes          | Only in bump near inner rim \(^4\) |

Note. \(^4\) The bump is centered \( r_b = 1 \) AU from the star.

The atmosphere’s thickness likely also depends on the net vertical magnetic flux, which is a product of the global transport of magnetic fields. Given the uncertainties regarding this transport, we here simply fix the atmosphere’s scale height in units of the gas pressure scale height to a value similar to that found by Hirose & Turner (2011). Their radiation MHD calculations have a net vertical magnetic flux with pressure \( 3 \times 10^5 \) times less than the midplane gas pressure.

4. DUST OPACITY

The disk’s opacity comes primarily from dust, which we assume is well mixed in the gas except where otherwise specified. We adopt opacities from Preibisch et al. (1993), who matched Mie calculations of dust particles’ optical response with data from molecular clouds. The grain model consists of silicate and carbonaceous particles, each with a power-law size distribution of exponent \(-3.5\). The minimum and maximum sizes are 0.04 and 1 \( \mu m \) for the silicate particles and 0.007 and 0.03 \( \mu m \) for the carbon particles. The opacity curves are shown in Figure 3 together with the albedos, or ratios of scattering to total opacity. Scattering contributes about half of the total cross section at optical wavelengths and is assumed isotropic.

Modeling of spectral energy distributions (SEDs) suggests that dust is depleted in T Tauri disk atmospheres by factors of 10 to \( 10^4 \) compared with the interstellar medium (Furlan et al. 2006, 2009). A gas-to-dust ratio of 12,800, in the same range, appears to be needed to understand the water emission from T Tauri stars (Meijerink et al. 2009). Furthermore, planet formation requires incorporating some of the solid material into larger bodies. We therefore consider two dust-to-gas mass ratios: the nominal interstellar value, as shown in Figure 3, and a 100 fold depletion. The dust opacities are simply scaled down by a depletion factor \( \epsilon \). In addition, we consider a scenario in which the dust takes the depleted abundance except in a ring around \( r_r = 1 \) AU, where the peak dust mass fraction matches that in the dusty scenario. The mass fraction is a Gaussian in radius, asymptoting to the depleted value far from the star. The three dust distributions are listed in Table 2.
To summarize, each model disk is uniquely specified by listing the magnetic support from Table 1 and the dust distribution from Table 2. Since we consider three magnetic configurations and three dust scenarios, there are nine models in all.

5. RADIATION FIELD AND TEMPERATURE

We compute the radiative equilibrium temperatures by emitting a large number of photon packets from the star into the disk, where they are scattered, absorbed, and reemitted as many times as needed until they escape to infinity. With this approach, the energy is conserved exactly. The stellar luminosity is divided equally among the packets. We use the temperature relaxation procedure of Bjorkman & Wood (2001), drawing the frequencies of the reemitted packets from the difference between the old and new emission spectra such that the local radiation field adjusts to the updated temperature. The gas and dust are assumed to share a single temperature at each point. For efficiency, when estimating the radiation absorption rates and the radiation’s mean intensity, we include the contributions from all along the packet paths (Lucy 1999). The intensity is accumulated in 20 contiguous, nonoverlapping wavelength bins including those centered on the photometric bands $U, B, V, R, I, J, H,$ and $K$, the four Spitzer IRAC channels at $3.6, 4.5, 5.8$, and $8 \mu$m (Fazio et al. 2004), and the Spitzer MIPS $24 \mu$m channel (Rieke et al. 2004). For contiguous wavelength coverage, these are rounded out with bands centered at wavelengths 1, 1.9, 2.79, 10, 12, 14.5, and $18 \mu$m. The center of each intensity bin appears as an open circle on the SEDs presented in Section 8.2 below.

We neglect accretion heating in computing the temperatures. Under magnetorotational turbulence, much of the released gravitational energy is deposited in the disk atmosphere, at low optical depths to the disk’s own radiation (Bai & Goodman 2009; Hirose & Turner 2011). Heating at low optical depths has a reduced effect on the midplane temperature. Also, the accretion heating falls off with radius faster than the stellar irradiation heating, so that including the accretion power would increase the disk’s thickness most near the inner rim. By neglecting the accretion heating, we thus obtain a lower limit on the fraction of the stellar luminosity reprocessed into the infrared near the disk’s inner rim.

