Centrifugal breakout reconnection as the electron acceleration mechanism powering the radio magnetospheres of early-type stars

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ABSTRACT
Magnetic B-stars often exhibit circularly polarized radio emission thought to arise from gyrosynchrotron emission by energetic electrons trapped in the circumstellar magnetosphere. Recent empirical analyses show that the onset and strength of the observed radio emission scale with both the magnetic field strength and the stellar rotation rate. This challenges the existing paradigm that the energetic electrons are accelerated in the current sheet between opposite-polarity field lines in the outer regions of magnetised stellar winds, which includes no role for stellar rotation. Building on recent success in explaining a similar rotation-field dependence of Hα line emission in terms of a model in which magnetospheric density is regulated by centrifugal breakout (CBO), we examine here the potential role of the associated CBO-driven magnetic reconnection in accelerating the electrons that emit the observed gyrosynchrotron radio. We show in particular that the theoretical scalings for energy production by CBO reconnection match well the empirical trends for observed radio luminosity, with a suitably small, nearly constant conversion efficiency $\epsilon \approx 10^{-8}$. We summarize the distinct advantages of our CBO scalings over previous associations with an electromotive force, and discuss the potential implications of CBO processes for X-rays and other observed characteristics of rotating magnetic B-stars with centrifugal magnetospheres.

Key words: stars: magnetic fields – stars: early type – stars: rotation – radio continuum: stars – magnetic reconnection

1 INTRODUCTION
Hot luminous, massive stars of spectral type O and B have dense, high-speed, radiatively driven stellar winds (Castor et al. 1975). In the subset (~10%; Grunhut et al. 2017; Sikora et al. 2019a) of massive stars with strong (> 100 G; Auriere et al. 2007; Shultz et al. 2019a), globally ordered (often significantly dipolar; Kochukhov et al. 2019) magnetic fields, the trapping of this wind outflow by closed magnetic loops leads to the formation of a circumstellar magnetosphere (Petit et al. 2013). Because of the angular momentum loss associated with their relatively strong, magnetised wind (ud-Doula et al. 2009), magnetic O-type stars are typically slow rotators, with trapped wind material falling back on a dynamical timescale, giving what’s known as a “dynamical magnetosphere” (DM).

But in magnetic B-type stars, the relatively weak stellar winds imply longer spin-down times, and so a significant fraction that still retain a moderately rapid rotation; for cases in which the associated Keplerian co-rotation radius $R_K$ lies within the Alfvén radius $R_A$ that characterises the maximum height of closed loops, the rotational support leads to formation of a “centrifugal magnetosphere” (CM), wherein the much longer confinement time allows material to build up to a sufficiently high density to give rise to distinct emission in Hα and other hydrogen lines (Landstreet & Borra 1978). A recent combination of empirical (Shultz et al. 2020) and theoretical (Owocki et al. 2020) analyses showed that both the onset and strength of such Balmer-α emission is well explained by a centrifugal breakout (CBO) model, wherein the density distribution of material within the CM is regulated to be near the critical level that can be contained by magnetic tension (ud-Doula et al. 2008). The upshot is that such hydrogen emission arises only
in magnetic stars with both strong magnetic confinement and moderately rapid stellar rotation.

Another distinctive observational characteristic of many such magnetic B-stars is their non-thermal, circularly polarized radio emission, thought to arise from gyrosynchrotron emission by energetic electrons trapped within closed magnetic loops. An initially favoured model by [Trigilio et al. (2004)] proposed that these electrons could be accelerated in the current sheet between field lines of opposite polarity that have been stretched outward by the stellar wind, as illustrated in the left panel of Figure 1. But a recent empirical analysis by [Leto et al. (2021)] has shown that the observed radio emission has a clear dependence on stellar rotation, providing strong evidence against this current-sheet model, which includes no role for rotation. Instead [Leto et al. (2021)] noted that their fits to the radio luminosity scale in proportion to a quantity that has the physical dimension of an electromotive force (EMF), which they speculated may be suggestive of an underlying mechanism. Indeed, the EMF is invoked [Hill (2001)] to model auroral emission from the interaction of high-energy magnetospheric particles with planetary atmospheres. However, such thermal atmospheric auroral dissipation of EMF-accelerated particles in the magnetosphere cannot explain the polarized radio emission that likely arises from gyrosynchrotron processes in the highly conductive magnetosphere itself.

The alternative theoretical scalings explored here were motivated by a more recent companion empirical analysis by [Shultz et al. (2021), hereafter Paper I], which confirms the basic results of [Leto et al. (2021)], but within a significantly extended sample that allows further exploration of potential empirical trends and scalings. In particular, we show below (section 3) that these empirical scalings for nonthermal radio emission can be well fit by models grounded in the same CBO paradigm that has been so successful for Hz emission. Specifically, it is now the magnetic reconnection associated with CBO events that provides the nonthermal acceleration of electrons, which then follow the standard picture of gyrosynchrotron emission of observed circularly polarized radio.

Figure 1 graphically illustrates the key distinctions between this new CBO paradigm (right) from the previous current-sheet-acceleration model (left) proposed by [Trigilio et al. (2004)].

To lay the groundwork for derivation in section 3 of these scalings for radio emission from CBO-driven reconnection, the next section 2 reviews the basic CM model and the previous application of the CBO paradigm to Hz. In section 2 we contrast our results with the EMF-based picture, and discuss the potential further application of the CBO paradigm, including for modeling the stronger X-ray emission of CM vs. DM stars [Naze et al. (2014)]. We conclude (section 5) with a brief summary and outlook for future work.

