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Too Cool for Stellar Rules: A Bayesian Exploration of Trends in Ultracool Magnetism

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Abstract

Ultracool dwarfs are objects in the red and brown dwarf regimes with electrically neutral atmospheres caused by their cool temperatures. To better constrain their magnetic behavior, we use a sample of 196 ultracool dwarfs observed in the 4.5-8.5 GHz range on the Karl G. Jansky Very Large Array (VLA) and the Australia Telescope Compact Array (ATCA). We take a Bayesian approach in analyzing this sample to understand trends in radio luminosity as a function of several fundamental parameters: spectral type, effective temperature, and rotation rate. This sample is composed of mostly null detections, along with a number of confirmed detections, and has both large uncertainties and intrinsic scatter. This is the first rigorous Bayesian analysis applied to radio emissions in the ultracool dwarf regime incorporating the many null detections available. We report the early results indicating decreasing trends in each parameter space.

1 Introduction

Even though ultracool dwarf formation is thought to be similar to the theorized stellar formation in earlier spectral types of the main sequence, the two types of objects have very different internal physics (Chabrier & Baraffe, 2000). While most stars are composed of differentiated convective and radiative layers, ultracool dwarfs are fully convective, lacking these differentiated layers. Additionally, their lower mass members do not fuse hydrogen at all. This group of objects, composed of both the lowest mass red dwarfs and of brown dwarfs, is united by their fully convective nature and their electrically neutral atmospheres (Mohanty *et al.*, 2002). Observations in the ultracool dwarf regime indicate magnetic fields in ultracool dwarfs can be on the order of kG, sometimes rivaling the strength of the sun's magnetic field (Williams *et al.*, 2015).

While it is theorized that magnetic activity in solar-type stars is driven by shearing at the tachocline (Parker, 1955), or the interface between the star's radiative and convective layers, ultracool dwarfs lack these layers and therefore cannot be driven by such a dynamo. While theories have been proposed that the ultracool dwarf dynamo is likely more similar to those of gas giants such as Jupiter (Schrijver, 2009), the exact observable properties of resulting magnetic fields remain unclear. This study seeks to provide observational constraints on these current theories.

1.1 Sample Construction

To study magnetic activity in ultracool dwarfs, we searched the literature in order to construct the largest sample to date of radio detections in this mass regime. Radio emission is a powerful proxy for magnetic activity since it originates from particle interactions with the stellar magnetic field. Our sample is composed of detections obtained from the updated Very Large Array (VLA) and the Australia Telescope Compact Array (ATCA) and available in the literature (Antonova *et al.*, 2013; Williams *et al.*, 2014, 2015; Kao *et al.*, 2016; Lynch *et al.*, 2016). Spectral type and rotation rate ($v\sin i$) measurements have been taken from the literature. Our temperature calculations follow the methods of Filippazzo *et al.* (2015) at the end of and beyond the main sequence.

The sample is shown in Figure 1 and is composed largely of upper limits. This sample has large uncertainties, often on both axes, and high intrinsic scatter.

2 Radio Emission Trends

To take advantage of all the information available in the uncertainties, since data on this end of the main sequence is often challenging to collect, we utilize a rigorous Bayesian analysis. This is the first analysis of this kind on such a large sample of radio emission in the ultracool dwarf regime.

2.1 Creating a Bayesian Routine

We employed the statistical model created and recommended by Kelly (2007) for specific use with analyzing linear trends in astronomical datasets containing many upper limits and heteroscedastic uncertainty across both the independent and dependent variables. The Kelly method estimates the distribution of independent variables as a weighted sum of Gaussians, where upper limits are given a lower weight and a larger likelihood distribution. Kelly's IDL code for this method is available online, and furthers the calculation process by running the models through a Markov Chain Monte

