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Correlations between Ca II H&K Emission and the Gaia M dwarf Gap

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ABSTRACT

Previous work has demonstrated a paucity of Hydrogen Alpha emission at the same Gaia G Magnitude as the Jao Gap in the solar neighborhood. The exact mechanism which results in this paucity is as yet unknown; however, the authors of the originating paper suggestion that it may be the result of complex variations to a stars magnetic topology driven by the Jao Gaps characteristic formation and breakdown of stars radiative transition zones. Here I present a brief summary of a potential extension to this work looking at Ca II H&K emission lines. Preliminary work with archival data shows a much stronger correlation between the calcium emission lines and the Jao Gap than was observed between hydrogen emission and the Jao Gap. If this observation withstands further testing then it may provide a new way to locate the gap in populations which lack the large counting statistics currently required — and which are only practically available from Gaia data at moment.

Keywords: Stellar Evolution (1599) — Stellar Evolutionary Models (2046)

1. INTRODUCTION

Due to the initial mass requirements of the molecular clouds which collapse to form stars, star formation is strongly biased towards lower mass, later spectral class stars when compared to higher mass stars. Partly as a result of this bias and partly as a result of their extremely long main-sequence lifetimes, M Dwarfs make up approximately 70 percent of all stars in the galaxy. Moreover, some planet search campaigns have focused on M Dwarfs due to the relative ease of detecting small planets in their habitable zones (e.g. Nutzman & Charbonneau 2008). M Dwarfs then represent both a key component of the galactic stellar population as well as the possible set of stars which may host habitable exoplanets. Given this key location M Dwarfs occupy in modern astronomy it is important to have a thorough understanding of their structure and evolution.

Jao et al. (2018) discovered a novel feature in the Gaia Data Release 2 (DR2) $G_{BP} - G_{RP}$ color-magnitude-diagram. Around $M_G = 10$ there is an approximately 17 percent decrease in stellar density of the sample of stars Jao et al. (2018) considered. Subsequently, this has become known as either the Jao Gap, or Gaia M Dwarf Gap. Following the initial detection of the Gap in DR2 the Gap has also potentially been observed in 2MASS (Skrutskie et al. 2006; Jao et al. 2018); however, the significance of this detection is quite weak and it relies on the prior of the Gap's location from Gaia data. Further, the Gap is also present in Gaia Early Data Release 3 (EDR3) (Jao & Feiden 2021). These EDR3 and 2MASS data sets then indicate that this feature is not a bias inherent to DR2.

The Gap is generally attributed to convective instabilities in the cores of stars straddling the fully convective transition mass (0.3 - 0.35 $M_\odot$) (Baraffe & Chabrier 2018). These instabilities interrupt the normal, slow, main sequence luminosity evolution of a star and result in luminosities lower than expected from the main sequence mass-luminosity relation (Jao & Feiden 2020).

The Jao Gap, inherently a feature of M Dwarf populations, provides an enticing and unique view into the interior physics of these stars (Feiden et al. 2021). This is especially important as, unlike more massive stars, M Dwarf seismology is infeasible due to the short periods and extremely small magnitudes which both radial

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and low-order low-degree non-radial seismic waves are predicted to have in such low mass stars (Rodríguez-López 2019). The Jao Gap therefore provides one of the only current methods to probe the interior physics of M Dwarfs.

(Jao et al. 2023) identify the Jao gap as a strong discontinuity point for activity in M dwarfs. Two primary observations from their work are that the Gap serves as a boundary where very few active stars in their sample of 640 M dwarfs exist below the gap and that the overall downward trend of activity moving to fainter magnitudes is anomalously high in within the 0.2 mag range of the gap. Their figures 3 and 13 are of particular relevance here and have been included below for convince. Based on previous work from Spada & Lanzafam 2020, Curtis et al. 2020, and Dungee et al. 2022 the authors propose that the mechanism resulting in the reduced fraction of active stars within the gap is that as the radiaive zone disipates due to core expansion, angular momentum from the outter convective zone is dumped into the core resulting in a faster spin down than would otherwise be possible. Effectively the core of the star acts as a sink, reducing the amount of angular momentum which needs to be lost by magnetic breaking for the outer convective region to reach the same angular velocity. Given that Hα emission is strongly coupled magnetic activity in the lower photosphere and that a stars angular velocity is a primary factor in its magnetic activity, a faster spin down will serve to more quickly dampen Hα activity.