Because we neglect the accretion heating, the disk’s interior is isothermal on cylinders. We therefore save the expense of computing temperatures in the most optically thick regions by simply bouncing back any packets reaching a certain mass column, chosen so the overlying material is optically thick at wavelengths near its thermal emission peak. The bounce threshold is set to $30 \rho_c$ g cm$^{-2}$ in all the calculations shown here. We replace the missing interior temperatures by the mean of the last few well-sampled values above.

The disk is divided into a grid of $N = 800$ cells spanning the four decades in radius from $r_0 = 0.25$ to $r_N = 2500$ AU. The cells are concentrated near the inner rim to better resolve the transition from optically thin to thick in the radial direction. Cell $j$’s inner radius $r_j$ is given by $\log(r_j/r_0) = C[(\Delta + 1)^{-1}/N - 1]$, where $\Delta = 4$ is the logarithm of the ratio of the grid’s outer to inner radius. We choose a concentration parameter $C = 0.3$. The strength of the concentration can be seen in Figure 1, where red squares mark the cell edges $r_j$. In the vertical direction, the grid has 280 cells uniformly spaced between the equatorial plane and height $z = 0.7r_j$, yielding a spacing 0.25% of the radius. This choice of upper boundary ensures that all the material with starlight optical depth greater than $10^{-3}$ lies on the grid, even in the flared outer parts of our nine model disks.

6. JOINT RADIATIVE AND MAGNETOHYDROSTATIC EQUILIBRIUM

Once new temperatures have been found through the Monte Carlo radiative transfer procedure, we restore vertical equilibrium by reconstructing the density profile within each disk annulus as in Section 3 while holding fixed the surface density and the variation of the temperature with the mass column.

We iterate five times between radiative transfer and magnetohydrostatic balancing. In each case the third, fourth, and fifth iterations show only minor differences, indicating the solution is close to converged. Each iteration of the radiative transfer calculation involves $10^7$ photon packets.

7. SYNTHETIC IMAGES AND SPECTRA

The procedure outlined above yields the density $\rho(r, z)$, temperature $T(r, z)$, and frequency-dependent mean radiation intensity $I_v(r, z)$. Note that $I_v$ is taken piecewise-constant across each of the 20 wave bands described in Section 5, the individual photon packets’ wavelengths having been discarded during the accumulation. From these three quantities we compute synthetic images and spectra by solving the transfer equation,

$$\frac{dI_v}{dr} = I_v - \frac{\kappa_v B_v(T) + \sigma_v J_v}{\kappa_v + \sigma_v},$$

on a grid of parallel rays extending toward the observer at infinity, following Yorke (1986). The symbols have their usual meanings (Mihalas 1978), with $\nu$ the frequency, $I_v$ the specific intensity, $J_v$ its angle average, $r_v$ the optical depth, and $\kappa_v$ and $\sigma_v$ the absorption and scattering opacities. The differential optical depth $dr$ over a step of length $dl$ is $(\kappa_v + \sigma_v)\rho dl$.

Solving the transfer equation in this way is preferable to binning the Monte Carlo photon packets in angle as they emerge from the system, because it yields images with adequate spatial resolution using far fewer packets.

8. RESULTS

8.1. Does the Atmosphere Absorb Starlight?

The magnetically supported atmosphere contains only a small fraction of the disk mass. A natural question to start with is therefore whether the atmosphere is optically thick enough to affect the reprocessing of the starlight. In Figure 4, we show the surfaces of unit starlight optical depth in the nine models. The dust-depleted cases (top) show clear differences between versions with and without the magnetic support. The starlight-absorbing surface lies 1.75 times higher at 1 AU, with magnetic support throughout (dashed green curve) than in the hydrostatic version (dashed blue curve). The ratio is 1.48 times for the magnetically supported bump (dashed red curve).

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**Table 2**

| Name        | Dust-to-gas Mass Ratio, 0.01e |
|-------------|-------------------------------|
| Depleted    | $10^{-4}$ throughout          |
| Dusty      | $10^{-2}$ throughout          |
| Dusty ring  | $10^{-4} \times (1 + 99 \exp[-4(r/r_0 - 1)^2])$ |

Note. The dusty ring is centered at $r_i = 1$ AU from the star.
The wavelength is 0.314 μm, near the starlight peak. The three dust-depleted disks are at top, the three dusty disks in the middle, and the three disks with dusty rings at bottom. In each panel, the disk with gas support only is shown by blue curves, the disk with magnetic support throughout by green curves, and the disk with a magnetically supported bump by red curves and shading. In each case, the upper (dashed) curve is the surface of unit optical depth for photons arriving from the star, while the lower (solid) curve is the surface of unit optical depth for photons traveling vertically downward. The yellow dots at the origin show the star to scale.

