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Disk Evolution of Classical Be Stars with Misaligned Binary Companions

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Abstract

Classical Be stars are rapidly rotating B type stars that are surrounded by a gaseous circumstellar decretion disk. Like many massive stars, Be stars are frequently found to exist in binary systems, with a wide array of orbital configurations. Recently, we have computed three-dimensional (3D) smoothed particle hydrodynamics (SPH) models of Be stars with equal-mass binary companions whose orbit is misaligned to the initial plane of the disk and found that the misaligned companion can cause the disk to undergo phenomena of Kozai–Lidov oscillations, and disk-tearing, in addition to the expected tilting and warping of the disk. We now show that these phenomena are not unique to equal-mass systems, but that there is a range of mass ratios for which disk-tearing and Kozai–Lidov oscillations can occur. We also find that an increase in viscosity can suppress these phenomena. Next, we combine our SPH models with the 3D nonlocal thermodynamic equilibrium Monte Carlo radiative transfer code HDUST to produce synthetic spectra of these systems. We show how both phenomena can change the Hα emission line profile, and how disk-tearing creates a detectable polarization signature. We also present a comparison of the observable trends in our disk-tearing model, and how these mimic the changes observed in Pleione (28 Tau). Overall our results demonstrate how phenomena from a misaligned binary companion can cause variations in observables across the whole disk, and that these phenomena need to be considered when analyzing the time evolution of Be star spectra.

Keywords: B-emission stars, circumstellar disks, binary systems

1. Introduction

Classical Be stars are well-known for developing gaseous circumstellar disks, which produce Balmer emission lines in the B star spectrum, in addition to adding excess continuum emission (especially in the IR) and linear polarization (see Rivinius et al., 2013, for a thorough review). The formation of these disks is best described by the viscous decretion disk (VDD) model of Lee et al. (1991), where mass is ejected at the stellar equator via some unknown mechanism and then transported outwards via viscous effects. Rapid rotation of the star (Townsend et al., 2004) and stellar pulsations (Baade et al., 2016) are thought to be the likely combination of mechanisms to produce these episodes of mass ejection into the disk.

Be stars are very frequently found in binary systems, and these binary companions are notably always more evolved stars (Bodensteiner et al., 2020), which has led to the belief that a Be star gains its rapid rotation via mass accretion when this more evolved star overflowed its Roche lobe. There is much recent evidence that all Be stars are perhaps in binary systems, thanks to many new companion detections (Klement et al., 2019; Wang et al., 2021; Klement et al., 2024, for example). Thus, the modelling of how a binary companion can effect the evolution of a Be star disk, and how these changes appear in a spectrum, can be highly valuable in helping determine the existence of a binary companion, and the nature of its orbit, in a Be star system.

In this work, we present new simulations of Be star binary systems where the binary companion's orbit is misaligned to the initial injection plane of the disk, which expand on the models previously presented by Suffak et al. (2022), by varying the binary mass ratio as well as the disk viscosity, to explore the parameter space over which a misaligned binary companion may cause the phenomena of disk-tearing and Kozai–Lidov oscillations. We also show that we can combine our hydrodynamic simulations with our radiative transfer code to produce high resolution predicted observables of the resulting disk configurations.

2. Simulation Details

This work utilises a 3D smoothed particle hydrodynamics (SPH) code created by Benz et al. (1990), modified by Bate et al. (1995) to include a second-order Runge–Kutta–Fehlberg integrator, and adapted for use with Be stars by Okazaki et al. (2002). We computed eight new SPH simulations, expanding upon the equal-mass ratio simulations of Suffak et al. (2022) that had binary misalignment angles of 40° or 60° and viscosity $\alpha = 0.1$, by varying the mass ratio as either 0.1 or 0.5, or varying the viscosity value to be 0.5 or 1.0.

Our predicted observables are computed with the 3D non-local thermodynamic equilibrium Monte Carlo radiative transfer code HDUST (Carciofi and Bjorkman, 2006). We use an interface between the SPH code and HDUST, first utilized in Suffak et al. (2024), to convert the SPH particle distribution at any time step into a computational grid of densities and velocities that HDUST can accept as input.