2. CORRELATION

Using Ca II H&K emission data from Boudreaux et al. (2022) and Perdelwitz et al. (2021) (quantified using the R_{HK} metric) we investigate the correlation between the Jao Gap magnitude and stellar magnetic activity. We are more statistically limited here than past authors have been due to therequirment for high resolution spectoscopic data when measuring Calcium emission; however, this is balanced by the aparent stronger correlation between Cacium emission and the Jao gap when compared to Hα emission.

The merged dataset is presented in Figure 1. There is a visual discontinuity around the Jao Gap mangitude; however, this manifests as an increase in the spread of the emission measurments rather than a change in the mean value. In order to quantify the signifigance of this discontinuity we measure the false alarm probaility of the change in standard deviation.

First we split the merged dataset into bins with a width of 0.5 mag. In each bin we measure the standard deviation about the mean of the data. The results

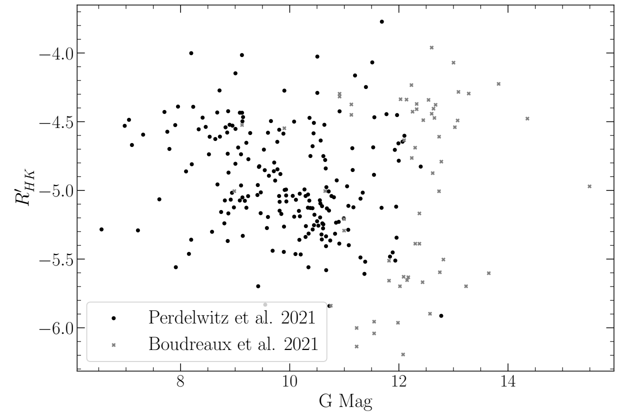

Figure 1. Merged Dataset from Boudreaux et al. (2022); Perdelwitz et al. (2021). Note the increase in the spread of R'_{HK} around the Jao Gap Magnitude.

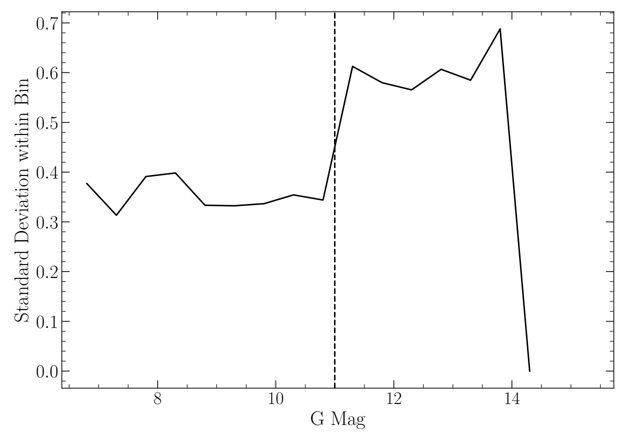

Figure 2. Standard deviation of Calcium emission data within each bin. Note the discontinuity near the Jao Gap Magnitude.

of this are shown in Figure 2. In order to measure the false alarm probabililty of this discontinuity we first resample the merged calcium emission data based on the associated uncertanties for each datapoint as presented in their respective publications. Then, for each of these "resample trials" we measure the probility that a change in the standard deviation of the size seen would happen purley due to noise. Results of this test are show in in Figure 3.

This rapid increase star-to-star variability would only arise due purley to noise 0.3 ± 0.08 percent of the time and is therefore likeley either a true effect or an alias of some sample bias. COME BACK TO HERE TO FLUSH OUT SAMPLE BIAS SECTION.

If the observed increase in variability is not due to a sample bias and rather is a physically driven effect then there is an obvious similarity between these findings and those of (Jao et al. 2023). Specifically we find a increase

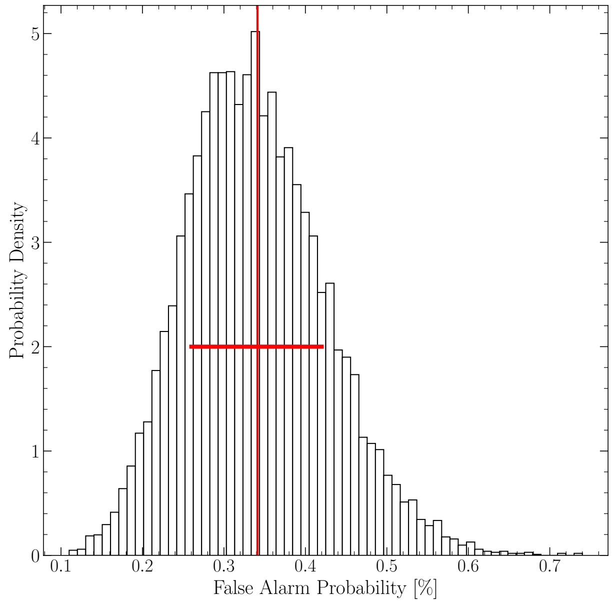

Figure 3. Probability distribution of the false alarm probability for the discontinuity seen in Figure 2. The mean of this distribution is $0.341\%\pm^{0.08}_{0.08}$.

