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Radiation-Driven Instability in Layered Protoplanetary Disk Structures

J. Makopa[1], E. Utete[2], B. C. Jones[3] & G.G. Nyambuya[4]
[1]Department of Applied Physics, National University of Science and Technology, AC 939, Ascot, Bulawayo, Zimbabwe
[2]Department of Mathematics, Gwanda State University, Epoch Mine Campus, P.O.Box 30, Filabusi, Zimbabwe
[3]Department of Mathematics, National University of Science and Technology, AC 939, Ascot, Bulawayo, Zimbabwe
[4]Department of Applied Physics, National University of Science and Technology, AC 939, Ascot, Bulawayo, Zimbabwe

ABSTRACT: *Protoplanetary disks (PPDs) are primarily composed of molecular hydrogen and helium, while trace molecular species such as CO act as important probes of the disk's vertical structure. ALMA observations reveal that gaseous species are vertically stratified, with emission surfaces extending several thermal scale heights above the midplane. While $H_{therm} = C_s/\Omega$ is the standard metric to characterize the vertical thickness of the PPD, it relies on a global sound speed C_s tied to the hydrogen-gas rich environment. This inherently limits the ability of the sound speed based criterion to explain the dynamical behaviour of different gaseous species under radiative or thermal pressure support. In this study, we introduce an optical analogue of the sound speed, which strongly depends on the molecular mass of the gaseous species and the energy of the incident photon. This formulation predicts species-specific radiative scale heights ($\mathrm{H_g^\gamma}$), where lighter molecules are elevated to higher altitudes through photon momentum coupling while heavier species remain confined near the midplane. The resulting thermoradiative pressure support reproduces the elevated CO emission surfaces (typically 2-5 $\mathrm{H_{therm}}$) observed in ALMA based surveys. This yields a self-consistent model for interpreting the vertical thermo-chemical structure of planet-forming disks.*

Background

PPDs contain a mixture of gas and dust whose vertical distribution carries important information about the physical processes operating in planet-forming environments. ALMA based observations reveal that molecular emission surfaces, particularly from CO isotopologues, are vertically stratified and often extend several thermal scale heights (2-5 $\mathrm{H_{therm}}$) above the disk midplane (Paneque-Carreño et al. 2025). Dust grains are distributed non-uniformly due to a combination of gravitational settling, radiation interaction, and temperature-dependent opacity (Semenov et al. 2003; Henning & Stognienko 1996). ALMA utilizes the CO rotational emission spectrum to precisely map the observed emission height of the CO molecules. By observing multiple CO isotopologues or lines that probe different optical depths, physicists are able to make empirical determinations of the vertical gas structure. Subsequently, the thermal scale height can then be inferred by fitting the observed CO emission map with a physical model (Lee et al. 2024). This approach relies on the global parameters of the hydrogen and helium gas dominating the disk. However, distinguishing the effects of radiative and thermal pressure on different gas and dust species remains challenging in existing hydrodynamic models. As a result, the dynamical role played by photon momentum transfer in the vertical stratification of different gas and dust species is often ignored. In this study we suggest that, once the midplane is sufficiently heated by stellar radiation, the effects of photon momentum transfer become significant. Therefore, in the modest view, the collective role of radiative pressure in the vertical stratification of gas and dust species above the disk's midplane are not examined in current analytical studies, limiting our ability to interpret ALMA based observations.

Aim

To decouple the effects of thermal and radiative pressure in the vertical structure of the disk.

Objective

To develop a self-consistent model that serves as a diagnostic for assessing how photon momentum transfer contributes to elevated and stratified molecular emission surfaces reported in ALMA based studies.

Model

Our model unifies thermal and radiative pressure support, leading to species-specific layers of gas and dust above the disk midplane. We hitherto demonstrated that both the acoustic sound speed and our radiative transfer velocity arise from fundamentally similar processes of energy–momentum transduction, but in different physical regimes, *i.e*:

1. Thermal Support The classical thermal scale height is given by:

$$\mathrm{H_{therm}} = \frac{\mathrm{C_s}}{\Omega}$$

where C_s is the local sound speed and Ω is the Keplerian frequency.

2. Our Gas Radiative Support (Photon Momentum Transfer)

$$\mathrm{V_g^\gamma} = \sqrt{\frac{2hcT}{mb}}$$

Where: m is the molecular mass, T is the local radiation temperature, h is Planck's constant, c is the speed of light, and b is Wien's displacement constant. Lighter molecules achieve higher altitudes due to stronger photon-mometum coupling (see Figure 1).

3. Extended Montesinos et al. 2021a's Dust Radiative Support

$$\mathrm{V_g^\gamma} = \frac{\kappa\sigma_{SB}T^4}{c\Omega}$$

Where: κ is the dust opacity, σ_{SB} is the Stefan–Boltzmann constant, and Ω is the Keplerian frequency.

