

ON A TRANSITION FROM SOLAR-LIKE CORONAE TO ROTATION-DOMINATED JOVIAN-LIKE MAGNETOSPHERES IN ULTRACOOL MAIN-SEQUENCE STARS

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Received 2009 April 27; accepted 2009 May 8; published 2009 June 24

ABSTRACT

For main-sequence stars beyond spectral type M5, the characteristics of magnetic activity common to warmer solar-like stars change into the brown-dwarf domain: the surface magnetic field becomes more dipolar and the evolution of the field patterns slows, the photospheric plasma is increasingly neutral and decoupled from the magnetic field, chromospheric and coronal emissions weaken markedly, and the efficiency of rotational braking rapidly decreases. Yet, radio emission persists, and has been argued to be dominated by electron–cyclotron maser emission instead of the gyrosynchrotron emission from warmer stars. These properties may signal a transition in the stellar extended atmosphere. Stars warmer than about M5 have a solar-like corona and wind-sustained heliosphere in which the atmospheric activity is powered by convective motions that move the magnetic field. Stars cooler than early-L, in contrast, may have a Jovian-like rotation-dominated magnetosphere powered by the star’s rotation in a scaled-up analog of the magnetospheres of Jupiter and Saturn. A dimensional scaling relationship for rotation-dominated magnetospheres by Fan et al. is consistent with this hypothesis.

Key words: planets and satellites: general – stars: late-type – stars: low-mass, brown dwarfs – stars: magnetic fields

1. INTRODUCTION

Main-sequence stars have a convective envelope around a radiative core from about spectral type A2 (with an effective temperature of $T_{\text{eff}} \approx 9000$ K) to about M3 ($T_{\text{eff}} \approx 3200$ K). Stars warmer than about F2 ($T_{\text{eff}} \approx 7000$ K) have a shallow convective envelope that sustains at most weak magnetic activity. As one of these stars, the Sun exhibits many of the properties of the magnetically driven variability of the population of F2–M3 dwarf stars. The radiative losses from their chromospheres, transition regions, and coronae generally decrease with age as stars lose angular momentum through a magnetized wind. The radiative losses from these distinct thermal domains scale through power laws with the average magnetic flux density on the stellar surface. All of these stars exhibit signatures of flaring that increase with increasing quiescent activity. The radio emission from all of these stars, albeit generally weak, scales linearly with the coronal X-ray emission, suggestive of persistent non-thermal energetic-particle populations within their outer atmospheres (e.g., Schrijver & Zwaan 2000, and references therein; see Berger et al. 2008, for a recent version of the radio/X-ray scaling).

Stars cooler than about M2 to M4 are expected to be fully convective (Chabrier & Baraffe 2000), lacking the convective overshoot layer and tachocline that are thought to be important to the solar dynamo. Yet these stars are capable of generating a magnetic field, with a rotation–activity relationship that continues clearly to at least spectral type M8 (e.g., Mohanty et al. 2002; Reiners & Basri 2009). However, their magnetic field appears to be a predominantly axisymmetrical large-scale poloidal field with at most a slow evolution in the surface pattern (Donati et al. 2008; also Reiners & Basri 2009), in contrast to warmer stars that show relatively rapidly evolving, nonaxisymmetric fields evolving subject to flux emergence and differential rotation.

Spectra of FeH lines reveal that stars at least down to M9 have magnetic fields, and that the coolest stars beyond M6 for which fields can be measured have magnetic flux densities of

$fB = 1.5$ kG or more (e.g., Berger et al. 2009; Hallinan et al. 2006, 2007; Reiners & Basri 2007). X-ray flaring has been reported down to at least M9.5 (e.g., Liebert et al. 1999; Reid et al. 1999; Fleming et al. 2003; Berger et al. 2008).

Beyond about M8, the relationship between chromospheric ($H\alpha$) or coronal (X-ray) emission and rotation rate becomes a weak tendency and even that disappears beyond L0 (e.g., Reiners & Basri 2009; Basri 2009; see Mohanty & Basri 2003, for a discussion of difficulties in assigning spectral types). Whereas essentially all stars of spectral type M8 have strong $H\alpha$ emission, this drops to 60% at L0, $\approx 15\%$ at L4, and to less than $\approx 10\%$ by L5 (e.g., Mohanty et al. 2002; Mohanty & Basri 2003; West et al. 2004; Reiners 2007; Reiners & Basri 2007; Schmidt et al. 2007).

