CrossMark

Be Star Disks: Powered by a Nonzero Central Torque

C. J. Nixon[1] and J. E. Pringle[1,2]

[1] School of Physics and Astronomy, University of Leicester, Leicester, LE1 7RH, UK; cjn@leicester.ac.uk
[2] Institute of Astronomy, Madingley Road, Cambridge, CB3 0HA, UK

Abstract

Be stars are rapidly rotating B stars with Balmer emission lines that indicate the presence of a Keplerian, rotationally supported, circumstellar gas disk. Current disk models, referred to as "decretion disks," make use of the zero-torque inner boundary condition typically applied to accretion disks, with the "decretion" modeled by adding mass to the disk at a radius of about 2% larger than the inner disk boundary. We point out that, in this model, the rates at which mass and energy need to be added to the disk are implausibly large. What is required is that the disk has not only a source of mass but also a continuing source of angular momentum. We argue that the disk evolution may be more physically modeled by application of the nonzero torque inner boundary condition of Nixon & Pringle, which determines the torque applied at the boundary as a fraction of the advected angular momentum flux there and approaches the accretion and decretion disk cases in the appropriate limits. We provide supporting arguments for the suggestion that the origin of the disk material is small-scale magnetic flaring events on the stellar surface, which, when combined with rapid rotation, can provide sufficient mass to form, and sufficient angular momentum to maintain, a Keplerian Be star disk. We discuss the origin of such small-scale magnetic fields in radiative stars with differential rotation. We conclude that small-scale magnetic fields on the stellar surface, may be able to provide the necessary mass flux and the necessary time-dependent torque on the disk inner regions to drive the observed disk evolution.

Unified Astronomy Thesaurus concepts: Accretion (14); Stellar accretion disks (1579); Hydrodynamics (1963); Magnetic fields (994); Emission line stars (460); Stellar coronal mass ejections (1881); Solar coronal mass ejections (310); Circumstellar disks (235)

1. Introduction

Be stars are rapidly rotating, main-sequence stars that somehow manage to form low-density, equatorial, circumstellar disks in Keplerian rotation. These circumstellar disks of gas that are the origin of the defining Balmer lines in Be stars are generally seen to be variable, and sometimes to come and go (see, e.g., the reviews by Porter & Rivinius 2003; Owocki 2006; Rivinius et al. 2013; Okazaki 2016). Not all rapidly rotating B stars display circumstellar disks, for example, the Bn stars are as numerous as the Be stars and show rapid rotation when seen equatorially through shallow and broad atmospheric lines, but no Balmer emission. We can define the breakup, or maximal, angular velocity of the star as $\Omega_{\rm K} = (GM_\star/R_\star^3)^{1/2}$, where $M_\star$ is the stellar mass and $R_\star$ is the stellar radius.[3] Then a typical Be star has an angular velocity of $\langle \Omega_\star \rangle \approx 0.8\,\Omega_{\rm K}$ (Porter & Rivinius 2003; Rivinius et al. 2013).

In this Letter, we concern ourselves with the formation, variability, and disappearance of the circumstellar disk material. In Section 2, we discuss current models for these variations. We show that the assumptions made in these models are not physically reasonable, in terms of the magnitudes of the required fluxes of mass, energy, and angular momentum. In Section 3, we discuss current ideas for disk formation— hydrodynamic and magnetic—and argue strongly for the latter, in terms of variable, small-scale, equatorial magnetic fields. In Section 4 we discuss the origins of such fields and why they are

likely only to be found in objects such as Be stars. We conclude in Section 5.

2. Current Models of Be Star Disk Variability

Models for the time variability of Be stars disks, and their use in modeling observations, especially of ω CMa, are provided by a number of authors (Hanuschik et al. 1993; Carciofi et al. 2012; Haubois et al. 2012; Ghoreyshi & Carciofi 2017; Ghoreyshi et al. 2018; Rímulo et al. 2018). In these works the modeling of the disk variations proceeds as follows:

1. The disk is assumed to have an inner boundary, $R_{\rm in}$, close to the stellar surface, $R_\star$, which has a zero-torque boundary condition ($f = 0$ in the notation of Nixon & Pringle 2021—see Section 3.2 below).[4]
2. The disk is assumed to have an outer boundary at which the disk sound speed is approximately equal to the escape velocity, typically at around $R_{\rm out} \approx 400$–$1000\,R_\star$. There the boundary condition is also zero torque, so that the disk loses mass freely at that radius.
3. At the start of an outburst event, mass is added to the disk at some rate $\dot{M}$, at a radius $R_{\rm add} = R_{\rm in}(1 + \epsilon)$ that is very close to the inner radius with typically $\epsilon \approx 0.02$. The matter is added to the disk with the Keplerian velocity for that radius. For the decline phase of an event, $\dot{M}$ is set to zero, and (almost) all of the disk drains through the inner boundary back onto the star.