3. Results

3.1. Disk dynamics

The evolution of disk mass, inclination, and eccentricity, when varying mass ratio are shown in Figs. 1 and 2 for the 40° and 60° misaligned simulations, respectively. In Fig. 1, the repeated occurrences of disk-tearing are seen in the sharp drops in disk inclination for $q = 1$

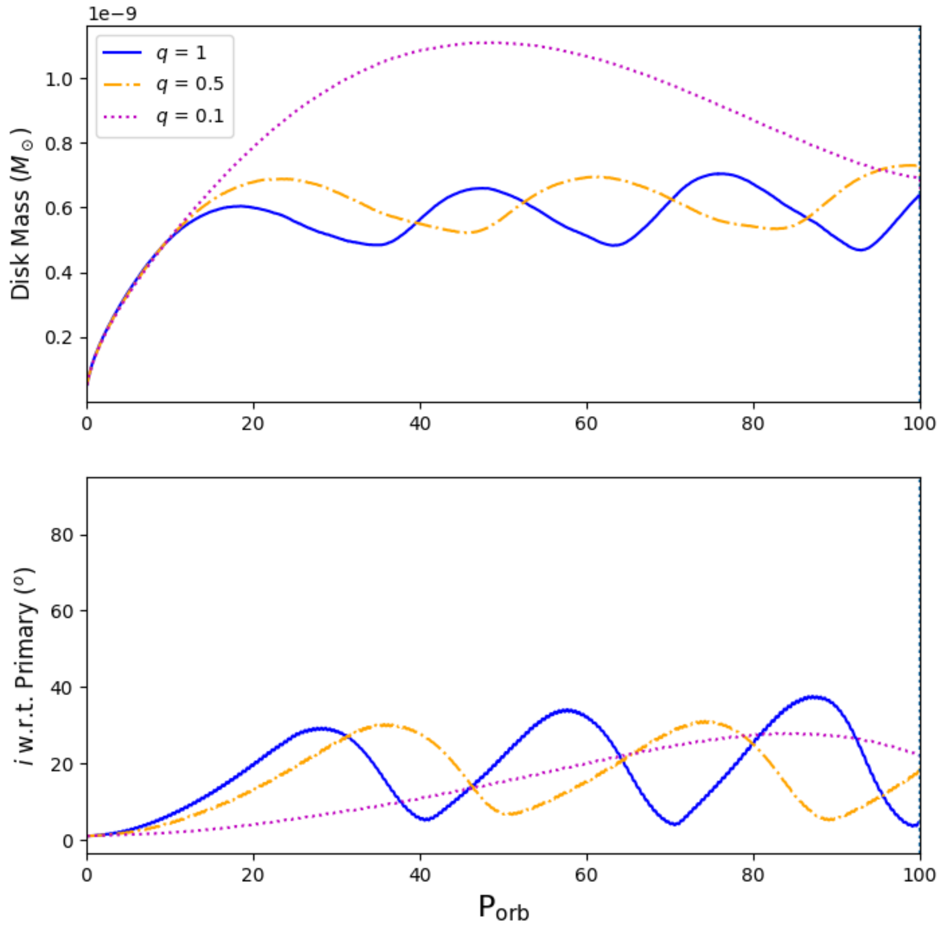

Figure 1: Evolution of the disk mass and inclination for models with a 40° misalignment angle and varying mass ratio (q) as indicated by the legend. The total disk mass is in the *top panel*, while the *bottom panel* shows the disk inclination with respect to the primary equatorial plane. The x-axis is in units of binary orbital periods.

and $q = 0.5$. We see that disk-tearing still occurs for the mass ratio of 0.5 just with a slightly longer tearing period than the equal-mass case, but tearing does not occur for a mass ratio of 0.1. Our models are consistent with the analytical estimate for the tearing radius given by Doğan et al. (2015). The oscillation of the disk mass is directly tied to the changing inclination of the disk, as discussed in Martin et al. (2011). After disk dissipation begins, we see all of the models precess as whole disks and no more tearing occurs.