2 BACKGROUND

2.1 Dynamical vs. Centrifugal magnetospheres

For a magnetic hot-star with stellar wind mass loss rate \( \dot{M} \) and terminal wind speed \( v_\infty \), MHD simulations [ud-Doula & Owocki (2002)] show that the channeling and trapping of the stellar wind can be characterised by a dimensionless wind-magnetic-confinement parameter,

\[
\eta_s \equiv \frac{B^2_{\text{eq}} R^2}{M v_\infty},
\]

where \( B_{\text{eq}} \) is the surface field strength at the magnetic equator and \( R_* \) is the stellar radius. This characterises the ratio of magnetic energy to wind kinetic energy. The radial extent of closed magnetic loops can be characterised by the Alfvén radius, which for an initially dipolar field with strong-confinement scales as

\[
\frac{R_A}{R_*} \approx \eta_*^{1/4}; \quad \eta_* \gg 1,
\]

Simulations of cases with rotation-aligned dipoles [ud-Doula et al. (2008)] showed further that the dynamical effect of rotation can be similarly characterised by a dimensionless parameter, now given by the ratio of the star’s equatorial rotation speed to the near-star orbital speed,

\[
W = \frac{v_{\text{rot}}}{v_{\text{orb}}} = \frac{2\pi R_*}{P_{\text{rot}}} \left( \frac{GM_*}{R_*^3} \right)^{-1/2},
\]

with \( M_* \) and \( P_{\text{rot}} \) the stellar mass and rotation period, and \( G \) the gravitation constant. For magnetically trapped material that is forced to co-rotate with the underlying star, centrifugal forces balance gravity in the common equator at the Kepler co-rotation radius, given by

\[
\frac{R_K}{R_*} = W^{-2/3}.
\]

For slowly rotating stars with \( R_K > R_A \), rotation has little dynamical effect, and so wind material trapped in closed magnetic loops below \( R_K \) simply falls back to the star on a dynamical timescale, giving then a dynamical magnetosphere (DM).

In contrast, for stars with both moderately rapid rotation (\( W \lesssim 1 \) and strong confinement (\( \eta_* \approx 1 \)), one finds \( R_K < R_A \). In the region \( R_K < r < R_A \) magnetic tension still confines material while the centrifugal force prevents gravitational fallback, thus allowing material build-up into a much denser centrifugal magnetosphere (CM).

2.2 Centrifugal breakout and Hz emission

As first analyzed in the appendices of [Townsend & Owocki (2003)], this CM mass buildup is limited to a critical surface density for which the finite magnetic tension can still confine the material against the outward centrifugal acceleration. For mass buildup beyond this critical density, the magnetic field lines become stretched outward by the centrifugal force, leading eventually to centrifugal breakout (CBO) events. Through analysis of 2D MHD simulations by [ud-Doula et al. (2008), Owocki et al. (2021)], showed that the resulting global surface density scales as

\[
\sigma(r) \approx \sigma_K \left( \frac{r}{R_K} \right)^{-6}; \quad r > R_K,
\]

where the characteristic surface density at the Kepler radius scales with the magnetic field strength and gravitational acceleration there,

\[
\sigma_K \approx 0.3 \frac{B_*^2}{17\pi g_*}.
\]
A key feature of this CBO-regulated density is that it is entirely independent of the stellar wind mass loss rate $M$ that controls the CM mass buildup. This helps explain the initially unexpected empirical finding by Shultz et al. (2020) that the onset and strength of observed Hα emission from magnetic B-stars is largely independent of the stellar luminosity, which plays a key role in setting the mass loss rate of the radiatively driven stellar wind.

Motivated by this key result, Owocki et al. (2020) examined the theoretical implications of this CBO-limited density scaling for such Hα emission, showing that it can simultaneously explain the onset of emission, the increase of emission strength with increasing magnetic field strength and decreasing rotation period, and the morphology of emission line profiles (Shultz et al. 2020). As initially suggested by Townsend & Owocki (2003), the breakout density at $R_K$ is set by $B_K$, and is independent of $M$; precisely this dependence on $B_K$, and lack of sensitivity to $M$, was found by Shultz et al. (2020) for both emission onset and emission strength scaling. Owocki et al. (2020) found an expression for the strength $B_K$, necessary for the density at $R_K$ to produce an optical depth of unity in the Hα line, and showed that the threshold $B_K/B_{K1}$ neatly divides stars with and without Hα emission. Two-dimensional MHD simulations of CBO by ud-Doula et al. (2006, 2008) yielded a radial density gradient associated with the CBO mechanism, which in conjunction with the density at $R_K$ set by $B_K$ can be used to predict the optically thick region and, hence, the scaling of emission strength (Owocki et al. 2020). Finally, a characteristic emission line profile morphology, common across all Hα-bright CM host stars, was reported by Shultz et al. (2020) and shown by Owocki et al. (2020) to be a straightforward consequence of a co-rotating optically thick inner disk transitioning to optically translucent in the outermost region.

A crucial subtlety that deserves emphasis is that, in contrast to expectations from 2D MHD simulations that CBO should manifest as catastrophic ejection events accompanied by large-scale reorganization of the magnetosphere (ud-Doula et al. 2006, 2008), which has indeed never been observed in the densest inner regions (Townsend et al. 2013, Shultz et al. 2020), the Hα analysis performed by Shultz et al. (2020) instead indicates that the magnetosphere must be continuously maintained at breakout density, with CBO occurring more or less continuously on small spatial scales. However, it is worth noting that the ‘giant electron-cyclotron maser (ECM) pulse’ observed by Das & Chandra (2021) may have been the signature of a large-scale breakout occurring in magnetospheric regions in which the density is too low to be probed by Hα or photometry.

Hα emission and gyrosynchrotron emission occur in the same part of the rotation-magnetic confinement diagram (see Fig. 3 in Paper I), and Hα emission EW and radio luminosity are closely correlated (see Fig. 6 in Paper I). Since Hα emission is regulated by CBO, this suggests that the same may be true of gyrosynchrotron emission. In the following we develop a theoretical basis for this connection, which we then compare to the empirical regression analyses and measured radio luminosities.