In contrast to the weakening of the rotation–activity relationship for the traditional chromospheric ($H\alpha$) and coronal (X-ray) indicators of magnetic activity beyond about M8, the radio luminosity continues to increase with increasing angular velocity up to at least L0 (Berger et al. 2008), with (often variable) radio emission detected to at least L3.5 (Berger 2006). Interestingly, the essentially linear relationship between radio and X-ray luminosities for all other cool stars breaks down beyond M5, with the X-ray luminosity dropping by a factor of about 3000 below that relationship at a given radio luminosity by spectral type L0 (Berger et al. 2008).

The reduction of the traditional diagnostics for chromospheric and coronal activity, the weakening of their dependence on rotation rate despite the presence of strong magnetic fields, and the increase in timescale for rotational braking (discussed in Section 4), may have their origin in the very low degree of ionization of the photospheric plasma. Mohanty et al. (2002) argue that beyond M5, the photospheric plasma is weakly coupled to the magnetic field, and the high resistivity and associated diffusivity of the plasma should render it very difficult to generate electrical currents by convection-driven field motions or to transmit any generated in the stellar interior to the corona (see also Mohanty & Basri 2003, who also discuss the role of dust in these cool atmospheres). The persistence of radio

Table 1
Characteristic Stellar Properties

Property	M7V	dL2	dL5
Stellar radius, $R_*(R_\odot)$	0.16 ^h	0.09 ^c	0.08 ^c
Effective temperature, $T_{*,\text{eff}}$ (K)	2700 ^a	2080 ^b	1700 ^b
Mass, $M_*(M_\odot)$	0.10 ^h	0.08 ^c	0.07 ^c
Surface gravity, $\log g$	3.9	5.4	5.4
Bolometric luminosity, $\log(L_{\text{bol}})$	30.7	29.7	29.3
Moment of inertia, $\log(I)^d$	51.4	50.8	50.6
Equatorial rotation velocity, v_{eq} (km s ⁻¹)	10 ^b	20 ^b	30 ^b
Rotational energy, $\log(W_{\text{rot}})$	43.0	43.5	43.7
Rotation period, P (d)	0.8	0.23	0.14
Change in rotation period, \dot{P}/P (Gyr)	3 ^e	7 ^e	> 10 ^e
Synchronous rotation (Equation (2)), R_S/R_*	10.2	7.3	5.7
Power from ISM wind (Equation (11)), $\log(P_w)$	18.4	17.8	17.7
Relative luminosity in H α , $\log(L_{\text{H}\alpha}/L_{\text{bol}})$	-4.3 ^b	-5.7 ^b	< -7 ^b
Power in H α , $\log(L_{\text{H}\alpha})$	26.4	24.0	< 22.3
Power in X-rays, $\log(L_X)$	$\lesssim 27.7^g$	$\lesssim 25.5^g$	$\lesssim 25.1^g$
Excess of radio to X-ray, $\delta(L_R/L_X)^f$	$\sim \times 10$	$\sim \times 3000$?
Loss of rotation energy (Equation (12)), $\log(W_{\text{rot}})$	26.0	26.1	< 26.2
Est. max. loss of rotation energy (Equation (9)), $\log(W_C)$	$\lesssim 27.4$	$\lesssim 25.9$	$\lesssim 25.8$
Power est. from Equation (13), $\log(W')$	24.9–25.9	24.8–25.8	25.1–26.1

Notes.

^a From Mohanty et al. (2004).

^b Reiners & Basri (2008); West et al. (2004).

^c Baraffe et al. (2003), at an age of 5 Gyr.

^d For an approximate gyration radius of $0.3R_*$, compared to Claret & Gimenez (1990).

^e Reiners & Basri (2008), their Figure 9.

^f Deviation from radio–X-ray relationship for warmer stars; Berger et al. (2008), their Figure 9.

^g Audard et al. (2007).

^h From Allen (1972).

emission into the L-type range, despite these changes in activity characteristic of all other cool stars, suggests we explore a fundamental change in the character of stellar magnetic activity: the weakening of a well-developed convection-powered stellar corona and associated stellar wind may cause the stellar outer atmosphere to change from a solar-like corona with heliosphere to a Jupiter-like magnetosphere shaped by the incoming wind of the interstellar medium (ISM) impinging on the stellar magnetic field, while powered by the stellar rotation.

