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The observed rotation/activity relations of ultracool dwarfs

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Abstract. Until recently, it was generally assumed that brown dwarfs and very low-mass stars would not be able to generate and sustain large-scale magnetic fields. Over the past several years, however, observations have shown that some of these "ultracool dwarfs" do precisely that. The available evidence does indicate that a substantial evolution in magnetic activity occurs at spectral types M7 and later — plausibly the onset of the evolution from stellar-type toward planetary-type magnetospheric physics. We discuss the stellar rotation/X-ray activity relationship and its ultracool analogue, which remains poorly-characterized. I show how collected observations are providing strong hints of rotational supersaturation of UCD X-ray activity, which will strongly inform the theoretical understanding of magnetospheres beyond the bottom of the main sequence.

Key words. Brown dwarfs — stars: activity — X-rays: stars

1. Introduction

Brown dwarfs and very low-mass stars — collectively, "ultracool dwarfs" or UCDs, defined here to have spectral types of M7 or later — are now known to be magnetized. The processes that form and dissipate UCD magnetic fields, however, remain unclear. High magnetic diffusivities require a dynamo to form and sustain the fields (Mohanty et al. 2002), but the standard solar-type "interface dynamo" depends critically on the tachocline, the shearing layer at the interface between the convective and radiative zones. UCDs, being fully convective, do not have this layer (Chabrier & Baraffe 2000). It is perhaps surprising, then, that magnetic activity does not seem to change significantly across the transition to full convection at spectral types of ~M4 (Delfosse et al. 1998; Mohanty & Basri 2003). However, observations show dramatic changes in magnetism at the UCD transition (~M7) with a wide variety of magnetic field configurations (Morin et al. 2010) and possible indications of a bimodal dynamo mechanism (e.g., Gastine et al. 2012). Simulations of fully-convective dynamos yield significantly varying results regarding expected field topologies and atmospheric circulation (Durney et al. 1993; Chabrier & Küker 2006; Browning 2008).

Besides presenting important problems in their own right, the questions surrounding magnetism in UCDs affect other aspects of their study. Although there may only be low coupling between magnetic fields and the outer stellar layers, due to their likely low levels of ionization (Mohanty et al. 2002), phase alignment between photometric and radio variations suggests that at least some UCD spots

Send offprint requests to: P. K. G. Williams are magnetically influenced (McLean et al. 2011), as does multicolor photometry suggestive of cool spots (Rockenfeller et al. 2006). Given the temperature sensitivity of UCD atmospheric chemistry, such spots may even harbor substantially different cloud structures (Heinze et al. 2013). The presence of magnetic fields in UCDs also affects their detailed spectra due to the existence of magnetically-sensitive molecular lines (e.g., Reiners & Basri 2007, see also the contribution by Kuzmychov in this volume). Finally, magnetic Maxwell stresses will also alter the internal structure of UCDs, potentially suppressing differential rotation (Browning 2008) or inhibiting convection, affecting their radii (Gough & Tayler 1966; Chabrier et al. 2007).

2. Rotation and activity in stars and UCDs

A key source of insight into stellar magnetic activity is the observed linkage between rotation, activity, and age (Kraft 1967; Pizzolato et al. 2003, see also the review by Scholz in this volume). Some of the aspects of this linkage are: (1) a correlation between rotation rates and activity levels, suggestive of a rotation-powered dynamo; (2) an anti-correlation between age and rotation or activity, suggestive of angular momentum loss through magnetized stellar winds; (3) a "saturation" level of rotation, above which activity tracers do not generally increase. The cause of the saturation effect is unclear: it could be due to saturation of the dynamo itself or of the filling fraction of active regions on the stellar disk; or due to centrifugal stripping of the coronal plasma (Wright et al. 2011, and references therein). Studies of stellar rotation and activity often use X-ray emission as an activity tracer (e.g., Pallavicini et al. 1981; Giampapa et al. 1996; James et al. 2000; Pizzolato et al. 2003; Wright et al. 2011), for which an additional trend is observed: (4) a "supersaturation" effect in some of the fastest rotators, in which their magnetic activity decreases from the saturation level (Randich et al. 1996; Wright et al. 2011). The supersaturation effect is likewise not well-understood. Two proposed explanations are further coronal centrifugal stripping (Jardine & Unruh 1999; Jardine 2004) or a "polar updraft" effect, in which nonuniform heating due to rotationally-driven gravity darkening pushes magnetic flux tubes toward the poles, reducing the overall surface filling fraction of active regions (Stępień et al. 1997, 2001). Supersaturation has not been detected when chromospheric emission is used to trace magnetic activity, which is supportive of the centrifugal stripping model (Marsden et al. 2009; Christian et al. 2011)

Intra-source variations can be damped by nondimensionalizing the parameters, normalizing emission by the stellar bolometric luminosity (e.g., L_X/L_{bol}) and putting rotation in terms of the Rossby number Ro $= P_{rot}/\tau_c$, where P_{rot} is the rotation period and τ_c is the convective turnover timescale (Pallavicini et al. 1981; Noyes et al. 1984; Pizzolato et al. 2003). While this approach is successful for a wide range of spectral types, ~F–M6, it breaks down at the UCD transition, as demonstrated by Stelzer et al. (2006), Berger et al. (2010), and in Figure 1. Kelu-1 AB is the only L dwarf to be detected in X-rays (Audard et al. 2007), and there appears to be a sharp dropoff in the X-ray emission of UCDs at the M/L transition, along with possibly significant variation in the M6–M9 range.

