MIDPLANE TEMPERATURES OF PROTOPLANETARY DISKS UNDERGOING LAYERED ACCRETION

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Introduction: The high optical depths of protoplanetary disks (including those like the solar nebula, surrounding T Tauri stars) prevent direct observation of their midplane temperatures, $T_{\text{mid}}$. Models of the formation of such meteoritic inclusions as calcium-aluminum-rich inclusions (CAIs) and chondrules rely critically on $T_{\text{mid}}$, which are usually constrained instead by analytical or numerical models, such as [1]. Inputs to these models include the observed mass accretion rate onto the protostar, $dM/dt$. Typically, $10^{-9} < \frac{dM}{dt} < 10^{-7} M_{\odot}$ yr\(^{-1}\) for T Tauri stars [2], and accretional heating is competitive with heating by starlight within inner regions of the disk. All models for $T_{\text{mid}}$ to date assume that accretional heating is uniform throughout the disk. This assumption is violated if the mechanism for mass flow through the disk is the magnetorotational instability (MRI) [3], since only the outer, ionized layers of the disk will be subject to the MRI, with little to no accretion in the interior “dead zone” [4]. The active layer column density has been estimated as $\Sigma_a \sim 100$ g cm\(^{-2}\) for disks adequately ionized by galactic cosmic rays [4], but estimates of the ionization fraction suggest only protostellar X rays are able to sufficiently ionize the disk, and imply $\Sigma_a \sim 10$ g cm\(^{-2}\) [5], or < 1% of the mass in a minimum-mass solar nebula disk (for which $\Sigma \sim 10^3$ g cm\(^{-2}\) at 1 AU). For a given $dM/dt$, midplane temperatures scale roughly as the fourth root of optical depth, or $\Sigma_a^{1/4}$ [1], so in cases where uniform accretional heating would predict high $T_{\text{mid}}$, layered accretional heating might predict temperatures only one third as large.

Results: We have developed a numerical code that calculates the temperatures and densities of a protoplanetary disk at all radii and heights above the midplane given the global properties of the protostar and disk, assuming simultaneous radiative and hydrostatic equilibrium. Accretional heating is included via a turbulent viscosity whose strength is controlled by dimensionless constant $\alpha$ [6]. We have tested a grid of values for $dM/dt$, $\alpha$, and $\Sigma_a$ with a 4000 K protostar. We find that when $dM/dt = 10^{-9} M_{\odot}$ yr\(^{-1}\), changing the column density of the active layer from 1 to 100 g cm\(^{-2}\) causes $T_{\text{mid}}$ at 1 AU to rise from 103 K to 135 K. With $dM/dt = 10^{-8} M_{\odot}$ yr\(^{-1}\) $T_{\text{mid}}$ at 1 AU rises from 103 K to 268 K. Finally, with $dM/dt = 10^{-7} M_{\odot}$ yr\(^{-1}\), we find that $T_{\text{mid}}$ at 1 AU will be 437 K for a 100 g cm\(^{-2}\) active layer. When compared to previously assembled sets of disk model results [1], we find that our predicted midplane temperatures are consistently lower, by roughly a factor of 2, than theirs based on uniform accretional heating. Significantly, we find the $dM/dt$ required for CAI formation temperatures ~ 1400 K, approaches $10^{-5} M_{\odot}$ yr\(^{-1}\). Mass accretion rates this high may be achieved only for very short timescales, < $10^7$ yr, implying the CAI formation epoch may have been << $10^9$ yr.