3 CBO-DRIVEN MAGNETIC RECONNECTION

3.1 Rotational spindown

The rotational energy of a star with moment of inertia $I$ and rotational frequency $\Omega$ is given by

$$E_{\text{rot}} = \frac{1}{2} I \Omega^2. \quad (7)$$

If we assume a fixed moment of inertia, the release of rotational energy associated with a spindown $-d\Omega/dt \equiv -\dot{\Omega}$ is

$$L_{\text{rot}} = I \dot{\Omega}. \quad (8)$$
For a magnetized star with a wind of mass loss rate $\dot{M}$, Weber & Davis (1967) argued that the loss of the star's angular momentum $J = I\Omega$ scales as

$$J = I\Omega = M\Omega R_\Lambda^2,$$

which gives the associated release of rotational luminosity the scaling,

$$L_{\text{rot}} = \dot{M}\Omega^2 R_\Lambda^2.$$

For a star with an equatorial field of strength $B_{\text{eq}}$ at the stellar surface radius $R_\ast$, ud-Doula & Owocki (2002) and ud-Doula et al. (2008) showed that the Alfvén radius depends on the dimensionless wind magnetic confinement parameter $\eta_\ast$ (Eqn. 1). Specifically, for a magnetic multipole of order $p (= 1, 2$ for monopole, dipole, etc.), with radial scaling as $B \sim r^{-(p+1)}$, $R_\Lambda$ scales as

$$R_\Lambda = \eta_\ast^{1/2p},$$

which for the standard dipole case ($p = 2$), reduces to the scaling given in Eqn. (2).

The Weber & Davis (1967) analysis treated the simple case of a pure radial field from a spilt monopole, with $p = 1$. But ud-Doula et al. (2008) showed a base dipole field leads to a spindown that follows the Weber & Davis (1967) scaling (Eqn. 9), where $R_\Lambda$ is given by Eqn. (11) with a multipole index set to the $p = 2$ value for a dipole.

### 3.2 Breakout from centrifugal magnetospheres

The above wind-confinement scalings work well for wind-magnetic braking, which operates through wind stress on open field lines, wherein the associated Poynting flux carries away most of the angular momentum.

But for rapid rotators with a strong field, the magnetic trapping of the wind into a centrifugal magnetosphere leads to some important differences for scalings of the associated luminosity.

First, as discussed in the appendices of Townsend & Owocki (2002) see their equation A7, for trapping and breakout from a CM, the wind speed $v_{\infty}$ in the usual wind confinement parameter $\eta_\ast$ is replaced with a characteristic dynamical speed of the stellar gravity, which we take here to be the surface orbital speed $v_{\text{orb}} \equiv \sqrt{GM_\ast / R_\ast}$ (since this is used in the definition of $W$ and thus $R_K$), giving the centrifugal magnetic confinement parameter

$$\eta_k \equiv \frac{B_\ast^2 R_\ast^2}{M v_{\text{orb}}}.$$  

A second difference stems from the fact that, even for an initially dipolar field, the rotational stress of material trapped in the CM has the effect of stretching the field outwards, thus weakening its radial drop off, and so reducing the effective multipole index to $p < 2$.

Finally, this stretching ultimately leads to centrifugal breakout (CBO) events, with associated release of energy via magnetic reconnection. In general the overall total luminosity available from CBO events should follow a general scaling analogous to that for $L_{\text{rot}}$,

$$L_{\text{CBO}} \approx \dot{M}\Omega^2 R_\Lambda^2 \eta_k^{1/p}.\quad (13)$$

#### 3.2.1 Split monopole case

As a first example, consider the limit in which field lines are completely opened by the wind ram pressure into a split monopole, with $p = 1$, which gives

$$L_{\text{CBO}}(p = 1) \equiv \dot{M}\Omega^2 R_\Lambda^2 \eta_k,$$

$$= \frac{\Omega^2 R_\ast^4 B_\ast^2}{v_{\text{orb}}},$$

$$= W\Omega R_\ast^2 B_\ast^2,$$

where $W$ is the critical rotation fraction (Eqn. 3). Note that the second equality recovers the empirical scaling $L_{\text{rad}} \propto B^2 R_\ast^4 / P_{\text{rot}}^2$ found by Leto et al. 2021 and verified in Paper I.

Remarkably, note also that in this monopole field case the dependence on wind feeding rate $\dot{M}$ has canceled. Dimensionally, the scaling now is as if the total magnetic energy over a volume set by $R_\ast^3$ is being tapped on a rotational timescale.

An alternative physical interpretation is that the field acts more like a conduit, trapping mass in a CM, with total rotational energy tapped on a breakout timescale, set in this monopole case by the orbital timescale.

#### 3.2.2 Dipole case

More generally, this breakout luminosity depends on the wind feeding rate.

In particular, for the pure dipole scaling with $p = 2$, we find

$$L_{\text{CBO}}(p = 2) = M\Omega^2 R_\Lambda^2 \eta_k^{1/2} / \sqrt{\eta_k} = L_{\text{CBO}}(p = 1)/\sqrt{\eta_k}.\quad (15)$$

This has $L_{\text{CBO}} \sim \sqrt{\dot{M}}$, with a weaker, linear scaling with $B_\ast$.

In general, empirical evaluation of $L_{\text{CBO}}$ thus requires evaluation of the wind feeding rate $\dot{M}$, where we have used the same CAK mass-loss rates as adopted in Paper I.

In the applications below, we consider multipole indices $1 < p < 2$, intermediate between these monopole and dipole limits.