(A color version of this figure is available in the online journal.)

The magnetic support’s effects are even stronger in the dusty cases (middle), where the corresponding ratios are 3.07 and 2.82. The magnetic support makes the starlight-absorbing surface taller by similar factors in the cases with dusty inner rings (bottom), where the ratios to the hydrostatic version are 3.06 and 2.87. Furthermore, synthetic images of the central 2.5 AU show that the magnetically supported material noticeably alters the appearance in the near-infrared J, H, and K bands (Figure 5), increasing the surface area of bright material lying within 1 AU. Considering all six scenarios with magnetic support, clearly the magnetically supported models all do a poor job of matching the 10 μm silicate feature’s steep short-wavelength side. The most likely reason is an incorrect shape for the starlight-absorbing surface, due to the simple choices we made for the profiles of surface density and magnetic support. The disk annuli near 0.5 AU do show synthetic spectra with suitably steep slopes from 6 to 10 μm, suggesting that the median silicate band shape might be better matched with a shorter magnetically supported bump placed nearer the star. A further possibility is that typical Herbig disks’ opacities have a wavelength dependence differing from the curves we used. Testing these ideas is a challenge for the future. Each calculation takes about a week of computer time, and many parameters remain to be varied.

At wavelengths beyond 15 μm, the flux and SED slope are affected by the shape of the disk surface at and outside 10 AU. Magnetic support generally means more starlight intercepted near 1 AU and less outside 10 AU, making the outer annuli cooler and leading to steeper declines in flux with wavelength. The anticorrelation between the 7 μm excess and the 13.5-to-7 μm flux ratio observed by Acke et al. (2009) can thus qualitatively be explained by a variation from one system to the next in the strength of the magnetic support.

8.2. Is the System Bright Enough at Near-infrared Wavelengths?

We wish to know whether the magnetic support increases the near-infrared excess enough to account for the observed SEDs. From the three SEDs in the top panel of Figure 7, one can see that all the dust-depleted models are too faint at wavelengths 2–4 μm by factors of 2 or more relative to the median Herbig system. Similar problems afflict the hydrostatic models that are dusty throughout, as well as those that are dusty only in a central ring (blue curves, middle and bottom). By contrast, the versions with magnetic support lie close to the median SED at near-infrared wavelengths (green and red curves). Considering all nine models together, we see that four exceed the median observed near-infrared excess. All four have, just outside the sublimation radius, both a magnetized atmosphere and a near-interstellar dust-to-gas mass ratio. The key to reprocessing the extra starlight is a sufficient column of dust in the atmosphere, so lower dust-to-gas ratios would allow a similar outcome if the disk contained more gas than our chosen model (Figure 1). With enough dust present, the magnetic support can readily account for the excess that is missing from hydrostatic models.

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On the near-infrared bump’s other side, from 2 μm shortward, there is interferometric evidence for emission arising within the sublimation radius in some systems (Eisner et al. 2007; Isella et al. 2008; Benisty et al. 2010; Eisner et al. 2010). Our radiative transfer modeling does not address this component of the system. However, if, as we propose, the near-infrared bump arises in material supported by the same magnetic fields that drive accretion, then correlations might be expected between the bump’s height, the surface density of the material within the sublimation radius, and the accretion signatures such as Hz emitted near the stellar photosphere. Simultaneous optical and infrared observations could help illuminate such a connection.

8.3. Can Grains Remain Suspended in the Atmosphere?

We have assumed that the grains providing the opacity are well mixed in the gas. This is valid if the grains are stirred up, either by the turbulence or by the magnetic buoyancy, faster than they settle.

Magnetorotational turbulence can loft material no more quickly than the velocity correlation timescale, which is a fraction of the orbital period (Fromang & Papaloizou 2006). The linear magnetorotational instability (MRI) is slow-growing or stabilized high in the atmosphere, where the plasma β is less than unity (Kim & Ostriker 2000). Even so, in nonlinear stratified shearing-box MHD calculations the velocity dispersion remains large at these heights (Miller & Stone 2000; Flaig et al. 2010; Okuzumi & Hirose 2011). However, out of an abundance of caution we set the stirring timescale to the slower magnetic buoyancy timescale, measured using the “butterfly” pattern visible when the magnetic pressure is plotted versus height and time. In shearing-box calculations this timescale is around 100 orbits, with or without a dead zone (Miller & Stone 2000; Flaig et al. 2010; Hirose & Turner 2011). The upshot is that the grains repopulate the atmosphere within 10 orbits if sufficiently coupled to the gas.