The 60° simulations in Fig. 2 show the same trend as the 40° simulations, in that Kozai–Lidov oscillations still occur for a 0.5 mass ratio once disk dissipation begins, but not for $q = 0.1$. The initial period of the Kozai–Lidov oscillation seen in our disks agrees with the timescale formula given by Martin et al. (2014).

The case of varying the viscosity parameter α is straightforward, in that a higher value α

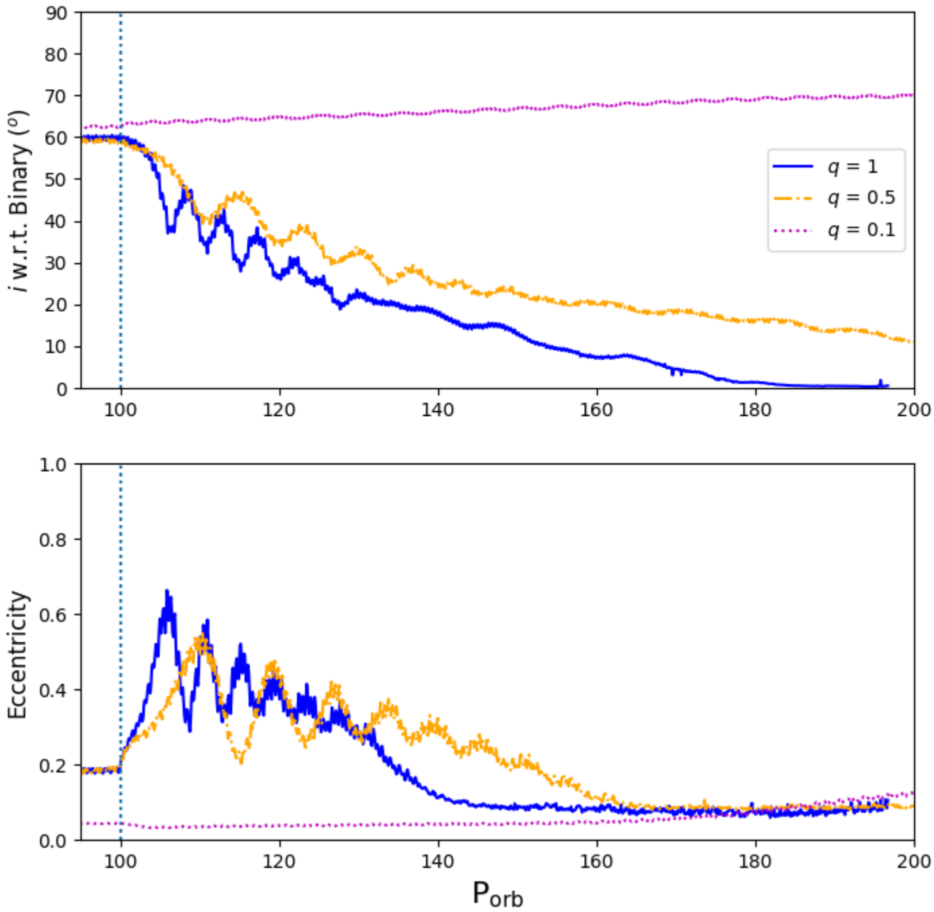

Figure 2: Kozai–Lidov behaviour of the disk inclination and eccentricity, for models with a 60° misalignment angle and varying mass ratio as indicated by the legend. The *top panel* shows the disk inclination with respect to the binary orbital plane, while the *bottom panel* shows the disk eccentricity. The *x*-axis is in units of binary orbital periods. The vertical dotted line indicates where disk dissipation begins.

suppresses most of the oscillations seen in Figs. 1 and 2. We do not see any disk tearing for α of 0.5 or 1.0, and only see Kozai–Lidov oscillations at α of 0.5. This is a direct consequence of the viscous torque within the disk being directly proportional to α. A higher viscosity leads to faster communication within the disk, and thus the disk is less susceptible to perturbations from the binary companion. However, it should be noted that other parameters of the system, such as the binary orbital period, inclination, and the mass-injection rate into the disk, could be changed such that these phenomena do occur for higher values of α.