2. RADIATIVE AND ROTATIONAL ENERGY LOSSES

Coronal emission and magnetic braking both weaken rapidly beyond mid-M. Up to about spectral type L0, the energy lost by rotational braking appears to be consistent with that expected from a solar-like coronal domain beneath an outflowing wind, as can be seen from the following argument. I start from the premise that the stellar atmosphere is essentially hydrostatically stratified. Near the stellar surface, an isothermal plasma has a pressure scale height

$$H_p = \frac{akTm_p R_*^2}{GM_*}, \quad (1)$$

with stellar radius R_* , temperature T , proton mass m_p , and gravitational constant G . Here, I assume a pure hydrogen gas for an order-of-magnitude estimate. The constant $a = 1$ for a neutral gas, and $a = 2$ for fully ionized hydrogen. A largely neutral photospheric gas of $T = 2000$ K on a compact ultracool star with surface gravity $g \sim 10^{5.4} \sim 9 g_\odot \text{ cm s}^{-2}$ would have $H_p(2000 \text{ K}) \sim 9 \text{ km}$.

In order to lead to magnetic braking, plasma of sufficient density needs to exist out to the lesser of the Alfvén radius

(to which corotation of star and high-atmospheric plasma is enforced) and the radius of synchronous rotation (beyond which centrifugal forces dominate). The latter (which is likely the smaller of the two for rapidly rotating L-type dwarf stars) is

$$R_S = \left(\frac{GM_*}{\Omega^2} \right)^{\frac{1}{3}}, \quad (2)$$

for stellar mass M_* and angular velocity $\Omega = 2\pi/P$, at rotation period P . The characteristic value of $R_S \sim 7R_*$ (see Table 1) is so much larger than $H_p(2000 \text{ K})$ that the plasma density at R_S would be insufficient to lead to significant angular momentum loss.

For a plasma at coronal temperatures the density scale height is much higher, of course. Only very few stars beyond M9 have been detected in X-rays (e.g., Audard et al. 2007; Robrade & Schmitt 2008). Their quiescent emissions are at a level of about $L_X/L_{\text{bol}} \sim 10^{-4}$, or $\log(L_X) \sim 25.5$, while others have even lower upper limits.

Assuming a hydrostatically stratified atmosphere, the electron density n_e associated with such an emission can be estimated from the X-ray luminosity L_X based on the plasma's volumetric emission, $n_e^2 \Lambda(T_C)$, and characteristic volume, $4\pi R_*^2 H_p(T_C)$,

$$L_X = 4\pi R_*^2 H_p(T_C) n_e^2 \Lambda(T_C) \quad (3)$$

for a plasma at temperature T_C , with an emissivity $\Lambda(T_C) \approx 2 \times 10^{-18} T^{-2/3}$ (for $\log(T_C) \in [5.5, 7.5]$); for $T_C = 1.5 \text{ MK}$, comparable to that of the bulk of the solar wind and consistent with the very-limited X-ray spectral information available on L-type dwarf stars (Robrade & Schmitt 2008), $\Lambda(1.5 \text{ MK}) \sim 10^{-21.8}$ (e.g., Schrijver & Zwaan 2000). The coronal-base

density thus estimated for L-type stars with $\log(L_X) \sim 25.5$ and $T_C = 1.5$ MK is $n_0 \sim 10^{8.8} \text{ cm}^{-3}$.

To estimate the plasma density at height R_S within the equatorial plane, the density for an isothermal atmosphere can be approximated from a balance between pressure gradient, gravity, and centrifugal acceleration:

$$\frac{dn(r)}{dr} = - \left(\frac{GM_* m_p}{2kT_C} \right) \frac{n(r)}{r^2} + \left(\frac{\Omega^2 m_p}{2kT_C} \right) n(r) r \quad (4)$$

(note that the stratification of a subsonic wind is very similar to a static stratified atmosphere, e.g., Hansteen 2009). With the above value of n_0 , $n(R_S) \approx 10^{5.6-5.8} \text{ cm}^{-3}$ for the characteristic L2 and L5 stars in Table 1 (the centrifugal force below R_S modifies the density profile by a factor of $\lesssim 2$ relative to the stratification in the absence of rotation).

Now assume that the centrifugal force beyond R_S accelerates plasma outward, which is replenished from below at (at most) the thermal velocity

$$v_{\text{th}} = \left(\gamma \frac{kT_C}{m_p} \right)^{\frac{1}{2}}, \quad (5)$$

for adiabatic index γ , so that the upper limit for the mass loss is

$$\dot{M} = \alpha 4\pi R_*^2 v_{\text{th}} m_p n(R_S), \quad (6)$$

with α a geometry factor. If the mass loss were isotropic, $\alpha \equiv 1$, but as mass is probably lost from only part of the surface area, I use $\alpha = 1/2$ below.