### 3.3 Application to radio emission

Let us next consider how well such breakout scalings for rotational luminosity correlate with observed radio luminosities, $L_{\text{rad}}$. Noting that the dimensional scaling of breakout
obliquity angle $\beta$ of the magnetic dipole axis from the rotational axis. Indeed, in the empirical regression analysis in Paper I the factor $f_\beta = (1 + \cos \beta)/2$ was found to improve the correlation. The plasma distribution in the CM is a strong function of $\beta$, since the densest material accumulates at $R_K$ at the intersections of the magnetic and rotational equatorial planes (Townsend & Owocki 2005). For the special case of an aligned rotator ($\beta = 0^\circ$) this will result in plasma being evenly distributed around $R_K$. With increasing $\beta$ the plasma distribution becomes increasingly concentrated at the two intersection points, leading to a warped disk that eventually becomes two distinct clouds. Therefore, the mass confined within the CM will be a maximum for $\beta = 0^\circ$ and a minimum for $\beta = 90^\circ$. If reconnection in the CM is the source of the high-energy electrons that populate the radio magnetosphere, we would then naturally expect that radio luminosity should decrease with increasing $\beta$. The right panel of Fig. 5 shows the residual radio luminosity as a function of $\cos \beta$, and demonstrates that radio luminosity in fact does increase with decreasing $\beta$; in fact, the relationship is much stronger than for log $L_{\text{bol}}$, with $r = 0.49$ and $b = 0.64$.

Fig. 4 replicates Fig. 2, with the difference that corrections for $M$ and $\beta$ are accounted for. Following Eqn. 16, $M$ dependence was determined by scaling Eqn. 13 with $\eta_0^\alpha$. A purely empirical correction for $\beta$ was adopted as $f_\beta^* = ((1 + \cos \beta)/2)^\alpha$, such that $f_\beta(\beta = 0^\circ) = 1$ and $f_\beta(\beta = 90^\circ) = 0$. By minimizing the residuals, the best-fit exponents are $q = -0.09$ and $x = 2$. The former exponent corresponds to $p = 1.1$, implying only a very slight departure from the monopole scaling. The latter indicates an increase in $L_{\text{rad}}$ by a factor of 4 as $\beta$ decreases from $90^\circ$ to $0^\circ$. As can be seen in Fig. 3 these corrections lead to a tighter correlation ($r = 0.92$) and a somewhat reduced ratio between $L_{\text{CBO}}$ and $L_{\text{rad}}$ to around 7 dex.

3.3.1 Emission threshold

In their development of a breakout scaling relationship for Hα emission from CMs, Owocki et al. (2020) defined a threshold magnetic field strength $B_K1$ as the strength of the magnetic field at $R_K$ necessary to confine a sufficient quantity of plasma at $R_K$ for the optical depth to reach unity. They demonstrated that all magnetic early B-type stars with $B_K/B_K1 > 1$ are Hα-bright, while all stars with $B_K < B_K1$
do not display Hα emission. By solving Eqn. 14 for $B_d$, we can derive a similar threshold value for the radio luminosity:

$$B_{\text{thresh}} = \left( \frac{\epsilon L_{\text{CBO}} P_{\text{rot}}}{2\pi R_*^2 W} \right)^{1/2},$$

(17)

where $\epsilon \sim 10^{-8}$ is an efficiency scaling determined from the empirical ratio between $L_{\text{CBO}}$ and $L_{\text{rad}}$, and additional dependence on $\beta$ and $\eta_*$ is implicitly ignored. Since what is actually observed is a flux density $F_{\text{rad}}$ rather than a luminosity $L_{\text{rad}} \propto F_{\text{rad}} d^2$, Eqn. 17 is necessarily a function of distance $d$. Amongst the radio-bright stars, the median flux density uncertainty is 0.1 mJy, while the median significance of a detection is around 10σ i.e. 1 mJy. We therefore take the flux density detectability threshold for the sample as 1 mJy and solve Eqn. 17 accordingly to obtain $B_1$ (i.e. the surface magnetic field necessary to generate 1 mJy of flux density at the star’s distance). The results are shown in Fig. 5.

As expected, all radio-bright stars have $\log B_d/B_1 \gtrsim 0$. The relationship for non-detected stars is not as clean as for the similar plot for Hα shown by Owocki et al. (2020), as there are a large number of stars with surface magnetic fields above this threshold. However, the radio observations comprising this sample, having been obtained at a variety of observatories with different capabilities over a span of over 30 years, are quite heterogeneous, with a wide range of upper limits, and many of the non-detected stars in this regime have upper limits comparable to 1 mJy. Further, generally only a single snapshot at one frequency is available, and it is possible that they were observed at inopportune rotational phases. These stars should certainly be reobserved with modern facilities.

The dashed line in Fig. 5 shows the theoretical detection limit for radio telescopes such as the upcoming Square Kilometre Array able to achieve $\mu$Jy precision, under the assumption that a 10σ detection (i.e. 10 $\mu$Jy) is necessary for the star’s radio emission to be securely detected. As can be seen, such facilities can at least double the number of stars with measured gyrosynchrotron emission. This is especially true when stars that have not yet been observed in the radio are included: the green triangles in Fig. 5 show those stars from the samples studied by Aurière et al. (2007), Sikora et al. (2019a,b), and Shultz et al. (2019b) without radio observations, essentially all of which are expected to have radio flux densities of above 10 $\mu$Jy and about half of which should have flux densities above 1 mJy.

3.3.2 How CBO reconnection can lead to radio emission

Breakout events are accompanied by centrifugally driven reconnection of magnetic fields that have been stretched outward by rotational stress acting against the magnetic tension of the initially closed loops. As these loops reconnect, the associated release of magnetic energy can strongly heat the ejected plasma. Some fraction of this reconnection energy can accelerate both ions and electrons to highly super-thermal energies, with some of these particles becoming trapped into gyration along closed magnetic field loops near the reconnection site. The associated gyrosynchrotron emission of the much lighter electrons can then produce the observed radio emission.