3.2. Predicted observables

In linking our SPH models with the radiative transfer code HDUST, we are able to predict photometry, polarization, hydrogen emission lines, and interferometric quantities for the disk as it experiences Kozai–Lidov oscillations or disk-tearing.

During Kozai–Lidov oscillations, we find that the observables, most notably the Hα line, and polarization level, have significant oscillations in tandem with the changing inclination of the disk as it dissipates. Photometry also shows these oscillations, however with a smaller relative amplitude (Suffak et al., in prep.). At times, the Hα line profile shows the elusive triple-peaked structure, which has been seen, but never before modelled, in Be stars (Štefl et al., 2009; Moritani et al., 2013, for example).

In the case of a tearing disk, the combination of an inner and outer disk at different inclinations is able to produce quadruply-peaked Hα lines due to the large inclination differences between the two disks. This is caused by the large relative velocity difference of the face-on inner disk and edge-on outer disk, which each produce a set of two peaks. A torn disk can also produce a sawtooth profile in the polarization position angle versus wavelength due to the differing hydrogen opacities between the two disk pieces (Suffak et al., 2024). The more dense inner disk is subject to higher opacities near ionization boundaries, and so its polarization contribution drops, while the tenuous outer disk produces a small, but constant, polarization signal itself and skews the position angle towards its value when the inner disk opacity is high.

We find a good comparison between the trends in observables of our disk-tearing model and the long-term trends seen in the Be star Pleione (28 Tau). Pleione has been proposed, and analytically supported, to have a tearing disk (Marr et al., 2022; Martin and Lepp, 2022). Figure 3 shows a side-by-side comparison of the trends in our model with those of Pleione, first published in Suffak et al. (2024). Our disk-tearing model is able to match the simultaneous drop in Hα equivalent width (EW) and V-band photometry, along with the concurrent rise in polarization degree seen in Pleione, trends which no other model has been able to replicate as of yet. The actual magnitudes of our observables do not match those of Pleione, which was expected because our original stellar and disk parameters were not chosen to match Pleione.

4. Conclusion

In this work, we have shown through simulations that a misaligned binary companion can cause the phenomena of disk-tearing and Kozai–Lidov oscillations in Be star disks. The oc-

