

Protoplanetary Disc Evolution in Binary Systems: A Combined SPH and Radiative Transfer Study

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I. INTRODUCTION

Smoothed Particle Hydrodynamics (SPH) simulations are crucial for modeling various astrophysical environments, including galaxies, giant molecular clouds, and protoplanetary discs (PPD). These hydrodynamic simulations primarily model gas interactions, treating gas as a fluid interacting with astrophysical bodies (stars, black holes, planets) often represented as sink particles that can accrete material [1]. While molecular hydrogen is the dominant component, the presence of dust significantly alters the optical and thermal properties of the gas. Therefore, accurate hydrodynamic simulations must consider both gas and dust to realistically reproduce observed astronomical structures.

PPDs are structures composed of gas and dust, typically with a gas-to-dust ratio of approximately 100:1. They form from the collapse of giant molecular clouds, with a protostar forming at the center and surrounded by an accretion disc. This disc is the birthplace of planetary systems. Understanding this PPD phase is crucial for determining planetary formation pathways, leading to Earth-like planets, stable planetary systems, or more exotic configurations. The transition from a PPD to a fully formed planetary system, such as our Solar System, remains poorly understood, highlighting the importance of simulation tools in advancing our knowledge.

While our Solar System serves as a common reference point for planetary systems—a single star orbited by planets—single stars constitute a fraction of stellar systems. Binary systems, comprising two gravitationally bound stars interacting with surrounding material, represent roughly one-third of all stellar populations [2], [3]. Such systems can host PPDs around either one star (circumstellar disc) or the binary pair (circumbinary disc). With few exceptions, computational models have simplified the problem by assuming a symmetric radiation and temperature field generated by a single star, even when modeling binary systems.

This study departs from this simplification by modeling the complete asymmetric radiation field of binary stars using the Monte Carlo radiative transfer code `Mcfost`, and computing the

hydrodynamics using the 3D-SPH code `PHANTOM`.

II. METHODS

We conducted 3D hydrodynamical simulations of circumstellar discs (CSDs) using the `PHANTOM` smoothed particle hydrodynamics code [4], along with live temperature field calculations provided by `Mcfost` [5], [6]. Two types of simulations were carried out: one involving pure gas SPH particles and the other treating dust particles using the dust one-fluid prescription [7], [8].

`PHANTOM` computes the positions and velocities of every SPH gas particle from the Lagrangian formalism by solving the equations

$$\frac{d\mathbf{v}}{dt} = -\frac{\nabla P}{\rho} + \Pi_{\text{shock}} + \mathbf{a}_{\text{ext}} + \mathbf{a}_{\text{sg}} + \mathbf{a}_{\text{selfgrav}}, \quad (1)$$

$$\frac{du}{dt} = \frac{P}{\rho^2} \frac{d\rho}{dt} + \Lambda_{\text{shock}} - \frac{\Lambda_{\text{cool}}}{\rho}, \quad (2)$$

where \mathbf{v} is the velocity vector, u is the specific internal energy, P is the gas pressure, ρ is the gas density, and the terms \mathbf{a}_{ext} , \mathbf{a}_{sg} and $\mathbf{a}_{\text{selfgrav}}$ represents the accelerations induced by an external force, a sink particle and self-gravity respectively. The terms Π_{shock} and Λ_{shock} are dissipation terms at a shock front. Finally, the term Λ_{cool} is a cooling term. As seen in both equations, the pressure term is crucial for accurately calculating variations in velocity and energy, which is achieved by incorporating an equation of state (EOS).

The EOS for an ideal gas is given by

$$P = (\gamma - 1)\rho u, \quad (3)$$

with γ as the adiabatic index. Additionally, it possesses the property that the specific internal energy depends solely on temperature. Consequently, defining the temperature field is equivalent to defining the internal energy.

Classically, the temperature profile is computed by assuming an isothermal distribution, which depends only on the radial coordinate. While variations in this approach can be introduced by adding a vertical temperature dependence, the profile remains fixed in space, centered on the central star, the primary heating source. By definition, an isothermal profile does not account for the disc's optical properties and additional radiation sources.