The basic scenario of electron acceleration in reconnection events, followed by gyrosynchrotron emission along magnetic loops, is indeed already a central component of the model for radio emission (Trigilio et al. 2004). However, this model is based on wind-driven reconnection, with no inclusion for any role of stellar rotation. As such, the available reconnection luminosity is expected to scale with the wind kinetic energy $L_{\text{wind}} = M v_\infty^2 / 2$. By comparison, the rota-
tional luminosity for a multipole exponent $p$ is larger by a factor

$$\frac{L_{\text{CBO}}(p)}{L_{\text{wind}}} = 2\eta_c^{1/p} \left( \frac{v_{\text{rot}}}{v_\infty} \right)^2 \approx \eta_c^{1/p} W^2 \left( \frac{v_\infty}{v_\infty} \right)^2$$

$$\approx \frac{\eta_c^{1/p} W^2}{9},$$

(18)

where the last equality stems from the standard result that the stellar wind speed scales with the escape speed as $v_\infty \approx 3v_{\text{esc}}$. For typical values for B-star magnetospheres with $\eta_c \approx 10^9$, $W \approx 1/2$ (Petit et al. 2013) and $p = 4/3$, we find $L_{\text{CBO}}(p = 4/3)/L_{\text{wind}} \approx 880$ (using the empirically derived value of $p \approx 1.1$ yields an even greater ratio of almost 8000). For these $W$ and $p$, the ratio is greater than unity for even moderate confinement values $\eta_c > 120$.

Regardless of the relative values, a central empirical result here is the finding that $L_{\text{rad}}$ has a clear scaling with rotation frequency as $I^2$ and with surface field as $B_{\text{sh}}^{2/p}$, dependences which are entirely missing from $L_{\text{wind}}$. Indeed, we find that $\log(L_{\text{rad}})$ shows only weak correlation with $L_{\text{wind}}$, with $r = 0.3$. This strongly disfavors the wind-driven reconnection model proposed by Trigilio et al. (2004); but it is consistent with the scenario proposed here that centrifugal-breakout reconnection provides the underlying energy that leads to the radio luminosity through gyrosynchrotron emission.

While we have cast available energy in terms of loss of the star’s rotational energy, one has to be careful not to take this too literally. Most (70+% of the angular momentum loss in spindown is through magnetic field Poynting stresses. But the CBO material that leads to reconnection should share the same basic Weber-Davis scaling with $R_A$, and it is that component that this scenario associates with the reconnection and the resulting electron acceleration and radio emission.

4 DISCUSSION

4.1 Comparison with alternative theoretical interpretations

The empirical scaling relationship discovered by Leto at al. (2021) and confirmed in paper I, $L_{\text{rad}} \propto B_{\text{sh}}^2 R_e^2 \rho^p I_{\text{rot}}^2 = (\Phi/P_{\text{rot}})^2$, is explained above as a consequence of electron acceleration via centrifugal breakout. However, Leto et al. pointed out that $\Phi/P_{\text{rot}}$ has the physical dimension of an electromotive force $E$ (EMF), which they speculated may be suggestive of an underlying theoretical mechanism. In this section we examine gyrosynchrotron emission from this standpoint. We perform a theoretical analysis to test if the physical conditions able to sustain large scale electric currents within the stellar magnetosphere can be verified.

This empirical association by Leto et al. (2021) of radio emission with the voltage of an EMF also stands in contrast with the previous theoretical model by Trigilio et al. (2004), which associates the acceleration of radio-emitting nonthermal electrons with the wind-induced current sheet that forms in the middle magnetosphere. However, Leto et al. (2021) conclusively demonstrated that the wind does not provide sufficient power to the middle magnetosphere to drive the observed levels of radio emission.

The highly ionized plasma in these magnetospheres implies a very high conductivity, and so currents can form even with a vanishingly small EMF. Instead, the current density $J$ is set by Ampère’s law as a result of a curl induced in a stressed field,

$$J = \frac{c}{4\pi} \nabla \times B.$$

(19)

Even in a non-rotating wind-fed magnetosphere, large-scale stressing of the magnetic field by the wind ram pressure forces outlying closed loops to open, with a Y-type neutral point at the top of the last closed loop; above this there develops a split monopole, with a current sheet separating field lines of opposite polarity. But unless there are instabilities or induced variability, this current sheet does not by itself lead to energy dissipation that can heat the plasma or accelerate electrons. This, together with the lack of observed radio emission from stars with slow rotation, thus strongly disfavors the Trigilio et al. (2004) model based on the wind-induced current sheet.

While the Leto et al. (2021) empirical association of observed radio emission with an EMF is interesting and insightful, there are some challenges to using this as a basis for a self-consistent theoretical model. The general principles regarding current vs. EMF scenarios can be well illustrated by a simple circuit model, using an Ohm’s law $I = E/R$ to related current $I$ and EMF $E$ through a resistance $R$. The associated dissipated power, or luminosity, scales as

$$L_{\text{emf}} = I^2 E = I^2 R = \frac{E^2}{R}.$$

(20)

If one fixes the current $I$ (as induced by the globally imposed magnetic curl), then the second equality shows that in the limit of vanishing resistivity $R \rightarrow 0$, the luminosity also vanishes; this underlies one fundamental issue with the current-sheet model advocated by Trigilio et al. (2004).

To understand the ramifications of the last equality of Eqns. (20) within the context of the empirical association of the gyrosynchrotron scaling law with an EMF, let us return to consideration of plasma conditions in such magnetospheres. In the notation of the present paper, the EMF can be written as $E = B_r R^2 \Omega/c$, where the speed of light $c$ comes in from the CGS form for the induction equation. In terms of a plasma resistivity $\rho$ (with units of time), the circuit resistance scales with resistivity times a length over area, which in this context gives $R \approx \rho R_e / R^2 = \rho / R_e$. Thus Eqn. (20) becomes

$$L_{\text{emf}} = \frac{B_r^2 R_e^2 \Omega^2}{\rho c^2} = (B_r^2 R_e^3 \Omega) \left[ \frac{v_{\text{rot}} R_e}{\rho c^2} \right],$$

(21)

(22)

where in the latter equality, $v_{\text{rot}} = \Omega R_e$ is the surface rotation speed at the stellar equator. Here the term in parenthesis separates out the dimensional luminosity, while the...
dimensionless ratio in square brackets can be identified as a magneto-rotational Reynolds’s number,

$$R_{\text{crit}} = \frac{v_{\text{orb}} R_*}{\rho c^2}. \quad (23)$$

Rather remarkably, Eqn. (22) has a form very similar to that derived above (cf. Eqn. 14) for the monopole ($p = 1$) CBO model. However an important, indeed crucial difference is that derived above (cf. Eqn. 14) for the monopole ($p = 1$) CBO model. However an important, indeed crucial differ-
p
chrotron scaling with EMF, and with the current sheet

Indeed, eqn. (21) is very similar to the scaling invoked

by Hill (2001, see their Eqn. 4) to model auroral emission

from Jupiter. In this case, the magnetospheric EMF' acceler-
erates ions and electrons to high-energy, which upon pene-
trating into the underlying jovian atmosphere is dissipated
through the low atmospheric conductance $\Sigma_J$ (correspond-
ing to high resistivity $\rho$), resulting in heating and associated
thermal bremsstrahlung to give auroral emission.