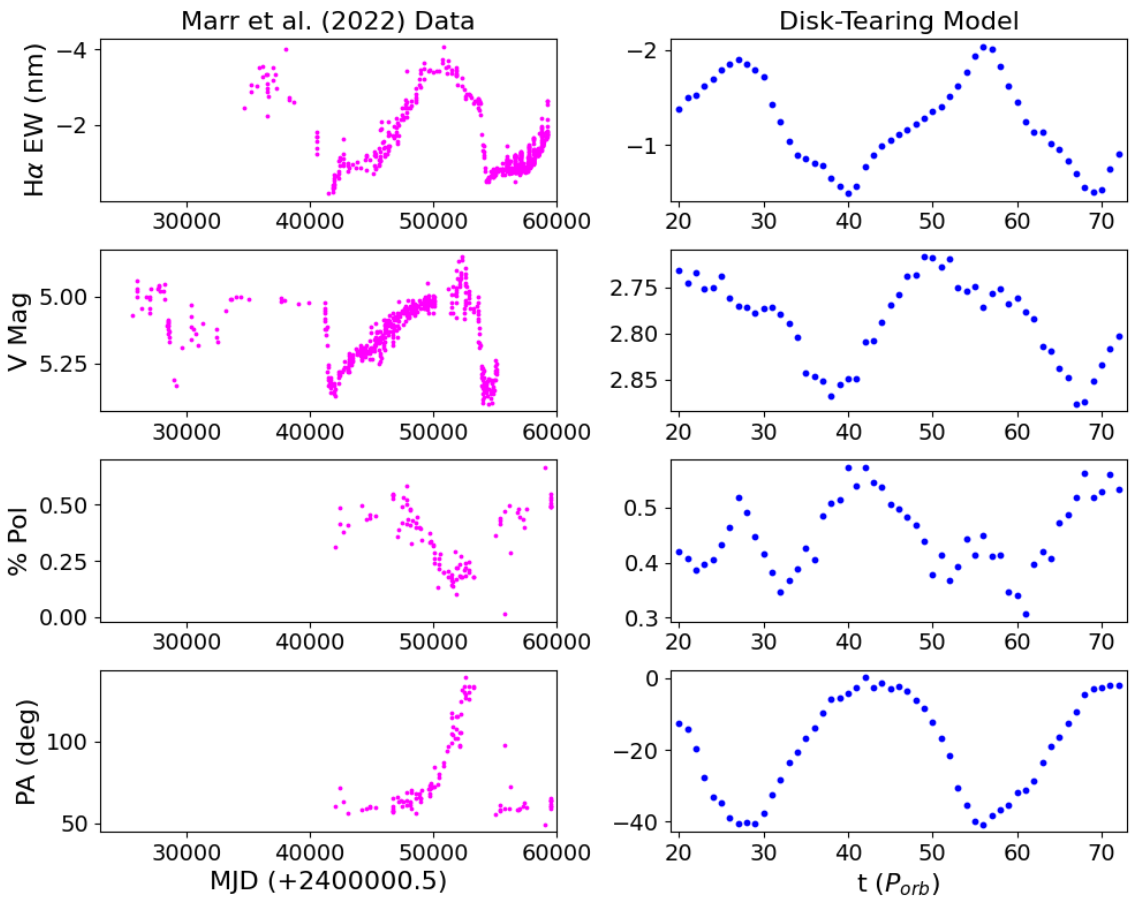

Figure 3: Data of Pleione collected by Marr et al. (2022) (*left*), and predicted observables of our disk-tearing model over two disk-tearing cycles (*right*). *Top* to *bottom* shows the Hα EW, V-band magnitude, polarization level, and polarization position angle. Reproduced from Suffak et al. (2024, Fig. 10) – CC BY 4.0.

currence of these phenomena is dependent on the binary mass, orbital period, eccentricity, and inclination, as well as the disk viscosity and mass-injection rate, and thus is not just limited to binaries with mass ratios near unity, or necessarily low viscosity disks. However, given that many Be stars are being found to have low mass companions and the binary mass is directly proportional to its torque on the disk, the occurrence of a disk undergoing a full tear is likely to be quite rare, while a warped disk would perhaps be more common in the low mass-ratio scenario.

In linking our SPH code with the radiative transfer code HDUST, we are also able to predict observables of these disks in misaligned systems. We find that the Kozai–Lidov mechanism could be detected in a Be star disk via oscillations in the Hα EW or the polarization percentage while the disk is dissipating. For a tearing disk, the key observational signatures can be quadruply-peaked emission lines, or a sawtooth-shaped profile in the polarization position angle versus wavelength. Both Kozai–Lidov oscillations and the disk-tearing mechanism would also cause large oscillations in the overall polarization position angle.

The trends in our disk tearing model match the overall trends in the Be star Pleione. Thus further observations of Pleione will be highly valuable to our future modelling efforts. According to our current disk tearing model, the disk of Pleione should be warping over the next five or six years, before tearing again in the early 2030s. The next large drop in EW and V magnitude should not occur until shortly after 2040, but the signatures of disk tearing should be visible in the next few years as Pleione moves into its tearing phase. We plan to explore further models of Pleione by adopting the binary parameters specifically for this system, which will allow us to put constraints on the disk viscosity that permits disk tearing in a low mass ratio ($q \approx 0.1$) system like Pleione. This will help make more accurate predictions of the timing of its tearing cycle and the nature of its disk. This work will not only help understand the nature of Pleione, but also the evolution of all Be star disk systems.

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Further Information

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Author contributions

M.W.S. computed all models for this work, analyzed all of the resulting data from said models, made the figures, and wrote the manuscript. C.E.J. and A.C.C. provided many valuable comments, suggestions, and ideas towards the analysis of these models, the resulting plots, and the writing of this work.

Conflicts of interest

The authors declare that there is no conflict of interest.

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