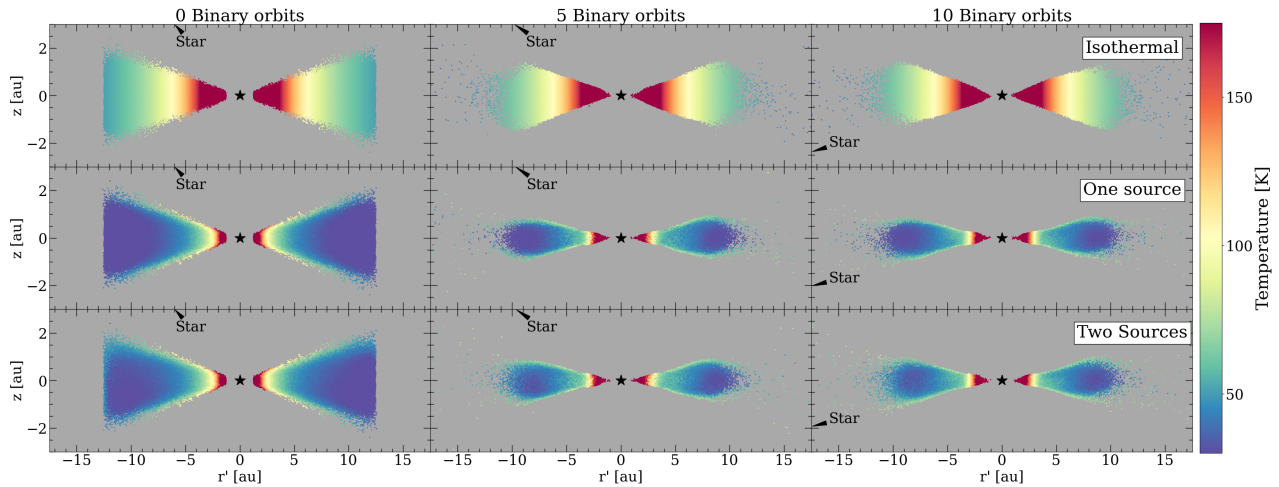


Fig. 1. The figure displays SPH particle temperatures under various radiative regimes in an inclined binary system. The first row shows a power-law temperature profile for reference. The second row depicts temperature maps calculated by `Mcfost`, considering only the primary star’s radiative heating. The third row shows simulations incorporating heating from both stars. Each column represents a snapshot in time: the initial state, and states after 5 and 10 binary orbits, respectively. An arrow indicates the secondary star’s position.

This becomes problematic when attempting to model multiple sources, such as binary or multiple stellar systems, since the hydrodynamics in the gaseous disc may not be accurately computed.

`PHANTOM` is capable of computing only isothermal profiles; therefore, `Mcfost` is responsible for calculating the entire radiative field and the resulting global temperature profile.

`Mcfost` is a 3D continuum and line radiative transfer code based on the Monte Carlo method. While it is widely used to generate synthetic images, its capability to compute temperature structures is the feature utilized by `PHANTOM`. `Mcfost` divides space into grids using a Voronoi tessellation centered on each SPH particle, such that physical quantities—such as gas and dust density, temperature, opacity, albedo, and scattering phase function—are constant within each cell. Radiation is modeled through “photon packets” with stars and the thermal emission of dust serving as the two primary radiation sources, emitting isotropically and uniformly. Depending on the cell’s optical properties, these photons can interact with the cells by being scattered, absorbed, or re-emitted.

This study uses simulations of a binary star system, modeling each star as a sink particle with a 1 au^1 accretion radius and a single CSD. Simulations explored various parameters: stellar masses (0.5 and $1 M_{\odot}^2$), binary-disc orbital inclinations (0° and 30°) to assess the impact of asymmetric illumination from the secondary star over the CSD around the primary, and dust treatments (none dust and a one-fluid model), also including a stellar-outburst scenario.

III. RESULT

Fig. 1 presents a direct comparison of temperature profiles within a protoplanetary disc, contrasting a simplified isothermal

¹1 astronomical unit (au) equals to 1.496×10^{13} cm.