What role does rotation play in this variation? The small total number of UCDs observed in X-rays and the possible dropoff at the M/L transition make the question difficult to answer — the dropoff may be due to a supersaturation effect in rapidly-rotating L dwarfs, or it may instead be related to one of the several other significant changes that occur at the M/L transition. To help elucidate the matter, we have obtained non-simultaneous *Chandra* and Very Large Array observations of a sample of seven UCDs with $v \sin i$ values ranging between < 3 and $40\,\mathrm{km\,s^{-1}}$ but spectral types constrained to lie between M6.5 and M9. As shown in Figure 1, all were detected by *Chandra*, with two showing significant signs of variability. The details of the observations and a comparison of the radio and X-ray results will be presented in a forthcoming work (Williams et al., in prep.).

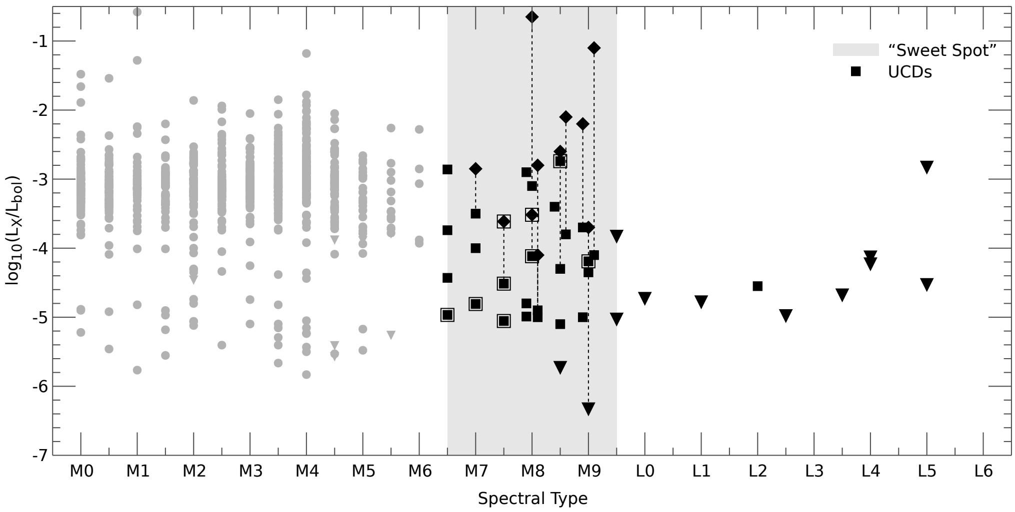

Fig. 1. X-ray activity as a function of spectral type. The full database of UCD measurements (*black symbols*) and analysis will be presented in a forthcoming work (B. A. Cook et al., in prep.). *Gray symbols* indicate contextual non-UCD measurements, taken from Giampapa et al. (1996); James et al. (2000); Martín & Bouy (2002); Pizzolato et al. (2003); Riaz et al. (2006); Reiners & Basri (2007); and references therein. *Diamonds* represent flaring emission, *squares* non-flaring detections, and *triangles* upper limits. *Lines* connect multiple measurements of the same source. *Shaded region* denotes a "sweet spot" regime where the X-ray activity of UCD sources is not yet severely suppressed, as appears to be the case for objects with SpT $\gtrsim$ L0. *Boxed symbols* are new measurements that will be presented in a forthcoming work (William set al., in prep.).

Figure 2 presents our database of UCD X-ray measurements in terms of the Rossby number. As identified by Berger et al. (2010), there are suggestions of a "supersaturation" effect in the UCD population, even if the L dwarf subsample is omitted. The data may also be interpreted in terms of a strong cutoff of X-ray emission at Ro $\lesssim 10^{-2.5}$, although all physical models of the supersaturation effect of which we are aware involve gradual rather than sudden changes in X-ray activity. The data for the rapid rotator Kelu-1 AB are somewhat in tension with this interpretation, although we note that its detection consists of 4 events with some evidence of clustering, so that the best, non-flaring value of L_X remains uncertain. Using a simple calculation of the centrifugal stripping (Keplerian corotation) radius in terms of Ro, the data do not offer strong support of that model, but a more detailed analysis is necessary. This will be presented in a companion paper (Cook et al., in prep.).