in variability just below the magnitude of the gap. Moreover, this variability increase is primarily driven by an increase in the number of low activity stars (as opposed to an increase in the number of high activity stars). We can further investigate the observed change in variability for only low activity stars by filtering out those stars at or above the saturated threshold for magnetic activity. Boudreaux et al. (2022) identify $\log(R'_{HK}) = -4.436$ as the saturation threshold. We adopt this value and filter out all stars where $\log(R'_{HK}) \geq -4.436$. Applying the same analysis to this reduced dataset as was done to the full dataset we still find a discontinuity at the same location (Figure 4). This discontinuity is of a smaller magnitude and consequently is more likley to be due purley to nouse, with a 7 ± 0.2 percent false alarm probability. This false alarm probility is however only concerned with the first point after the jump in variability. If we consider the false alarm probability of the entire high variabilty region then the probability that the high variability region is due purley to noise drops to 1.4 ± 0.04 percent.

We observe a strong, likeley statistically signifigant, discontinuty in the star-to-star variability of Ca II K & K emission coincident with the magnitude of the Jao Gap. However, modeling is required to determine if this discontinuty may be due to the same underlying physics.

3. MODELING

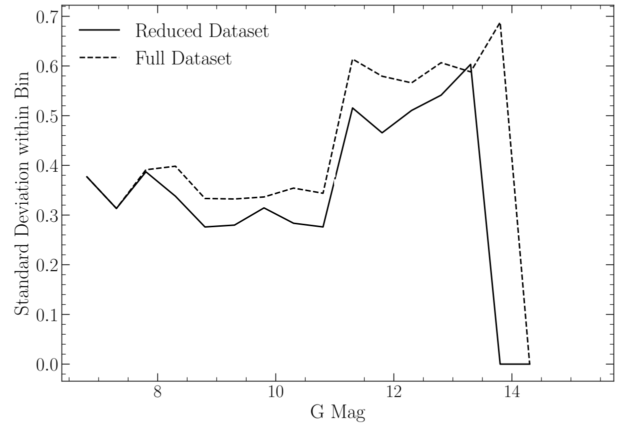

Figure 4. Spread in the magnetic activity metric for the merged sample with any stars $\log(R'_{HK}) > -4.436$ filterd out.

One of the most pressing questions related to this work is whether or not the increased star-to-star variability in the activity metric and the Jao Gap, which are coincident in magnitude, are driven by the same underlying mechanism. The challenge when addressing this question arrises from current computational limitations. Specifically, the kinds of three dimensional magnetohydrodynamical simulations — which would be needed to derive the effects of convective kissing instabilities on the magnetic field of the star — are infeasible to run over gigayear timescales while maintaing thermal timescale resolutions needed to resolve periodic mixing events.

In order to address this and answer the specific question of *could kissing instabilities result in increased star-to-star variability of the magnetic field*, we adopt a very simple toy model. Kissing instabilities result in transient radiative zone seperating the core of a star (convective) from its envelope (convective). When this radiative zone breaks down two important things happen: one, the entire star becomes mechanically coupled, and two, convective currents can now move over the entire radius of the star. Jao et al. (2023) propose that this mecahnical coupling may allow the stars core to act as an angular momentum sink thus accelerating a stars spin down and resulting in anomolously low Hα emission.

Regardless of the exact mechanism by which the magnetic field may be effected, it it reasonable to expect that both the mechanical coupling and the change to the scale of convective currents will have some effect on the stars magnetic field. On a microscopic scale both of these will change how packets of charge within a star move and may serve to disrupt a stable dynamo. Therefore, in the model we present here we make only one primary assumption: *every mixing event may modify the stars magnetic field by some amount.* Within our model this assumption manifests as a random linear perturbation applied to some base magnetic field at every mixing event. The strength of this perturbation is sampled from a normal distrubution with some standard deviation, σ_B.