Table 1: Sample of obtained results for HD 100546 ($\mathrm{M=2.66\ M_\odot}$). Iron Rich Silicates (IRS) and Iron poor Silicates (IPS) are chemically homogenous dust aggregates.

R (AU)	T (K)	κ (m^2/kg) IRS	κ (m^2/kg) IPS	C_s (m/s)	V_g^γ (m/s) (CO)	V_g^γ (m/s) IRS	V_g^γ (m/s) IPS
1	1408	0.408	0.020	2249	2039	1137.00	46.00
5	700	0.393	1.094	1585	1437	613.00	1706.00
13	40	0.027	0.059	379	344	0.002	0.004
17	576	0.193	0.942	1438	1304	865.00	1526.00
34	220	0.527	1.345	889	806	142.00	363.00
45	100	0.179	0.376	599	543	3.130	6.580
53	25	0.007	0.018	300	272	0.001	0.002
100	50	0.043	0.090	424	384	0.160	1.450
200	38	0.015	0.035	370	335	0.050	0.120

Table 1 shows a sample from the pool of results for different molecular tracers analysed in this study.

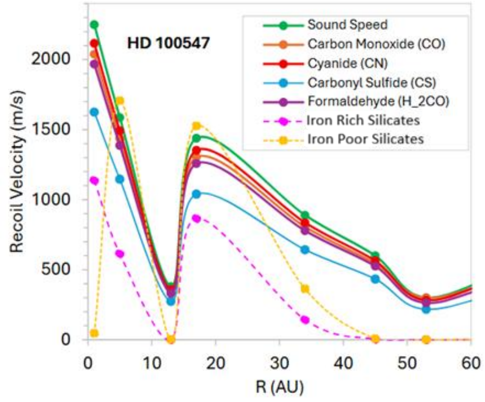

Figure 1: Radiative transfer velocities for a representative sample of gaseous and dust species in HD 100546 relative to the sound speed.

Results

In a shear-dominated, azimuthally rotating disk, the interplay between thermoradiative pressure support and gravity yields the tracer scale height. This is a residual scale height of the observable emission layer that emerges from the balance between dynamical confinement and thermoradiative pressure support

$$\mathrm{H_{tracer} = H_{Dyn} - (H_{therm} + H_g^\gamma)},$$

Where: $\mathrm{H_{Dyn}} = \frac{\mathrm{V_{freefall}}}{\Omega}$ is the dynamical upper bound for vertical excursions ($\mathrm{V_{freefall}} = -\frac{2\mathrm{H}}{3\mathrm{t}}$), and $\mathrm{H_g^\gamma} = \frac{\mathrm{V_g^\gamma}}{\Omega}$ is the radiative scale height. To recover the classical thermal scale height, three assumptions must hold and these are: 1) there is no net freefall motion, meaning that the vertical component of the freefall velocity is zero ($\mathrm{V_{freefall}} = 0$); 2) radiative pressure support is absent, so the radiative velocity term vanishes ($\mathrm{V_g^\gamma}$=0 and $\mathrm{V_d^\gamma}$=0); and 3) the disk is supported only by thermal pressure. When radiative pressure dominates vertical support, the characteristic timescale over which a gas parcel adjusts vertically is given by the ratio

$$\mathrm{t_{rad}} = \frac{\mathrm{H_g^\gamma}}{\mathrm{V_g^\gamma}} = \Omega^{-1}$$

For dynamical stability, the disturbance must propagate through the gas in less than one orbital time. If communication takes longer than the orbital timescale, radiative pressure restores the equilibrium before the disturbance spreads.

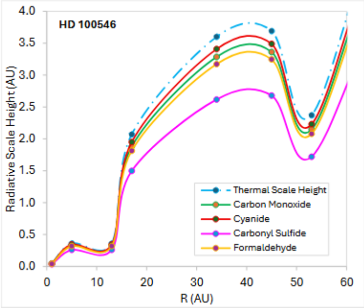

Figure 2: Radiative scale heights for a representative sample of gaseous molecular species in HD 10546 relative to the thermal scale height.

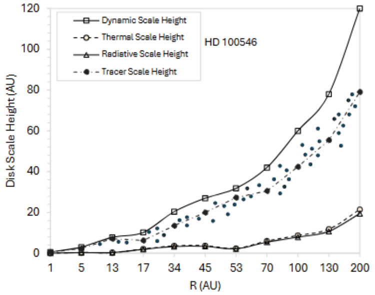

Figure 3: The CO tracer scale height in HD 100546.

The key outcome of this work is the realization that photon momentum transfer can elevate molecular species to specific scale heights, consistent with the CO emission surfaces observed in ALMA based surveys.

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