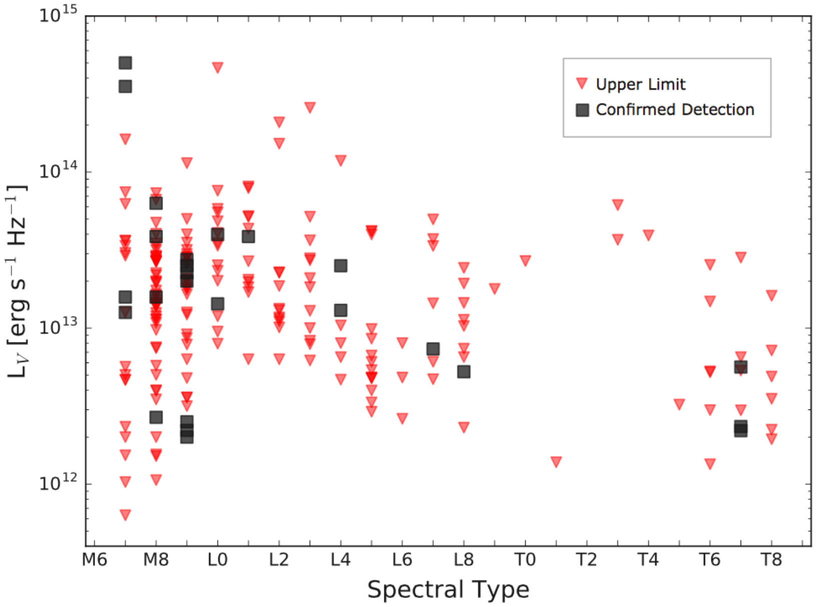

Figure 1: A sample of 196 ultracool dwarf radio detections collected from the literature. Confirmed detections are shown as black squares and upper limits are shown as red triangles.

Carlo (MCMC) routine to search for many iterations of likely distributions. For the purpose of this project, we used Josh Meyer's Python translation of the Kelly method, linmix[1].

2.2 Trends in Several Parameter Spaces

Observational trends in radio emissions can provide insight into the potential sources for ultracool dwarf magnetic activity. Therefore, we analyze the emission as a generalized linear function of several fundamental parameters — spectral type, temperature, and $v\sin i$ — to look for initial trends.

We show the relationship between spectral type and radio emission in Figure 1. The black circles indicate confirmed observations of radio emission, and the grey inverted triangles show the upper limits. The black trend line is the mean average of all the possible MCMC outcomes, which are shown in the blue lines. As can be seen, radio emission appears to decrease as we progress to later spectral types, indicating a decrease in magnetic activity too. However, spectral types in this regime are not exclusively dependent on temperature, and can be influenced by gravity, metallicity, and dusty atmospheres as well (Cruz *et al.*, 2009).

Due to the problems with spectral types we chose to look at temperature instead. Not only does temperature provide a continuous variable, as opposed to the discrete parameter of spectral type, but it can also provide insight into how magnetic fields might change as ultracool dwarfs cool over time. We show the relationship between temperature and radio emission in Figure 2. Here too, the radio emission, and by proxy, magnetic activity, shows a decrease with temperature, but the variance of temperature distributions are larger than those of spectral type, and the decreasing trend becomes less reliable. Some of the individual MCMC lines show an increase in emission as temperature decreases.

Lastly, we show the relationship between rotation rate and radio emission in Figure 3. Due to their low luminosities, $v\sin i$ measurements are challenging to measure in the ultracool dwarf regime, and many values provided in the literature have large uncertainties. Here too, the results suggest decreasing radio emission with decreasing $v\sin i$, but the simple linear regression does not properly account for the intrinsic scatter and variability within the dataset.

3 Ongoing Work

Although linear regression trends do provide initial insight on the influence of spectral type, temperature, and $v\sin i$ on ultracool dwarf magnetic activity, they do not account fully for the scatter or variance of emission detections and upper limits.

To better account for the scatter and variance in radio emission observations, we can expand our current Bayesian routine to account for the vertical spread in each parameter space of our dataset. We will analyze a symmetric distribution of the data around the mean line, using again an MCMC routine across the variables to provide insight into all probable model iterations. We can then use these iterations to test more complex models of radio emission, including expectations of emission patterns according to current ultracool dwarf dynamo theory.

Additionally, we will be testing our dataset for the possibility of multiple populations. We will investigate models with two or more populations of ultracool dwarfs: those that are confirmed to be magnetically active and those that are not. We will employ current mixture model methods to separate out subpopulations, testing for different emission trends among the fundamental parameters in the different populations. A mixture model analysis will allow us to probe not only possible causes for magnetic activity in ultracool

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[1] https://github.com/jmeyers314/linmix

dwarfs, but could also indicate different formation mechanisms and/or different internal structure.

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References

Antonova, A., Hallinan, G., Doyle, J. G., Yu, S., Kuznetsov, A., *et al.* 2013, A&A, 549, A131.