Synthetic stars are sampled from a grid of stellar models evolved using the Dartmouth Stellar Evolution Program (DSEP). Each stellar model was evolved using a high temporal resolution (timesteps no larger than 10,000 years Check this) and typical numerical tolernances of one part in 10^5. Each model was based on a GS98 (Grevesse & Sauval 1998) solar composition with a mass range from 0.3 $M_\odot$ to 0.4 $M_\odot$. Finally, models adopt OPLIB high temperature radiative opacities, Ferguson 2004 low temperature radiative opacities, and include both atomic diffusion and gravitational settling. A Kippenhan-Iben diagram showing the structural evolution of a model within the gap is shown in Figure 5.

Each synthetic star is assigned some base magnetic activiy ($B_0 \sim \mathcal{N}(1, \sigma_B)$) and then the number of mixing events before some age t are counted based on local maxima in the core temperature. The toy magnetic activiy at age t for the model is given in Equation 1. An example of the magnetic evolution resulting from this model is given in Figure 6. Fundamentally, this model presents magnetic activity variation due to mixing events as a random walk and therefore results will increasingly divergence over time.

$$B(t) = B_0 + \sum_i B_i \sim \mathcal{N}(1, \sigma_B) \tag{1}$$

Applying the same analysis to these models as was done to the observations as described in Section X.X we find that this simple model results in a qualitatively similar trend in the standard deviation vs. magnitude graph (Figure 7). The interpretation here is important, what this qualitative similarity demonstrates is that it may be reasonable to expect kissing instabilities to result in the observed increased star-to-star variation. Importantly, we are not able to claim that kissing instabilities *do* lead to these increased variations, only that they reasonably could. Further modeling, observational, and theoretical efforts will be needed to more definitivley answer this question.

3.1. *Limitations*

The model presented in this paper is very limited and it is important to keep those limitations in mind when interpreting the results presented here. Some of the main challenges which should be leveled at this model are the assumption that the magnetic field will be altered by some small random perturbation at every ixing event. This assumption was informed by the large number of free parameters avalible to a physical star during the establishment of a large scale magnetic field and the associated likeley stocastic nature of that process. However, it is similarly belivable that the magnetic field will tend to alter in a uniform manner at each mixing event. For example, since differnetial rotation is generally proportinal to the temperature gradient within a star and activity is strongly coupled to differential rotation then it may be that as the radiative zone reforms over thermal timescales the homoginization of angular momentum throughout the star results in overall lower amounts of differential rotation each after mixing event than would otherwise be present.

Moreover, this model does not consider how other degenerate sources of magnetic evolution such as stellar spin down, relaxation, or choronal heating may effect star-to-star variability. These could convably lead to a similar increase in star-to-star variability which is concident with the Jao Gap magnitude as the switch from fully to partially convective may effect efficienty of these process.

4. CONCLUSION

The Jao Gap provides an intriguing probe into the interior physics of M Dwarfs stars where traditional methods of studying interiors break down. However, before detailed physics may be inferred it is essential to have models which are well matched to observations. Here we investigate whether the OPLIB opacity tables reproduce the Jao Gap location and structure more accurately than the widely used OPAL opacity tables. We find that while the OPLIB tables do shift the Jao Gap location more in line with observations, by approximately 0.05 magnitudes, the shift is small enough that it is likely not distinguishable from noise due to population age and chemical variation. However, future measurement of [Fe/H] for stars within the gap will be helpful in constraining the degree to which the gap should be smeared by these theoretical models.

We also find that both the color and magnitude of the Jao Gap are correlated to the convective mixing length parameter. Specifically, a lower mixing length parameter will bring the gap in the populations presented in this paper more in line with the current best estimate for the actual gap magnitude. Using this relation it may be possible for mixing length to be calibrated for low mass stars such that models match the Jao Gap location. Further, the Jao gap location may provide a test of alternative convection models such as entropy calibrated convection (Spada et al. 2021). Both of these potential uses require careful handeling of other uncertanties such