On the other hand, settling removes grains from the atmosphere with a speed such that the drag force balances the vertical component of the star’s gravity. The drag force is in the Epstein regime, where the gas molecules’ mean free path exceeds the grain size. The settling time is the distance to the midplane divided by the settling speed and, for compact spherical particles, is given by

$$\frac{t_{\text{sett}}}{t_K} = \frac{1}{4\pi^2} \frac{t_K}{t_{\text{drag}}},$$

where $t_K$ is the Keplerian orbital period and the drag stopping time $t_{\text{drag}} = \rho_d a/(\rho_c c_s)$ depends on the grains’ internal density $\rho_d$ and radius $a$, using the notation from Turner et al. (2010).

Now the grains to be concerned with are those that absorb the starlight and give off the disk inner rim’s thermal infrared emission. The starlight peaks near a wavelength of 0.3 μm, the infrared emission near 3 μm. The biggest contribution to the opacity is from grains with circumference comparable to the wavelength (van de Hulst 1957). Most important for the starlight opacity are thus grains smaller than $a = 0.1$ μm, and for the infrared opacity grains around 0.5 μm in radius. In discussing the settling of these particles, we take an internal density $\rho_d = 3$ g cm$^{-3}$, similar to that of terrestrial basalt. Densities are lower for carbon-rich grains.

In the top panel of Figure 8, we show by dotted curves the height to which the 0.1 μm grains settle within 10 orbits. The settling heights are overlaid on the surfaces of unit direct starlight optical depth for the dusty models from Figure 4. It can be seen that settling is important only in the uppermost reaches of the atmosphere. For each of the three disk configurations, the dotted curve lies above the unit-optical-depth curve on the part of the disk most directly facing the star. If settling were to remove all grains above the dotted curve, an unlikely prospect, the height of the starlight-absorbing surface at 2 AU would be reduced about 11% in the hydrostatic disk, 27% in the disk with magnetic support throughout, and 10% in the disk with the magnetically supported bump. Note that the starlight-absorbing height beyond the bump is determined by the optically thick bump itself. Furthermore, the settling would be unimportant right up to the starlight-absorbing surface in all the models if the inner disk had gas surface densities a few times greater than we have assumed.
Figure 6. Midplane temperature vs. radius in the nine model disks. The dust-depleted disks are shown in the top panel, the dusty disks in the middle, and the disks with dusty rings at bottom. As in Figure 4, blue shows the disk with gas support only, green the disk with magnetic support throughout, and red the disk with a magnetically supported bump.

(A color version of this figure is available in the online journal.)

Figure 7. SEDs of the nine model Herbig systems. The dust-depleted disks are shown at top, the dusty disks in the middle, and the disks with dusty rings at bottom. As in Figure 4, blue is for the disk with gas support only, green the disk with magnetic support throughout, and red the disk with a magnetically supported bump. Open circles mark the center of each intensity bin. The thin black curves indicate the stellar spectrum, a Kurucz model. The thick black lines, marking the median Herbig SED, fall in a gray band reaching from the first to the third quartile (Mulders & Dominik 2012). The dark gray curves and triangles indicate a spectrum and photometry of the star AB Aur. All are normalized at 0.55 μm.

(A color version of this figure is available in the online journal.)
Figure 8. Top: settling surfaces for 0.1 μm grains in the three dusty disks. Dotted curves mark the height above which the settling time is less than 10 orbits. The dashed curves show the starlight-absorbing surface with the grains well mixed and are reproduced from Figure 4 (middle). The disk with gas support only is shown in blue, that with magnetic support throughout in green, and that with a magnetically supported bump by the red curve and shading. In all three cases, settling can lower the starlight-absorbing surface only slightly. Bottom: corresponding settling surfaces for 1 μm grains (dotted curves), together with the unit vertical optical depth surfaces for thermal infrared emission (solid curves and shading). The same three models appear with the same colors as in the top panel. The settling line lies well above the infrared-emitting surface throughout, indicating that settling is unimportant at the infrared photosphere. (A color version of this figure is available in the online journal.)