Stellar magnetism may be investigated with a variety of tracers, including chromospheric emission lines, UV emission from the transition region, coronal X-rays, and radio emission tracing nonthermal plasma (e.g., West et al. 2004; Osten et al. 2005; Stelzer et al. 2006; Smith & Redenbaugh 2010). It is also studied with time-domain monitoring and more sophisticated techniques such as FeH spectroscopy and Zeeman-Doppler imaging (e.g., Reiners & Basri 2007; Morin et al. 2010; Basri et al. 2011). In the coolest substellar objects, however, radio observations become the best way to trace magnetism: their rapid rotation washes out Zeeman signals; the overall luminosity decreases strongly; and X-ray and Hα emission drop off even more precipitously (Figure 1; Gizis et al. 2000; West et al. 2004; Stelzer et al. 2006; Berger et al. 2010). Radio emission, on the other hand, remains robust, with UCDs being strongly radio-overluminous compared to their X-ray emis-

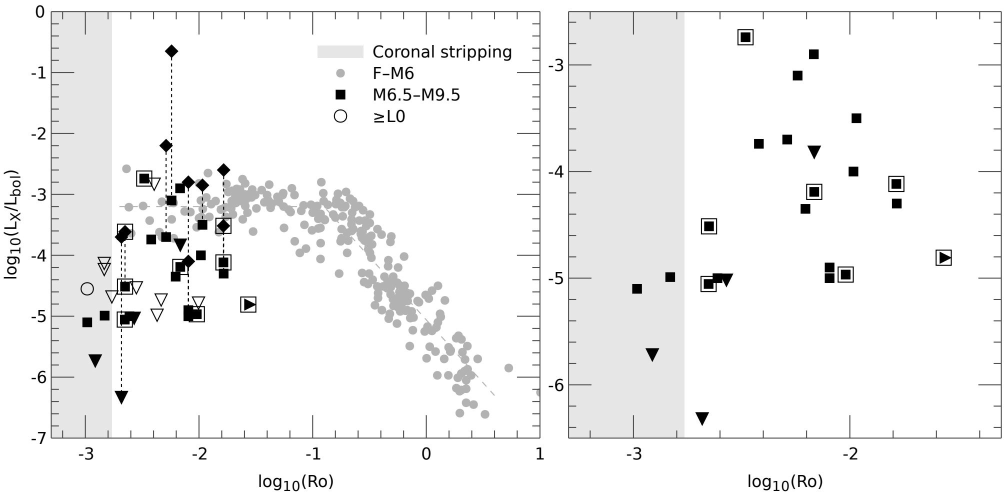

Fig. 2. X-ray activity as a function of rotation as parametrized by the Rossby number. *Left panel:* comparison of UCDs with solar-type stars. Symbols are the same as in Figure 1. Contextual data are from Pizzolato et al. (2003). *Filled black symbols* indicate UCDs in the spectral type "sweet spot" (M6.5–M9.5; cf. Figure 1), and *unfilled symbols* L dwarfs and later. *Shaded region* denotes approximate rotation rate at which centrifugal stripping of the corona may be relevant. *Boxed symbols* are new measurements that will be presented in a forthcoming work (Williams et al., in prep.). *Right panel:* the same dataset, isolating non-flaring "sweet spot" measurements. The data are consistent with either a "supersaturation" interpretation, in which $L_X/L_{bol} \propto \mathrm{Ro}^{\approx -2}$, or a "cutoff" interpretation in which L_X/L_{bol} drops significantly at Ro $\approx 10^{-2.5}$. The decrease in X-ray emission does not appear to correlate well with the coronal stripping point, although Ro is an imperfect proxy for R_{kep}/R_*. Recent analysis of stellar X-ray/rotation relations also discourages the coronal stripping interpretation (Wright et al. 2013).

sion when interpreted in terms of stellar relations (Güdel & Benz 1993). Our large radio surveys of UCDs (Berger 2002, 2006; McLean et al. 2012) have in fact shown that radio emission, unlike X-ray emission, continues to increase with rotation, with no indications of either saturation or supersaturation (McLean et al. 2012).

3. Outlook

Further sensitive X-ray observations will be vital to establishing the similarities and differences between stellar and substellar dynamo action. Radio observations, however, may hold the most promise for pushing from the brown dwarf toward the exoplanetary regime. Upgrades to facilities such as the Very Large Array have delivered major improvements in sensitivity; although the latest-type radio detected object had until recently been an L3.5 dwarf, this barrier has decently been demolished with radio detections of a T6.5 dwarf, 2MASS J10475385+2124234 (Route & Wolszczan 2012; Williams et al. 2013), as well as an L5+T7 binary, 2MASS J13153094−2649513 AB (Burgasser et al. 2013). The first claimed detection of radio emission from an exoplanet has also recently been published (Lecavelier des Etangs et al. 2013).

While the construction of a substantial statistical sample of radio and X-ray observations of UCDs will continue apace, searches for unusual and nearby UCDs that can be studied in detail (e.g., Luhman 16; Luhman 2013) are an essential, complementary undertaking.

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