The stellar magnetic field can enforce corotation out to a distance R_A where the plasma β becomes of order unity, given by

$$\frac{B_0^2}{4\pi} \left(\frac{R_*}{R_A} \right)^6 = 2n(R_A)kT_C, \quad (7)$$

if the field is approximated by a dipole of characteristic strength B_0 at the stellar surface; $n(r)$ is assumed to be given by Equation (4).

Outflowing plasma in a spherical shell carries an angular momentum

$$\dot{L} = \frac{2}{3} \Omega R_A^2 \dot{M}, \quad (8)$$

and a rotational energy of

$$W_C = \dot{L} \Omega. \quad (9)$$

With the values in Table 1, one finds $W_C \approx 10^{25.8} \text{ erg s}^{-1}$ for $\log(L_X) \sim 25.5$. For the characteristic L2 star in Table 1, this compares well to the estimated loss W_{rot} from rotation–age studies (see Section 4), so that we can conclude that the existence of a faint thermal corona in early L-type stars is compatible with the inferred magnetic braking.

The estimated W_C is about an order of magnitude larger than W_{rot} for the M7 dwarf star. This may be because of the exponential dependence of W_C on T_C , or because the corona of the M7 star may be solar-like, in the sense that a few relatively bright and dense regions dominate the emission, so that the base density from Equation (3) would be an overestimate for the highest coronal loops.

The estimates in this section obviously depend on the assumed values of L_X and T_C . The value of W_C scales with L_X about as a square root, so that our conclusions are not strongly modified if

the characteristic value of L_X observed for the L-dwarf binary Kelu-1 is somewhat larger than what is characteristic of the ensemble of similar L-type dwarf stars. The dependence on T_C is much stronger, not surprisingly, because of the near-exponential stratification of density in units of the pressure scale height: for $T_C = 1-3$ MK, $\log(W_{\text{rot}}) = 24.2-27.3$.

3. THE MAGNETOSPHERES OF THE COOLEST DWARF STARS

Even though magnetic braking remains compatible with the concept of a hot corona, the radio emission in ultracool dwarfs is disproportionately strong. One possible cause for this that should be explored, and can then be ruled out, is the interaction with the ISM. Observations suggest that there is relatively little heated coronal plasma well into the L-type spectral range, so there should not be much of an associated stellar wind either. The motion of a star with at most a weak wind relative to the ISM should lead to the formation of a magnetopause. The energy input into the stellar magnetosphere from this interaction is expected to be low, based on the following.

The standoff (or Chapman–Ferraro) distance of the magnetopause is set by where the dynamic pressure $\rho_w v_w^2$ of the ISM wind with density ρ_w and relative velocity v_w equals the magnetic pressure of the stellar field. Observations suggest that the large-scale field of very cool dwarf stars can be approximated by a dipole field, so that the field scales with μ/r^3 , with the magnetic moment $\mu = B_* R_*^3$, where B_* is the field strength near the stellar equator. R_{CF} for a late M-type or L-type dwarf star can thus be estimated from $\rho_w v_w^2 \propto B^2(R_{\text{CF}})/8\pi$, or

$$\frac{R_{\text{CF}}}{R_*} \sim 3.5 \left(\frac{B_G^2}{n_0 v_{100}^2} \right)^{1/6}. \quad (10)$$

The constant of proportionality is determined by using the observation that for Earth $R_{\text{CF},\oplus} \approx 10$ Earth radii (Russell 2007), for a wind speed of $v_{100} \sim 4$ (in units of 100 km s^{-1}) and a characteristic solar-wind particle density $n_0 = 10 \text{ cm}^{-3}$ (Feldman et al. 1977), and $B_G \sim 0.6$ G for the Earth’s polar field strength (Allen 1972).

The relative motion of stars through the ISM averages about 40 km s^{-1} for a sample of very cool dwarf stars (e.g., Wood et al. 2005; Schmidt et al. 2007). For a hypothetical dwarf star that has no stellar wind, that moves through an ISM like that around the solar system with $n_0 = 0.1$ (e.g., Wood et al. 2002) at $v_{100} = 0.4$, and $B_G = 1.5$ kG, one finds $R_{\text{CF},*}/R_* \approx 32$; that relative scale is similar to the geometry in the case of Jupiter’s magnetosphere, for which $R_{\text{MP}}/R_J = 42$ (e.g., Walker & Russell 1995).