In principle, a theoretical model grounded in the EMF

could invoke a stronger resistivity in some local dissipation
layer, which would enter directly into the predicted scal-
ings for the generated luminosity. But it is unclear how this
small-scale dissipation could be reconciled with the large-
scale EMF that is taken to scale with the stellar radius, and
how such a dissipation could remain fixed over the range of stellar and magnetospheric parameters, in order to preserve
the inferred empirical scaling of the observed radio luminos-
ity with the global EMF.

These difficulties with an association of gyrosynchrotron scaling with EMF, and with the current sheet model, stand in contrast to some key advantages of the CBO mechanism proposed here.

First, this CBO model specifies a more modest magnetic dissipation rate, set by the base dimensional rate $B^2 R^3 \Omega$ reduced by the rotation factor $W < 1$, instead of the enor-
mous $R_{\text{crit}} \sim 10^{12}$ enhancement of an EMF mechanism.

This CBO dissipation can be quite readily replenished over time by the centrifugal stretching of closed magnetic field lines by the constant addition of mass from the stellar wind. As such, the ultimate source of energy thus comes not from the field – which acts merely as a conduit – but from the star’s rotational energy.

Second, these eventual centrifugal breakout events lead naturally and inevitably to magnetic reconnection. This thus preserves the longstanding notion (Trigilio et al. 2004) that such reconnection provides the basic mechanism to accelerate electrons to high energies, whereupon the gyration along the remaining field lines connecting back to the star results in the gyrosynchrotron emission of the observed radio luminosity.

Third, and perhaps most significantly, instead of the previous notion (Trigilio et al. 2004) that this reconnection

is driven by the stellar wind – with no consideration of any role for stellar rotation – our model for CBO-driven reconnec-
tion puts rotation at the heart of the process, and so yields a scaling for luminosity that matches the strong de-
pendence on rotation rate, as well as on magnetic field energy. Indeed, while the wind can certainly open the mag-
etic field and lead to the formation of a current sheet, this does not itself provide a power source, but merely results in a slower radial decline of the magnetic field strength as compared to that of a dipole. By contrast, CBO provides a clear power source for the acceleration of electrons to high energies.

Thus, although only a small fraction of the breakout lumi-

nosity $L_{\text{CBO}}$ ends up as radio luminosity, with an inferred effective efficiency $\epsilon \approx 10^{-8}$, the strong correlation between observed and predicted scalings provides strong empirical support for such a CBO model.

4.2 Energy source - magnetic or rotational?

The energy term in Eqn. 1 has $B^2 R^3$, and it would therefore be natural to assume that the magnetic field is the energy source powering radio emission. However, as suggested in § 3.2.1 this is probably not the case. The mean magnetic energy $E_{\text{mag}}$ amongst the radio-bright stars is about $10^{42}$

\[ \text{erg}, \]

whereas the mean rotational kinetic energy $E_{\text{rot}}$ in the same sub-sample is about $10^{37}$ \text{erg}, i.e. the star’s rotation is a vastly greater energy reservoir. Indeed $E_{\text{mag}} > E_{\text{rot}}$ for only 3 stars (HD 46328, HD 165474, and HD 187474), all of which have $P_{\text{rot}} \sim \text{years}$ (and none of which are, of course, detected at radio frequencies).

An additional consideration is that, if the magnetic field were the energy source, radio emission should over time draw down the magnetic energy of the star. The peak radio luminosity is around $10^{29}$ erg s$^{-1}$, implying that the magnetic energy of the most radio-luminous stars would be consumed in about $10^{13}$ s $\sim 0.3$ kyr. To the contrary, fossil magnetic fields are stable throughout a star’s main sequence lifetime. For Ap/Bp stars below about 4 $M_\odot$, the decline in surface magnetic field strength is entirely consistent with flux conservation in an expanding stellar atmosphere (e.g. Kochukhov & Bagnulo 2006; Landstreet et al. 2007; Sikora et al. 2019b), while for more massive stars there is an additional, gradual decay of flux (e.g. Landstreet et al. 2007, 2008; Fossati et al. 2015; Shultz et al. 2019b) that is however, much longer than the abrupt field decay timescale that would be implied if the breakout luminosity was pow-
ered by the magnetic field. Furthermore, the most plausible mechanism for flux decay is found in small-scale convective dynamos formed in the opacity-bump He and Fe convection zones inside the radiative envelope (e.g. MacDonald & Petit 2010; Jermyn & Cantiello 2020), which naturally explains why flux does not decay in A-type stars (which lack these convection zones), and why flux apparently decays more slowly for the strongest magnetic fields (Shultz et al. 2019b) since strong fields inhibit convection (Sundqvist et al. 2013; MacDonald & Petit 2019).

In contrast to the magnetic field, which decays slowly or not at all, magnetic braking is quite abrupt (Shultz et al. 2019b, Kesetthelyi et al. 2020), making the larger rotational energy reservoirs of rapidly rotating stars a more far more plausible power source. Quantitatively, for the most radio-
luminous stars in the sample it would take about 30 Myr for
the energy radiated by gyrosynchrotron emission to remove
the total rotational energy of the star. For stars with masses
above 5 M⊙ (the mass range of the brightest radio emitters),
is comparable to or greater than the main sequence
time.