The situation for the largest grains contributing to the opacity curves is shown in the bottom panel of Figure 8. Particles 1 μm in radius settle significantly only in gas lying well above the 3 μm photosphere.

The dusty models shown in Figure 8 impose the most severe settling constraint because their high opacity means the starlight is absorbed in gas with the lowest density. In the corresponding plots for the three dust-depleted disks (not shown), the starlight-absorbing surface falls well below the height where settling begins to matter. We conclude that the grains contributing most to the starlight opacity in our model disks are never more than marginally affected by settling, while the grains important for the thermal emission are unaffected.

The Lorentz force plays a minor role in the grains’ movements even in the disk with magnetic support throughout. Consider a grain traveling at its settling speed through a magnetic field with pressure 10 times the local gas pressure. Struck by electrons from the surrounding plasma, the grain charges to the Coulomb limit, in which the electric repulsion reduces the cross section for colliding with further electrons to the point where the grain receives electrons and slower moving ions at equal rates. The mutual electric potential between the grain and an electron approaching its surface is then about 3 times the thermal energy, as we determine by solving Equation (35) of Okuzumi (2009). Grains 0.1 μm in radius near the silicate sublimation front charge to about 20 electrons. Under these conditions, we find that the Lorentz force exceeds the gravitational and drag forces only for grains located at and above the uppermost, dashed green curves in Figure 8.

9. SUMMARY AND CONCLUSIONS

Many young intermediate-mass stars show near-infrared excesses that have proved too large to explain using hydrostatic models. The hydrostatic disks are geometrically thin near the silicate sublimation radius, intercepting and reprocessing too small a fraction of the starlight. On the other hand, MHD calculations indicate that magnetically supported atmospheres are a generic feature of protostellar disk annuli undergoing accretion driven by magnetorotational turbulence. The MHD results show that magnetic forces suspend small amounts of material well above the hydrostatic photosphere. To see whether such an atmosphere can account for the excess near-infrared emission, we added simple exponential atmospheres to global models of the disk around a Herbig star. We placed the models jointly in vertical magnetohydrostatic balance and in radiative equilibrium with the starlight using Monte Carlo transfer calculations and constructed synthetic observations of the resulting structures. Our main findings are that (1) the atmosphere near the sublimation radius is optically thick to the starlight, and (2) if the dust abundance there is close to the interstellar value, the resulting near-infrared excess is sufficient to explain the median Herbig SED. We therefore suggest that magnetically supported atmospheres are a common feature of at least the thermally ionized inner annuli in Herbig disks.

Magnetically supported disk atmospheres have several further interesting implications. First, the disk thickness measures not the temperature, as long assumed, but the magnetic field strength. The gas pressure support yields only a lower bound on the height of the starlight-absorbing surface. The disk thickness is thus a gauge of the strength of the magnetic activity. Second, the disk atmosphere is quite diffuse. The exponential density profile falls off more slowly with height than the traditional Gaussian. The extended low-density atmosphere offers a natural explanation for the finding from interferometry that the visibilities are better fitted by hydrostatic disks combined with spherical or near-spherical halos than by either component alone. Kinematic diagnostics will be valuable in the future to help distinguish whether the extended material forms a turbulent magnetized atmosphere, an escaping wind, or perhaps most likely, both. Third, the inner disk’s atmosphere can throw a shadow across the material outside. A flared shape may bring the distant parts of the disk back up into the starlight. Dips in the radial surface brightness profile then do not have to be surface density deficits but could be the shadows cast at sunset by magnetically supported hills. Fourth, the atmosphere can obscure our view of the star even when the system is viewed at moderate inclination. Accounting for time-variable circumstellar extinction will be easier with magnetic fields holding some gas and dust aloft. In considering the consequences for the extinction, it is worth noting that we took a horizontally and time-averaged atmospheric density profile, ignoring the structure that is universally part of magnetic activity in MRI turbulence, as well as in other contexts such as the solar chromosphere.

We gratefully acknowledge discussions with C. Dominik, M. Flock, G. Mulders, and A. Natta. The research was carried out in part at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration and with the support of the NASA
Origins of Solar Systems program through grant 11-OSS11-0074. N.J.T. was also supported by the Alexander von Humboldt Foundation through a Fellowship for Experienced Researchers. S.H. was supported by Japan Society for the Promotion of Science KAKENHI grants 24540244 and 23340040.

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