---

[3] Note that a rapidly rotating star is strongly distorted with the equatorial radius being larger than the polar one. Thus the definition of $R_\star$ is somewhat uncertain. We gloss over this difficulty here, but refer the reader to Porter & Rivinius (2003) and Rivinius et al. (2013) for a fuller discussion.

[4] This means that, contrary to the impression given in these papers, these disks are not bona fide decretion disks (Pringle 1991; Nixon & Pringle 2021).

These models imply that the rate at which mass is added to the disk greatly exceeds the rate at which matter finds its way into the observable circumstellar disk. For example, in a steady disk with a zero-torque inner boundary, the fraction of added mass that finds its way into the circumstellar disk is $\approx 0.5\epsilon (R_{\rm in}/R_{\rm out})^{1/2} \approx 3 \times 10^{-4}$ (Nixon & Pringle 2021). This agrees with the estimate given by Rímulo et al. (2018) (see also Ghoreyshi et al. 2018). During the growth phase, Rímulo et al. (2018) find that the disk is required to grow at a rate $\dot{M}_{\rm disc} = 10^{-9}\, M_\odot\, {\rm yr}^{-1}$, which can be comparable to a typical mass-loss rate in the stellar wind (Krtička 2014).[5] This implies that typically mass is added to the disk at a rate $\dot{M} \sim 3 \times 10^{-6}\, M_\odot\, {\rm yr}^{-1}$, which is around 3×10^3 times the stellar wind mass-loss rate. For a typical Keplerian velocity of $\approx 700\, {\rm km\, s}^{-1}$ this requires an energy input of several percent of the stellar luminosity. Moreover, because the addition of mass implies the addition of angular momentum, it is apparent that adding mass, and therefore angular momentum, at these rates would imply an unrealistically large flux of angular momentum (i.e., torque) at the stellar surface.

We conclude that while the current models provide a simple means of modeling the Be star disks at radii away from the stellar surface, as they stand, they also contain hidden assumptions that are not physically plausible.

3. Models for Disk Formation

Rivinius et al. (2013), in an extensive and authoritative review article, provide a discussion and historical overview of the many mechanisms that have been proposed for the formation and variability of disks in Be stars. Rivinius et al. (2013) conclude that the current best options for providing sources of mass and angular momentum to the circumstellar Be star disks are *either* (i) material launched hydrodynamically from the stellar surface by nonradial pulsations, *or* (ii) material launched by *small-scale* magnetic fields.[6]

3.1. Hydrodynamic Disk Launching

The attraction of tying the launching of Be star disks to the observed nonradial pulsations is that there seems to be a strong correlation between the disk launching and variability and the presence and detailed behavior of such pulsations (e.g., Baade et al. 2016, 2018; Semaan et al. 2018; Neiner et al. 2020). In Section 2 we have detailed the physical requirements for the launching and maintenance of a Be star disk in terms of the current models. Owocki (2006) explains why such requirements cannot be met by a purely hydrodynamic mechanism (such as disk launching by nonradial pulsations). The fundamental, and insuperable, problem is that the velocity of the launched material, relative to the stellar surface, typically exceeds the sound speed at the stellar surface by factors of ~ 5–30. Furthermore, as we have seen, unless the launching mechanism can also provide a continuous supply of angular momentum the mass and energy fluxes within the star disk interface are implausibly large. Providing such a supply of angular momentum by purely hydrodynamic means would involve hypersonic, severely dissipative fluid motions. Thus, a

more plausible picture for the relationship between disk launching and maintenance and nonradial pulsations might be one in which the launching mechanism and/or presence of a disk causes the nonradial pulsations, rather than the other way round.[7]