Chabrier, G. & Baraffe, I. 2000, Annual Review of Astronomy and Astrophysics, 38, 337.

Cruz, K. L., Kirkpatrick, J. D., & Burgasser, A. J. 2009, The Astronomical Journal, 137, 3345.

Filippazzo, J. C., Rice, E. L., Faherty, J., Cruz, K. L., Van Gordon, M. M., *et al.* 2015, The Astrophysical Journal, 810, 158.

Kao, M. M., Hallinan, G., Pineda, J. S., Escala, I., Burgasser, A., *et al.* 2016, The Astrophysical Journal, 818, 24.

Kelly, B. C. 2007, The Astrophysical Journal, 665, 1489.

Lynch, C., Murphy, T., Ravi, V., Hobbs, G., Lo, K., *et al.* 2016, Mon. Not. R. Astron. Soc., 457, 1224.

Mohanty, S., Basri, G., Shu, F., Allard, F., & Chabrier, G. 2002, The Astrophysical Journal, 571, 469.

Parker, E. N. 1955, The Astrophysical Journal, 122, 293.

Schrijver, C. J. 2009, The Astrophysical Journal, 699, L148.

Williams, P. K. G., Casewell, S. L., Stark, C. R., Littlefair, S. P., Helling, C., *et al.* 2015, The Astrophysical Journal, 815, 64.

Williams, P. K. G., Cook, B. A., & Berger, E. 2014, The Astrophysical Journal, 785, 9.

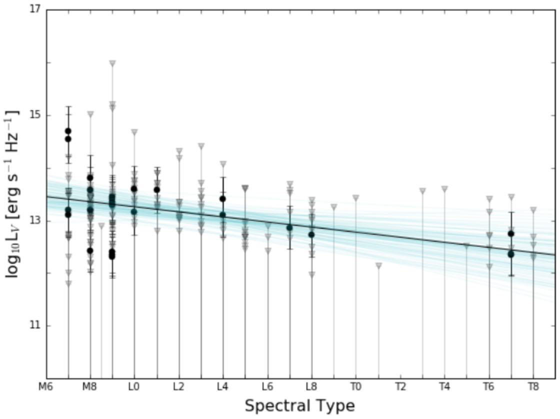

Figure 2: Radio luminosity as a function of spectral type. Black circles indicate confirmed radio detections and grey triangles indicate upper limits. Every 25th MCMC iteration is shown in blue, and the mean line of all the iterations is shown in black.

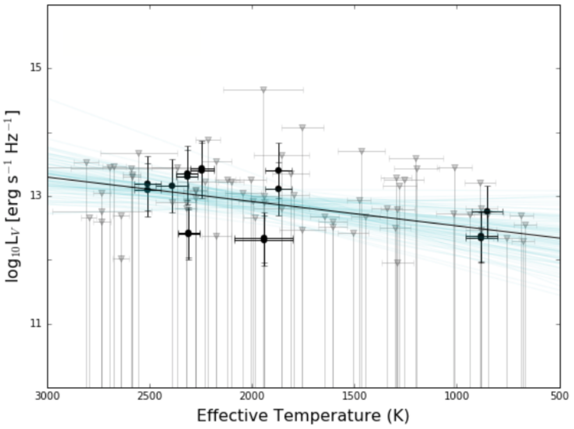

Figure 3: Radio luminosity as a function of temperature. Note that some MCMC iterations show an increasing trend.

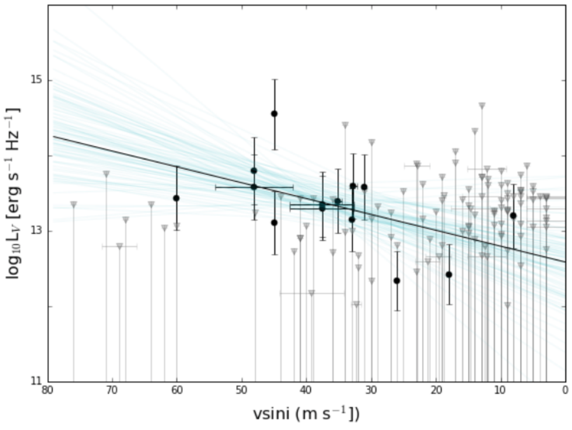

Figure 4: Radio luminosity as a function of $v\sin i$. There are large uncertainties on both axes.