It therefore seems that the magnetic field cannot serve
as the energy source, but rather acts as a conduit for the
extraction of rotational energy and its conversion into
gyrosynchrotron emission. The magnetic energy lost in break-
out events is immediately replenished as mass is injected
into the CM by the wind, with the ion-loaded magnetic field
then stretching under the centrifugal stress acting on the
co-rotating plasma.

4.3 The case of Jupiter

[Leto et al. (2021)] showed that the scaling relationship for
the non-radio thermal emission from dipole-like rotating
magnetospheres also fits the radio luminosity of Jupiter1
suggesting an underlying similarity in the physics driving gy-
rosynchrotron emission from giant planets and magnetic hot
stars. Adopting the same parameters as used by [Leto et al.
(B⊙ = 4 G, Ptot = 0.41 d, M1 = 1.9 × 1027 kg, and
R1 = 7.1 × 108 km) gives W = 0.3. The breakout lumin-
osity is then log L_{CBO}/L⊙ ∼ −15.9 or, at 1 cm, Lν ∼
10^8 erg s⁻¹ Hz⁻¹, translating to an expected flux density
of around 40 Jy at a distance of 4 AU. This is about an or-
erd magnitude higher than the observed radio luminosity of Jupiter [de Pater & Dunn 2003; de Pater et al. 2003]. How-
ever, it is worth noting that in the extrapolation shown by
[Leto et al.] Jupiter’s EMF of 376 MV is near the lower en-
velope of the range of uncertainty inferred from hot stars,
i.e. Jupiter is somewhat less luminous than predicted by a
direct extrapolation of the hot star scaling relationship.
Furthermore, 1 dex is at the upper range of the scatter about
the L_{CBO} relationship (see Figs. 2 and 4).

One possible explanation for Jupiter being less lumin-
ous than predicted is that Jupiter’s primary ion source, the
volcanic moon Io, is effectively a point source offset from
the centre of the Jovian magnetosphere. This is in con-
trast to stellar winds, which feed the magnetosphere isotrop-
ically and continuously from the centre. The result is that
hot star magnetospheres are relatively more populated, and
therefore is more material available for the genera-
tion of gyrosynchrotron emission. Another potential issue is
that in the Jovian magnetosphere reconnection takes place
in the magnetotail due to stretching by the solar wind; its
azimuthal extent will therefore be limited, in analogy to the
obliquity dependence found in stellar magnetospheres. Ex-
ploring whether the approximate consistency between the
Jovian and stellar radio luminosities is indeed due to a sim-
ilarity in the underlying physics, or is merely coincidental,
will require a detailed analysis that is outside the scope of
this paper.

1 This radio emission arises within Jovian magnetosphere, and
so is distinct from the optical auroral emission discussed above,
which arises from interactions in the upper Jovian atmosphere.

4.4 A solution to the low-luminosity problem?

It is notable that magnetospheres are detectable in radio
frequencies in stars with CMs that are too small to be de-
tectable in Hα. In addition to being a more sensitive mag-
etospheric diagnostic, this may also suggest an answer to
the low-luminosity problem identified by [Shultz et al. 2020]
and [Owocki et al. 2020]. While CBO matches all of the
characteristics of Hα emission from CM host stars, emission
disappears entirely for stars with luminosities below about
log Lbol/L⊙ ∼ 2.8. This could be either a consequence of a
‘leakage’ mechanism, operating in conjunction with CBO
to remove plasma via diffusion and/or drift across magnetic
field lines [Owocki & Cram 2015], or due to the winds of
low-luminosity stars switching into a runaway metallic
wind regime [Springmann & Pauldrach 1992; Babz 1994;
Owocki & Pilu 2002]. In the former case the leakage mech-
anism only becomes significant when M is low. In the latter
case, Hα emission is not produced for the simple reason that
the wind does not contain H ions. Notably, the peculiar sur-
face abundances of magnetic stars may lead to enhanced
mass-loss rates as compared to non-magnetic, chemically
normal stars [Krticka 2014].

Since CBO apparently governs gyrosynchrotron emis-
sion, and is seen in stars down to log Lbol/L⊙ ∼ 1.5, the
leakage scenario seems to be ruled out as an explanation for
the absence of Hα emission. This therefore points instead to
runaway metallic winds. One possible complication is that,
as is apparent from the direct comparison of Hα emission
equivalent widths to radio luminosities (see Fig. 6 in Paper
I), stars without Hα so far are also relatively dim in the
radio (at least for those stars for which Hα measurements
have been obtained). These stars have systematically lower
values of BK than have been found in more luminous Ho-
bright stars (Fig. 3 in Paper I). Thus, a crucial test will
be examination of both Ho and radio for a star with a lu-
ninosity well below 2.8, but BK ∼ 3, i.e. it must be cool,
very rapidly rotating (Ptot ∼ 0.5 d), and strongly magnetic
(Bu ∼ 10 kG). So far no such stars are apparently known.

A further complication to the runaway wind hypothe-
sis is provided by 36Lyn, a relatively cool (Teff ∼ 13 kK),
radio-bright star which, while it does not show Hα emission,
does display eclipses in Hα [Smith et al. 2000] and there-
fore must have H inside its magnetosphere which, presumably,
originated in the stellar wind. Why no other star in 36Lyn’s
Teff range should show evidence of a similar phenomenon
is not currently understood, although its peculiar magneto-
sphere may be related to the remarkably high toroidal com-
pONENT of its magnetic field in comparison to other magnetic
stars, in which the toroidal component is generally quite
weak [Oksala et al. 2018; Kouchukov et al. 2019]. Alterna-
tively, this may be due to a simple selection effect; 36Lyn’s
eclipses are only detectable for about 10% of its rotational
cycle, and eclipse absorption would be broader and shallower
for more rapidly rotating stars.

4.5 X-rays from CBO?

The reconnection energy from CBO events might also be an
important for the X-rays observed from magnetic stars.