3.2. Nonzero Central Torque Accretion Disks

Recently, Nixon & Pringle (2021) have noted that a more appropriate inner boundary condition might be one in which the torque at the inner boundary is finite, but *nonzero*. They show the properties of both steady and time-dependent disks for which there is an angular momentum source (torque) at the inner edge that is a factor f times the advective angular momentum sink there. In this notation, standard accretion disks (e.g., Pringle 1981) correspond to $f = 0$, and standard decretion disks (e.g., Pringle 1991) correspond to the limit $f \to \infty$. In the Be star case, a source of angular momentum ($f > 0$) can be achieved if the inner disk boundary is now at the Alfvén radius, $R = R_M$ (Pringle & Rees 1972), which is determined by the radius at which the disk is being truncated by small-scale magnetic fields (see Rivinius et al. 2013). We then require that radius, R_M, to be greater than the corotation radius R_Ω at which the stellar angular velocity equals the disk Keplerian velocity. If we define the breakup angular velocity of the star as $\Omega_K = (GM_\star/R_\star^3)^{1/2}$, then for a typical rotation velocity of $\Omega_\star \approx 0.8\Omega_K$ (Porter & Rivinius 2003; Rivinius et al. 2013) we find that $R_\Omega/R_\star \approx (\Omega_K/\Omega_\star)^{2/3} \approx 1.16$. For a typical inner disk density of $\rho_0 \sim 10^{-10}$–$10^{-12}\, {\rm g\, cm}^{-3}$ (Silaj et al. 2010), and temperature of $T_0 \sim 15,000$–$20,000$ K, the field strengths required to ensure that $R_M \geqslant R_\Omega$ would be around $B \sim 5$–50 G, on radial scales of around $\sim 0.2R_\star$. Such fields are not currently observable (e.g., Wade et al. 2016).

If these conditions could be achieved, then more physically plausible, time-dependent disk models, essentially equivalent to those described in Section 2, could operate as follows:

1. In the disk growth phase, matter (and angular momentum) is added to the disk at some radius $R_{\rm add} > R_\Omega$. The inner disk boundary is such that a continuing (magnetic) torque is provided to the disk material. In the parameterization of Nixon & Pringle (2021) this implies $f \gg 1$.[8] It would be plausible for the matter to be provided to the disk by the same magnetic processes that provide the inner torque (like solar coronal mass ejections, but on a much reduced scale, or a small-scale multipole version of the slingshot prominences" discussed by Villarreal D'Angelo et al. 2018, 2019 and Jardine & Collier Cameron 2019).
2. In the decline phase, magnetic activity declines until $R_M < R_\Omega$, decreasing the rate at which mass is added to the disk, and removing the inner magnetic torque (so that now $f \ll 1$).

We have argued above that in order for most of the material launched into the disk to remain there (at least initially) it is

---

[5] Here we use the stellar parameters given by Okazaki (2016) for a typical B0 main-sequence star.

[6] There is a long history of discussion of disk formation by large-scale (quasi-dipole) fields, but Rivinius et al. (2013) rule these out on both theoretical and observational grounds (see also Section 4).

[7] For example, if, as we argue below, disk launching comes about as a result of a peak in dynamo action, and if such a peak is able to lead to the excitation of nonradial pulsations.

[8] Note that simply increasing the value of f from $f = 0$ (standard accretion) to $f \gtrsim 1$ at the inner boundary is likely not sufficient as significant accretion can then still continue, despite the net flow of angular momentum being reversed (see Popham & Narayan 1991). Note too that a true decretion disk occurs only in the limit $f \to \infty$ (Nixon & Pringle 2021).

necessary for the launching mechanism to be able to provide a continuing source of angular momentum. Thus, we conclude that the existence and the evolution of the disk is most plausibly provided by the time-dependent behavior and activity of small-scale magnetic fields close to the equatorial stellar surface.

4. Magnetic Fields

The idea that the inner parts of Be star accretion disks are controlled by small-scale magnetic fields is not new. Smith (1989) interpreted the transients and ejections in λ Eri in terms of small-scale magnetic flaring processes similar to those on the Sun, T Tauri stars, and several other types of magnetically active cool stars. He suggests that "quasi-cycles" in at least some classical Be stars find their origin in chaotic knots of magnetic field that periodically drift to the surface, as on the Sun, and dissipate through flaring triggered by sudden changes in field topology, perhaps jostled by surface velocity fields provided by, for example, their nonradial pulsations. Further, Smith et al. (1994, 1997) suggest that their observations of variability in λ Eri can be interpreted as being due to magnetic loops and magnetically induced flares. More recently Smith et al. (2016) have applied such ideas to the X-ray production in γ Cas. Owocki (2006) (see also ud-Doula & Owocki 2002) considers large-scale dipole magnetic fields as a means of providing torques on an outflowing channeled wind and concludes that this mechanism is not viable. Rivinius et al. (2013) note that no magnetic fields have yet been detected on any Be star, and suggest an upper limit to an ordered, net, line-of-sight field component of around 100 G. They also discuss the evidence for small-scale magnetic activity as a explanation for rapid line variability in the optical and the UV.

