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Protoplanetary disks in close binaries

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Abstract

As of today there are 5 known exoplanets on S-type orbits in close binaries systems with separations of $\sim$20 AU. These systems offer new insight into planet formation, if it is assumed that such planets indeed formed together with the binary. At such close separations the disk around the primary star is perturbed by the companion, which makes planet formation difficult and puts current planet formation models to the test.

Here, we study the evolution of the protoplanetary disk around the primary star in systems like γ Cephei. We build upon previous results and perform 2D hydrodynamical simulations using state of the art methods. We compare the effects of different numerical parameters and physical models on the long term evolution of the disk. We include locally isothermal, polytropic and ideal equations of states as well as self gravity. To test the influence of numerics, we vary the simulated domain size, viscosities and boundary conditions. Our results show that the locally isothermal equation of state is not suited for circumprimary disks while the polytropic and ideal equation of state are in good agreement. We found that the domain size used in comparable studies is often too small and needs to be at least twice the size of the disk. Viscosities and boundary condition also play a crucial role in the long term evolution of the disk.

1. Introduction

There are currently 5 known exoplanets on S-type orbits (orbiting the primary star) in close binaries with separations of 20 AU [8]. At such small binary separations the disk around the primary star is perturbed by the companion star which puts constraints on the planet formation process. Therefore, alternative explanations have been put forward to explain how planets can form inside a close binary. The binary could have been further apart in the past when the planet was formed [3] or entirely different planet formation channels such as gravitational instability [1] are assumed.

In this work the planet formation process in close binaries is studied using the γ Cephei system. Because of its extreme conditions this system puts our current planet formation model to the test. The system has a semi major axis of 20 AU, an eccentricity of 0.4 and the observed planet is close to the orbital stability limit where models predict planet formation to be difficult, as the eccentricities evoked by the companion causes planetesimal collisions to become destructive [6]. Planet formation in binaries has been numerically investigated before (e.g. [7] [2], [5]), yet many details are still poorly understood, such as the importance of the boundary condition, and there is still a large parameter space that has not been explored yet. This work starts from the results presented in [5] but varies more parameter to test their impact on the disc structure.

2. Method

For the simulations the FARGO code [4] is used. Based on [5] we change the simulations parameters. For the domain size, five different sizes are used to test for convergence. Additionally the different equations of state, locally isothermal, polytropic and ideal are compared against each other. For the inner boundary the reflecting and viscous outflow where used, and at the outer boundary the open boundary condition was used. The values for the α viscosity are chosen between 10^{-2} and 10^{-4}.

3. Results

For the locally isothermal equation of state the disk eccentricity increases with increasing domain size of the simulation while the polytropic and ideal equation of state are less sensitive to the domain size. The disk becomes significantly more eccentric (up to $e \approx 0.3$) for the locally isothermal equation of state. On the other hand, both the polytropic and ideal equation of state produce similar disks dynamics with lower eccentricities ($e \leq 0.2$) . For the ideal equation of state a phase transition is observed (see the small jump in eccentricity in Fig.1 at T = 1300 T_{bin}) at which the disks radius suddenly increases by $\sim 8\%$ and stops precessing . But it is not yet clear if this phase transition is caused by numerical or physical causes.

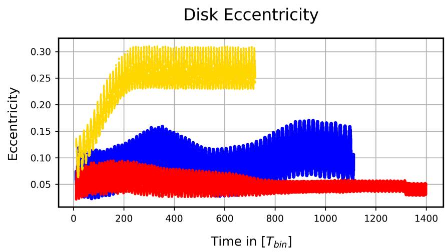

Figure 1: Eccentricity of the circumprimary disk for different equations of state. Yellow: Isothermal, blue: Polytropic and red: Ideal equation of state.

Reducing the α viscosity reduces the disk radius. The discs radius is given by a balance of viscous versus gravitational torques. The smaller disk is less affected by the perturber and becomes less eccentric $e \leq 0.05$ for $\alpha = 10^{-4}$. Likewise, higher α values increase disk size and disk eccentricity.

At the outer edge of the simulation domain open boundary and a no torque condition are used, as this setup has only small effects on the inside of the domain. At the inner edge only reflective boundaries can be used to study the long term evolution of the disk. Open boundary conditions or viscous outflow causes the disk to be accreted onto the star in a few hundred orbits. At the inner boundary the radial velocities are damped to zero and the disk density and energy are damped to the azimuthal mean to prevent the reflective boundaries affecting the disk dynamics. This causes the eccentricity to become more stable. Studying the effect of the boundary conditions is still ongoing.

The dynamics in the disk is changed when the outer boundary is extended from 8 AU to 12 AU. Increasing the outer boundary any further does not change the disk dynamics but decreases the mass loss. With the larger outer boundary, mass ejected from the disk can be accreted back onto the disk. Moving the inner boundary further inward stabilizes eccentricity but surprisingly increases the amount of mass ejected out through the outer boundary.

4. Summary and Conclusions

The results of this parameter study show that using locally isothermal equation of state results in a significantly higher eccentricity and implausible dependency to scaling domain size. While the polytropic and ideal equation of state lead to more consistent results with respect to the domain size. The outer boundary at 8 AU was found to be too small, while 12 AU seems to be sufficient, as it contains the whole Roche volume of the primary. It was found that for polytropic and ideal equation of state paired with low alpha viscosity produces the lowest eccentricities. Overall the simulations have shown, that additional work is required to find a set of simulation parameters to reasonably describe the eccentricity and conclude on the possibility of planet formation in a binary like γ Cephei. In the next step we will perform simulations including dust and planetesimals to directly measure their relative velocities.

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