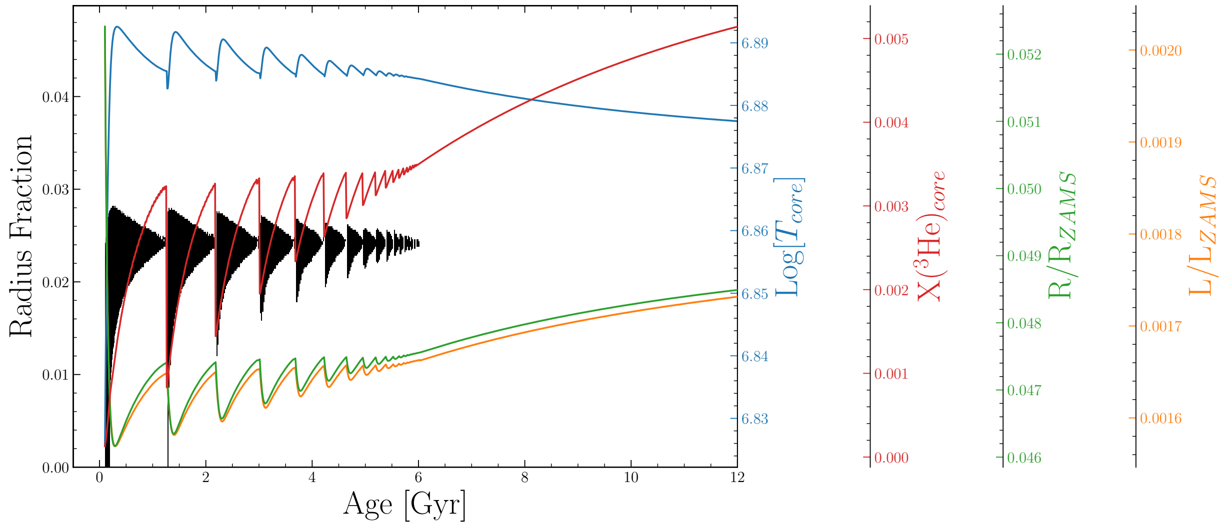

Figure 5. Kippenhan-Iben diagram for a 0.345 solar mass star. Note the periodic mixing events (where the plotted curves peak).

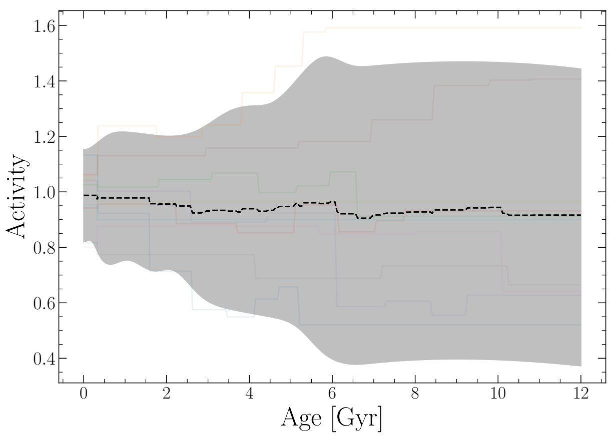

Figure 6. Example of the toy model presented here resulting in increased divergence between stars magnetic fields. The shaded region represents the maxium spread in the two point correlation function at each age.

as the uncertanties in bolometric correction, popupulation composition, and population age. As we currently do not have reason to suspect that the mixing length for the low mass stars in the DR2 and ERD3 CMD is substantially lower than that of the sun we leave the investigation of these potential additionl uses for future work.

Finally, we do not find that the OPLIB opacity tables help in reproducing the as yet unexplained wedge shape of the observed Gap.

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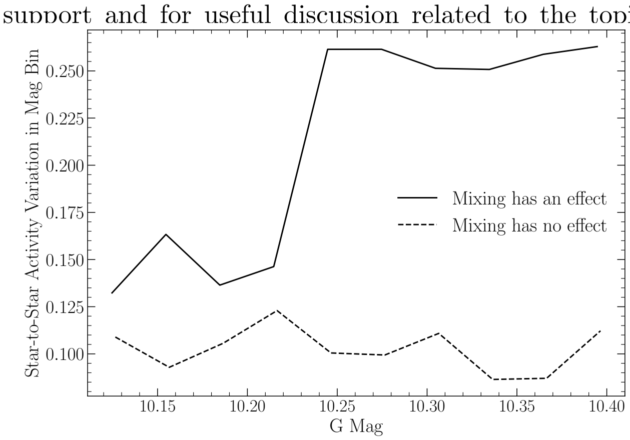

Figure 7. Toy model results showing a qualitivativley similar discontinuoty in the star-to-star magnetic activity variability.

Software: The Dartmouth Stellar Evolution Program (DSEP) (Dotter et al. 2008), `BeautifulSoup` (Richardson 2007), `mechanize` (Chandra & Varanasi 2015), `FreeEOS` (Irwin 2012), `pyTOPSScrape` (Boudreaux 2022)

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