For slow rotators with only a dynamical magnetosphere,
and no centrifugal magnetospheric component, the observed
X-rays follow quite closely the scaling predicted by the “X-rays from Analytic Dynamical Magnetosphere” (XADM) model developed by ud-Doula et al. (2014), as shown in Figure 6 of Nazé et al. (2014). With a 10% scaling adjustment to account for the X-ray emission duty cycle seen in MHD simulations, the overall agreement between observed and predicted X-ray luminosities is quite remarkable for such DM stars (denoted by open circles and triangles), spanning more than four orders of magnitude in X-ray luminosity!

However there are several stars with observed X-ray luminosities well above (by 1-2 orders of magnitude) the 10%-XADM scaling; all are CM stars. These are the very stars that the analysis here predicts to have CBO reconnection events that could power extra X-ray emission, and so supplement the X-rays from wind confinement shocks predicted in the XADM analysis.

To lay a basis to examine whether CBO reconnection X-rays might explain this observed X-ray excess for CM stars, footnotes might explain this observed X-ray excess for CM stars, we present the X-ray luminosities from the XADM model (dashed) of ud-Doula et al. (2014) with CBO models of various indices $p$ (solid), plotted vs. associated magnetic confinement parameter, with all luminosities normalized by the kinetic energy luminosity of the stellar wind, $L_{\text{wind}} = M v_{\infty}^2/2$. The horizontal dotted line represents the asymptotic luminosity for XADM in the strong-confinement limit. Note that, for this $W = 0.5$ case, the CBO luminosities are significantly enhanced over that from the XADM model. Results for other rotations can be readily determined by scaling the CBO models with $W^2$.

To test this possibility that CBO plays a role in augmenting X-ray emission, a next step should be to test whether the observed X-rays from CM stars follow the CBO scaling with $\eta_1^{1/\beta} W^2$, as given by eqn. (15) when scaled to $L_{\text{wind}}$, or more generally by eqns. (12) and (13).

5 SUMMARY AND FUTURE OUTLOOK

The radio luminosities of the early-type magnetic stars were empirically found to be related to the stellar magnetic flux rate (Leto et al. 2021, Paper I). Leto et al. (2021) did not provide a definitive physical explanation regarding the origin of the non-thermal electrons. To provide the theoretical support for explaining how non-thermal electrons originate, in this paper we have extended the centrifugal breakout model that successfully predicts the Hα emission properties of stars with centrifugal magnetospheres (Shultz et al. 2021, Owocki et al. 2020), deriving a break out luminosity $L_{\text{CBO}} \propto (B^2 R_j^4 / P_{\text{rot}}) W$, where the first term in brackets has natural units of luminosity, and the dimensionless critical rotation parameter $W$ is an order-unity correction that includes the additional $R_* = 20$ and $P_{\text{rot}}$ dependence. The radio luminosity is then $L_{\text{rad}} = \epsilon L_{\text{CBO}}$, where $\epsilon \sim 10^{-8}$ is an efficiency factor. Crucially, there is a nearly 1:1 correspondence between $L_{\text{rad}}$ and $\epsilon L_{\text{CBO}}$.

The basic scaling relationship is appropriate for a split monopole. Generalization to higher-order multipoles is accomplished with a correction $\eta_1^{1/\beta}$, where $\eta_1$ is the centrifugal magnetic confinement parameter and $p$ is the multipolar order ($1$ for a monopole, $2$ for a dipole, etc.). The small residual dependence of radio luminosity on bolometric luminosity is removed by adopting $p \sim 1.1$, i.e. a nearly monopolar field. The minimal residual dependence on $L_{\text{bol}}$ (which in line-driven wind theory sets the mass loss rate through a scaling $M \sim L_{\text{bol}}^{3/2}$) confirms that the radio magnetosphere is nearly independent of the mass-loss rate. However, we find that there is a stronger dependence of the residuals on the obliquity $\beta$ of the magnetic axis with respect to the rotation axis, with $L_{\text{rad}}$ increasing by about a factor of $4$ from $\beta = 90^\circ$ to $0^\circ$. This is consistent with expectations from the rigidly rotating magnetosphere model that the amount of plasma trapped in a centrifugal magnetosphere is a strong function of $\beta$ (Townsend & Owocki 2005), since with less plasma in the CM, there will be fewer electrons available to populate the radio magnetosphere.

While radio emission and Hα emission are explained by a unifying mechanism, they probe different parts of the magnetosphere as well as different parts of the centrifugal breakout process. Hα emission probes the cool plasma trapped in the CM, which has not yet been removed by breakout. During a breakout event, some of the energy released by magnetic reconnection accelerates electrons to relativistic velocities, which then return to the star, emitting gyrosynchrotron radiation as they spiral around magnetic field lines. Following the result reported in this paper, we explain the radiation belt model proposed by Leto et al. (2021) to be the magnetic shell connected to the centrifugal breakout region close to the magnetic equator. This largely preserves the Trigilio et al. (2004) model, with the primary difference being the mechanism of electron acceleration.

Overall, the results here provide a revised foundation
on which to build a detailed theoretical model for how centrifugal-breakout reconnection leads to acceleration of electrons and the associated radio gyrosynchrotron emission. In particular, we might be able to quantify the level of reconnection heating through MHD simulations, and how it scales with \( W, \eta_c \), etc., as has been done for other scalings like spindown.

Future theoretical work should focus on the details of the acceleration of the electrons through reconnection, and their subsequent gyrosynchrotron emission of polarized radio emission (and perhaps other observable spectral bands like X-rays), with the specific aim to understand, and quantitatively reproduce, the inferred emission efficiencies \( \epsilon \). This work should also extend to explore the connection with electron cyclotron maser (ECM) radio emission that has been detected in many of the same stars showing gyrosynchrotron emission [Das et al. 2021].

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**DATA AVAILABILITY STATEMENT**

No new data were generated or analysed in support of this research. All data referenced were part of the associated Paper I [Shultz et al. 2021].

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