²1 Solar mass (M_{\odot}) equals to 1.988×10^{33} g.

model with a more realistic model incorporating radiative transfer calculations performed using `Mcfost`. The radial cylindrical coordinate, r' , is defined by negative values representing the near side of the disc relative to the secondary star and positive values representing the far side.

The isothermal model fails to capture the temperature variations the radiative transfer approach reveals. The radiative simulations show significant temperature gradients in both the radial and vertical directions; specifically, the mid-plane regions exhibit significantly lower temperatures than the surface layers. This disparity arises because the radiative model correctly accounts for optical processes such as opacity. This more realistic temperature distribution results in a reduced vertical scale height in the radiative disc compared to the isothermal disc. This is a direct result of the disc needing to become vertically more compact to maintain hydrostatic equilibrium under the influence of gravity and the newly calculated temperature distribution.

The inclusion of the secondary star’s radiative heating dramatically amplifies these effects on disc structure and dynamics. When illuminated by the secondary star, the disc expands significantly, increasing the scale height by approximately 25% on the near side and nearly 10% on the far side. As it is shown in Fig. 2. These substantial alterations in the disc’s vertical structure have significant implications for dust dynamics, notably influencing the processes of dust settling and coagulation. Using one-fluid dust simulations, in contrast to dust-free simulations, which assume a constant 100:1 gas-to-dust ratio, allows for a more realistic representation of dust behavior. By explicitly simulating the dust as a separate fluid, the one-fluid approach reveals that dust efficiently concentrates in the mid-plane, making the effects illustrated in Figs. 1 and 2 more prominent.

Using `Mcfost`, we can simulate variations in stellar luminos-

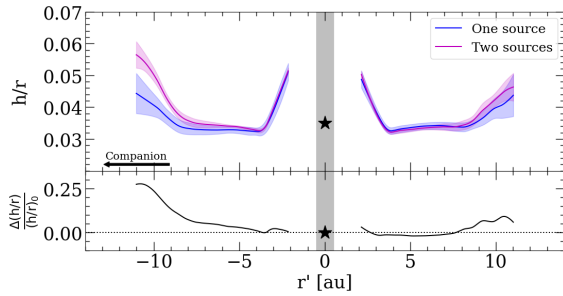


Fig. 2. The top panel of the figure compares the median disc scale height over a single binary orbit for two radiative simulations: one considering only the primary star as the source of heating (blue) and another considering both stars (magenta). The bottom panel shows the relative difference in scale height between these two models.

ity, even for a single star. To demonstrate the benefits of live temperature calculations, we modeled a stellar outburst event that dramatically increased the energy input to the disc. Fig. 3 illustrates the resulting shift in the disc’s isothermal lines after a 1000-fold increase in the secondary star’s luminosity. The substantial energy influx caused by the outburst creates distinct regions within the disc that are readily identifiable using SPH simulations. These regions are of particular astrochemical interest, notably showcasing areas where dust sublimation occurs and facilitating the detailed characterization of chemical zones.

IV. DISCUSSION

Previous models of PPDs significantly simplified the temperature structure by assuming a uniform, isothermal temperature profile throughout the disc. This simplification, while computationally efficient and cheap, neglected the crucial role of radiative transfer and the complex, asymmetric distribution of heat sources, especially in binary star systems. The development and application of a hybrid computational tool that couples sophisticated radiative transfer calculations with detailed hydrodynamic simulations marks a considerable advancement. This approach allows for the accurate computation of a non-symmetric, realistic temperature field within the PPD, considering the contributions of multiple stars and their varying luminosities. This more realistic representation of the thermal environment within the PPD has profound implications for understanding several key aspects of planetary formation, such as dust evolution, ice lines, and the overall dynamics of the disc [9], [10], leading to a qualitative improvement over previous, simpler models. The resulting enhanced understanding of chemical composition as a function of position and time is crucial for deciphering the complex interplay between gas-phase and solid-state chemistry, ultimately influencing the formation and composition of planetesimals and planets, and providing a critical link between disc conditions and the observable properties of exoplanetary systems.