The question then is: what is the source of such small-scale magnetic fields? And why do they only appear in Be stars? The presence of large-scale magnetic fields in a subset of early-type stars (for example, the Ap/Bp stars) is usually ascribed to processes occurring at late stages of the formation process, for example, a late merger that induces strong differential rotation (Ferrario et al. 2009; Jermyn & Cantiello 2020). But "conventional wisdom" suggests that early-type stars, lacking outer convective zones, cannot produce active magnetic regions (see, e.g., Zinnecker & Preibisch 1994a, 1994b). This conclusion was questioned by Tout & Pringle (1995), who argued that, even in a purely radiative star, dynamo activity could be driven by differential rotation combined with the effects of buoyancy (Parker instability) on the sheared seed fields. This idea was followed up in more detail by Spruit (2002) and by Braithwaite & Spruit (2004). Recent MHD simulations of the interaction between differential rotation and magnetic fields in radiatively stable fluids are presented by Simitev & Busse (2017) and Jouve et al. (2020). In an investigation of spots on radiative A- and B-stars, Balona (2019) concludes that in such stars "differential rotation may be sufficient to create a local magnetic field via dynamo action."

Thus the next question is: why should these stars possess sufficient *differential* rotation to power dynamo action? Both Be stars and Bn stars are known to rotate rapidly, although there is a value of the rotation rate above which all the rapid rotators are Be stars (Rivinius et al. 2013). Most modeling of the shape and structure of these rapidly rotating stars is usually made using the assumption of uniform rotation (e.g., Rivinius et al. 2013). However, it is well established that stellar rotation,

together with the requirements of local hydrodynamic and thermal equilibrium leads to secondary flows within the star, which in turn lead to redistribution of the stellar angular momentum distribution. In radiative stars, such flows tend to lead to differential rotation, with the rotation velocities peaking at the equator (Tassoul & Tassoul 1982; Garaud 2002). Differential rotation would also be the norm if, as suggested by Bodensteiner et al. (2020) and El-Badry & Quataert (2020), Be stars are binary interaction products, spun up by mass transfer. In the presence of differential rotation, all that is then required is an initial source of magnetic flux. Seed fields for a dynamo could be provided originally during the formation process, or later by subsurface convection zones (Charbonneau & MacGregor 2001; Jermyn & Cantiello 2020), and by MRI-driven dynamo action in the disk itself (e.g., Martin et al. 2019). Thus we propose that the small-scale magnetic fields needed to power Be disks (both in terms of mass and in terms of angular momentum) are produced by small-scale dynamo action in a differentially rotating zone close to the stellar equator. On this hypothesis, it might also be these motions that give rise to the behavior of the nonradial pulsation modes.[9]

In this picture the Bn stars would be those rapid rotators that *currently* have fields that are too weak to ensure $R_M > R_\Omega$, so that disk formation can take place. We suggest that this might come about for a combination of reasons: (i) since Bn stars appear on average to rotate more slowly than Be stars it follows that Bn stars would need on average to have higher surface dynamo fields in order to launch a circumstellar disk, and (ii) stars that rotate more slowly would tend on average to have less efficient dynamos, thus having dynamo cycles that spend more of the time in a low state, and so spending more of the time unable to launch a disk.

5. Conclusions

We suggest that the variability of the circumstellar disks around Be stars should be modeled in terms of accretion disks with variable, but finite, central torque (Nixon & Pringle 2021). We have argued that both the disk mass and the central torque are most likely provided by small-scale magnetic activity occurring close to the equator of the rapidly spinning Be star. We have put forward ideas as to how magnetic activity can be initiated and maintained in rapidly rotating stars with radiative envelopes, and have suggested that in this picture it is the nature of the dynamo that gives rise to the distinction between Be stars and Bn stars.

ORCID iDs

C. J. Nixon https://orcid.org/0000-0002-2137-4146

[9] It is worth noting here that material being reaccreted from the disk can act as a source not only of magnetic flux, but also as a source of shear that can act as a driving mechanism for nonradial stellar pulsations (Papaloizou & Pringle 1978, 1980).