To estimate how much power the ISM wind might impart onto a stellar bowshock and potentially into the stellar magnetosphere, we estimate the power in the bulk kinetic energy over the cross section of the bow shock with cross section πR_{CF}^2 :

$$P_w \approx 3 \times 10^{20} n_0 v_{100}^3 \left(\frac{R_{\text{CF}}}{R_*} \right)^2 \left(\frac{R_*}{R_\odot} \right)^2, \quad (11)$$

so that at $n_0 = 0.1$, $v_{100} = 0.4$, and $R_* = 0.3 R_\odot$, $P_w \approx 10^{20-22} \text{ erg s}^{-1}$ for characteristic M7 to L5 stars. This lies orders of magnitude below the $H\alpha$ and X-ray luminosities (see Table 1) and below the power that needs to be extracted from the stellar rotation with age (see below). Hence, the ISM wind is not a significant source of magnetospheric activity in dwarf stars through mid-L, even if it shapes a close-in astropause.

4. FROM A STELLAR CORONA TO A PLANETARY MAGNETOSPHERE

As the solar-like corona fades away from mid-M to mid-L, one may expect increasing signatures of a rotation-dominated magnetosphere toward late L-type stars like that for Jupiter. In such a magnetosphere, energy is taken from the star's rotational energy through a torque applied by outflowing plasma. The energy loss, W_{rot} , can be estimated from the rotation–age relationship. Reiners & Basri (2008) infer timescales for magnetic braking that increase from about 3 Gyr for an M7 star to 7 Gyr for an L2 star, and over 10 Gyr for an L5 star (the latter is relatively poorly constrained and, perhaps, much larger). Using

$$W_{\text{rot}} = \frac{d}{dt} \frac{1}{2} I \Omega^2 \quad (12)$$

yields $W_{\text{rot}} \sim 10^{26} \text{ erg s}^{-1}$ (Table 1). In the early L-type range, this is comparable to W_C from Equation (9) that could be taken away by the outflow from the relatively weak corona, i.e., that would be plausibly consistent with the existence of such a weak corona. But both W_{rot} and W_C exceed X-ray and $H\alpha$ losses, i.e., the rotational energy loss exceeds the radiative losses, in contrast to what is seen in warmer solar-type stars.

Let us now explore an order-of-magnitude scaling for the power expected from a rotationally dominated magnetosphere. Fan et al. (1982) argue for a scaling based on a dimensional analysis (“principle of similitude”) that relates the magnetic moment, $M_B = B\ell^3$, the rotation period, P , and the radius, R_a , at which the acceleration process begins to the power, W' , generated

$$W' = \frac{4\pi^2 K}{c^2} \frac{M_B^2}{P^2 R_a}, \quad (13)$$

where the constant K has to follow from a measurement until a full theory is developed. Based on the properties in Table 1, using a mean photospheric field strength of 1.5 kG, and with R_S for R_a , values are found for $^{10} \log(K \cdot W_{\text{rot}}/W')$ of 0.6, 0.4, and 0.6 for the characteristic M7, L2, and L5 stars, respectively. Fan et al. (1982) estimate a range of values for the constant $^{10} \log(K)$ for Jupiter from -1.7 to -0.7 . The value of K for Jupiter lies, remarkably, within the range of values needed to let W_{rot} and W' be comparable for the stars in Table 1. In contrast, this scaling applied to the Sun yields $\log(W'_{\odot}) \sim 21.3$ – 22.3 , which is well over a thousand times less. At least W' for ultracool dwarfs is much larger than the solar value, while with the only available calibration point—Jupiter—one concludes that W' is close to both W_{rot} and W_C for an early L-type star.

5. DISCUSSION AND CONCLUSIONS

Somewhere along the spectrum of stars, brown dwarfs, and planets, a transition from an outflow-driven asterosphere to a field-shielded rotating magnetosphere must occur. Based on the observational evidence, I argue that this transition occurs at the bottom end of the true stellar range of the main sequence: for stars cooler than about spectral type M5, the properties characteristic of solar-like activity progressively disappear, while, in contrast to warmer stars, magnetic braking extracts more energy from the star than needed to power the chromospheric $H\alpha$ and (weak) coronal X-ray emissions. Objects cooler than about L0–L2 may exhibit outer-atmospheric phenomena similar to those in the rotation-driven magnetosphere of Jupiter rather than to those in convection-driven corona and wind of the Sun.