V. CONCLUSION

Our findings reveal the importance of considering realistic radiative transfer effects when modeling protoplanetary discs,

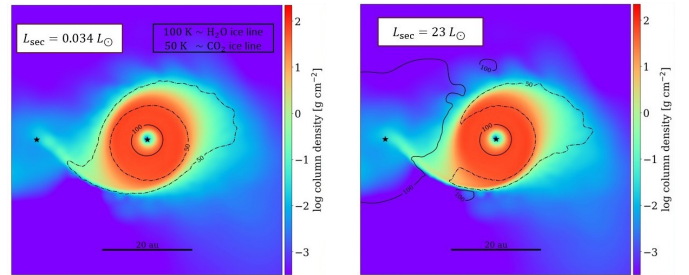


Fig. 3. The figure shows surface density and temperature radial profiles of a disc before and after a secondary star outburst event. The secondary star’s luminosity is given in solar luminosities; 1 Solar luminosity equals to 3.83×10^{26} W. Two important isothermal lines are included: a solid line representing the water ice line (around 100 K) and a dot-dashed line representing the carbon dioxide ice line (around 50 K).

especially in binary systems. The significant discrepancies between isothermal and radiative models emphasize the need for more sophisticated approaches. The observed variations in temperature profiles and disc scale height profoundly influence dust dynamics and the location of ice lines linked to disc chemistry. These results significantly impact our understanding of planetesimal formation, chemical evolution, and ultimately, the diversity of planetary systems observed.

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REFERENCES

- [1] M. R. Bate, I. A. Bonnell, and N. M. Price, “Modelling accretion in protobinary systems,” *MNRAS*, vol. 277, pp. 362–376, Nov. 1995.
- [2] D. Raghavan, H. A. McAlister, T. J. Henry, D. W. Latham, G. W. Marcy, B. D. Mason, D. R. Gies, R. J. White, and T. A. ten Brummelaar, “A Survey of Stellar Families: Multiplicity of Solar-type Stars,” *ApJS*, vol. 190, no. 1, pp. 1–42, Sep. 2010.
- [3] A. Tokovinin, “From Binaries to Multiples. II. Hierarchical Multiplicity of F and G Dwarfs,” *AJ*, vol. 147, no. 4, p. 87, Apr. 2014.
- [4] D. J. Price, J. Wurster, T. S. Tricco, C. Nixon, S. Toupin, A. Pettitt, C. Chan, D. Mentiplay, G. Laibe, S. Glover, C. Dobbs, R. Nealon, D. Liptai, H. Worpel, C. Bonnerot, G. Dipierro, G. Ballabio, E. Ragusa, C. Federrath, R. Iaconi, T. Reichardt, D. Forgan, M. Hutchison, T. Constantino, B. Ayliffe, K. Hirsh, and G. Lodato, “Phantom: A Smoothed Particle Hydrodynamics and Magnetohydrodynamics Code for Astrophysics,” *Publications of the Astronomical Society of Australia*, vol. 35, p. e031, Sep. 2018.
- [5] C. Pinte, F. Ménard, G. Duchêne, and P. Bastien, “Monte Carlo radiative transfer in protoplanetary disks,” *A&A*, vol. 459, no. 3, pp. 797–804, Dec. 2006.
- [6] C. Pinte, T. J. Harries, M. Min, A. M. Watson, C. P. Dullemond, P. Woitke, F. Ménard, and M. C. Durán-Rojas, “Benchmark problems for continuum radiative transfer. High optical depths, anisotropic scattering, and polarisation,” *A&A*, vol. 498, no. 3, pp. 967–980, May 2009.
- [7] G. Laibe and D. J. Price, “Dusty gas with one fluid in smoothed particle hydrodynamics,” *MNRAS*, vol. 440, no. 3, pp. 2147–2163, May 2014.
- [8] —, “Dust and gas mixtures with multiple grain species - a one-fluid approach,” *MNRAS*, vol. 444, no. 2, pp. 1940–1956, Oct. 2014.
- [9] T. Birnstiel, M. Fang, and A. Johansen, “Dust Evolution and the Formation of Planetesimals,” *Space Sci. Rev.*, vol. 205, no. 1–4, pp. 41–75, Dec. 2016.
- [10] K. I. Öberg, S. Facchini, and D. E. Anderson, “Protoplanetary Disk Chemistry,” *ARA&A*, vol. 61, pp. 287–328, Aug. 2023.