References

Baade, D., Pigulski, A., Rivinius, T., et al. 2018, A&A, 610, A70
Baade, D., Rivinius, T., Pigulski, A., et al. 2016, A&A, 588, A56
Balona, L. A. 2019, MNRAS, 490, 2112
Bodensteiner, J., Shenar, T., & Sana, H. 2020, A&A, 641, A42
Braithwaite, J., & Spruit, H. C. 2004, Natur, 431, 819
Carciofi, A. C., Bjorkman, J. E., Otero, S. A., et al. 2012, ApJL, 744, L15
Charbonneau, P., & MacGregor, K. B. 2001, ApJ, 559, 1094
El-Badry, K., & Quataert, E. 2020, arXiv:2006.11974
Ferrario, L., Pringle, J. E., Tout, C. A., & Wickramasinghe, D. T. 2009, MNRAS, 400, L71
Garaud, P. 2002, MNRAS, 335, 707
Ghoreyshi, M. R., & Carciofi, A. C. 2017, in ASP Conf. Ser., 508, The B[e] Phenomenon: Forty Years of Studies, ed. A. Miroshnichenko et al. (San Francisco, CA: ASP), 323
Ghoreyshi, M. R., Carciofi, A. C., Rímulo, L. R., et al. 2018, MNRAS, 479, 2214
Hanuschik, R. W., Dachs, J., Baudzus, M., & Thimm, G. 1993, A&A, 274, 356
Haubois, X., Carciofi, A. C., Rivinius, T., Okazaki, A. T., & Bjorkman, J. E. 2012, ApJ, 756, 156
Jardine, M., & Collier Cameron, A. 2019, MNRAS, 482, 2853
Jermyn, A. S., & Cantiello, M. 2020, ApJ, 900, 113
Jouve, L., Lignières, F., & Gaurat, M. 2020, A&A, 641, A13
Krtička, J. 2014, A&A, 564, A70
Martin, R. G., Nixon, C. J., Pringle, J. E., & Livio, M. 2019, NewA, 70, 7
Neiner, C., Lee, U., Mathis, S., et al. 2020, A&A, 644, A9
Nixon, C. J., & Pringle, J. E. 2021, NewA, 85, 101493
Okazaki, A. T. 2016, in ASP Conf. Ser., 506, Bright Emissaries: Be Stars as Messengers of Star-Disk Physics, ed. T. A. A. Sigut & C. E. Jones (San Francisco, CA: ASP), 3
Owocki, S. 2006, in ASP Conf. Ser., 355, Stars with the B[e] Phenomenon, ed. M. Kraus & A. S. Miroshnichenko (San Francisco, CA: ASP), 219

Papaloizou, J., & Pringle, J. E. 1978, MNRAS, 182, 423
Papaloizou, J. C., & Pringle, J. E. 1980, MNRAS, 190, 43
Popham, R., & Narayan, R. 1991, ApJ, 370, 604
Porter, J. M., & Rivinius, T. 2003, PASP, 115, 1153
Pringle, J. E. 1981, ARA&A, 19, 137
Pringle, J. E. 1991, MNRAS, 248, 754
Pringle, J. E., & Rees, M. J. 1972, A&A, 21, 1
Rímulo, L. R., Carciofi, A. C., Vieira, R. G., et al. 2018, MNRAS, 476, 3555
Rivinius, T., Carciofi, A. C., & Martayan, C. 2013, A&ARv, 21, 69
Semaan, T., Hubert, A. M., Zorec, J., et al. 2018, A&A, 613, A70
Silaj, J., Jones, C. E., Tycner, C., Sigut, T. A. A., & Smith, A. D. 2010, ApJS, 187, 228
Simitev, R. D., & Busse, F. H. 2017, GApFD, 111, 369
Smith, M. A. 1989, ApJS, 71, 357
Smith, M. A., Hubeny, I., Lanz, T., & Meylan, T. 1994, ApJ, 432, 392
Smith, M. A., Lopes de Oliveira, R., & Motch, C. 2016, AdSpR, 58, 782
Smith, M. A., Murakami, T., Ezuka, H., et al. 1997, ApJ, 481, 479
Spruit, H. C. 2002, A&A, 381, 923
Tassoul, J. L., & Tassoul, M. 1982, ApJS, 49, 317
Tout, C. A., & Pringle, J. E. 1995, MNRAS, 272, 528
ud-Doula, A., & Owocki, S. P. 2002, ApJ, 576, 413
Villarreal D'Angelo, C., Jardine, M., Johnstone, C. P., & See, V. 2019, MNRAS, 485, 1448
Villarreal D'Angelo, C., Jardine, M., & See, V. 2018, MNRAS, 475, L25
Wade, G. A., Petit, V., Grunhut, J. H., & Neiner, C. 2016, in ASP Conf. Ser., 506, Bright Emissaries: Be Stars as Messengers of Star-Disk Physics, ed. T. A. A. Sigut & C. E. Jones (San Francisco, CA: ASP), 207
Zinnecker, H., & Preibisch, T. 1994a, in ASP Conf. Ser., 62, The Nature and Evolutionary Status of Herbig Ae/Be Stars, ed. P. S. The, M. R. Perez, & E. P. J. van den Heuvel (San Francisco, CA: ASP), 281
Zinnecker, H., & Preibisch, T. 1994b, A&A, 292, 152