The energetics of the main auroral oval of Jupiter dominate over the phenomena associated with the lower-latitude structures that are connected directly with the movement of Io, Europa, and Ganymede through the Jovian magnetic field, and those associated with the higher-latitude polar-cap emissions that appear to be driven by the solar wind. Jupiter's main auroral oval is not—in contrast to Earth's—the separator between open and closed planetary magnetic field in the interaction with the interplanetary magnetic field, but instead is mapped to lower-latitude closed magnetic field (see, e.g., the summarizing discussion by Cowley et al. 2003). This auroral structure is thought to be generated by the precipitation of energetic electrons created by the electric current system that is involved in a phenomenon referred to as “corotation” (or rather the breakdown thereof) in the middle magnetosphere: beyond the interface where the Jovian magnetic field is strong enough to enforce corotation of the plasma, a current system is induced that includes a disk-shaped near-equatorial extrusion in which field and plasma interact through Lorentz forces to extract energy from the planet's rotation.

If the rotation of the coolest dwarf stars similarly powers their magnetosphere, this energy is ultimately drawn from the energy of rotation. In the case of the Jupiter, Io and Ganymede provide plasma conveniently high in the magnetosphere, outside the distance of geosynchronous rotation but within the Alfvén radius. In the case of the ultracool dwarf stars, it is of course possible that one or more close-in planets act as a similar plasma source, but rather than postulating such planets, I hypothesize that plasma is provided by a tenuous hot stellar corona formed either by residual solar-like activity (perhaps associated with the overturning field of a turbulent dynamo) or magnetospheric activity (somehow formed by the breakdown of corotation). How, quantitatively, this balance changes between L0 and L5 remains to be established.

For stars up to late-M, the power extracted from the stellar rotation lies below the characteristic $H\alpha$ and X-ray emissions. The estimated rate W_{rot} at which rotational energy is lost from an L2-type dwarf, in contrast, is larger than the characteristic outer-atmospheric losses based on the coronal X-ray luminosity. In the scenario of the rotationally dominated magnetosphere, Eviatar & Siscoe (1980) argued that at most half of the total power taken from Jupiter's rotational energy would be available for radiative emissions, including the aurorae. The rough estimate of the radiative losses of L-type dwarfs (as reflected by L_X) is not inconsistent with that argument, but further observations are needed to test this in more detail.

The quiescent radio emission from F–M-type stars appears to be predominantly gyrosynchrotron emission from high-energy coronal electrons (see, e.g., the review by Güdel 2002). Hallinan et al. (2008) argued that the radio signal of several very cool dwarf stars (M8.5, M9, and L3.5) is associated with the electron–cyclotron maser (ECM) process; they base that argument on the observation that the radio signal is periodically fully circularly polarized, whereas there is also an unpolarized component which they attribute to depolarized ECM emission because its brightness temperature is incompatible with incoherent synchrotron radiation. They pointed out that the ECM mechanism is thought to be responsible for kHz–MHz emission from Jupiter (compare the review by Zarka 1998). Thus, both the enhanced radio to X-ray ratio and the radio polarization signature support the analogy of the magnetospheric processes around Jupiter and around ultracool rapidly rotating dwarf stars.

The plasma transport in the magnetospheres of Jupiter and Saturn is thought to occur by convective cells triggered by the centrifugal interchange instability, in which cool, dense volumes change places with hotter, less dense volumes (e.g., Hill et al. 2005; Chen & Hill 2008). In the case of ultracool dwarf stars, the stellar equivalent of this process into the stellar magnetotail shaped by the ISM wind could be the process by which angular momentum is removed from the star.

In view of the arguments discussed in this Letter, it appears warranted to consider the possibility of a very similar system of currents in the case of main-sequence stars cooler than about L0 as in the Jovian magnetosphere. Perhaps much, if not most, of the H α emission and the relatively weak coronal X-ray in stars cooler than L0 is associated with activity (including aurorae) driven by the breakdown of corotation as occurs on a smaller scale for Jupiter, while the stellar radio emission may be a signature of high-energy particles accelerated in that process. A dimensional analysis, developed by Fan et al. (1982), applied to the case of L-type stars supports this hypothesis quantitatively.

I thank G. L. Siscoe, J. L. Linsky, and B. de Pontieu for helpful discussions and for their comments on the manuscript.

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