An Empirical Correction for Activity Effects on the Temperatures, Radii, and Estimated Masses of Low-Mass Stars and Brown Dwarfs

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We present empirical relations for determining the amount by which the effective temperatures and radii—and therefore the estimated masses—of low-mass stars and brown dwarfs are altered due to chromospheric activity. Our relations are based on a large set of well studied low-mass stars in the field and on a set of benchmark low-mass eclipsing binaries. The relations link the amount by which an active object’s temperature is suppressed, and its radius inflated, to the strength of its H\textalpha emission. These relations are found to approximately preserve bolometric luminosity. We apply these relations to the peculiar brown-dwarf eclipsing binary 2M0535–05, in which the active, higher-mass brown dwarf has a cooler temperature than its inactive, lower-mass companion. The relations correctly reproduce the observed temperatures and radii of 2M0535–05 after accounting for the H\textalpha emission; 2M0535–05 would be in precise agreement with theoretical isochrones were it inactive. The relations that we present are applicable to brown dwarfs and low-mass stars with masses below 0.8 M\odot and for which the activity, as measured by H\textalpha, is in the range \(-4.6 < \log L_{\text{H\textalpha}}/L_{\text{bol}} < -3.3\). We expect these relations to be most useful for correcting radius and mass estimates of low-mass stars and brown dwarfs over their active lifetimes (few Gyr). We also discuss the implications of this work for determinations of young cluster IMFs.

1 Introduction

Observational evidence strongly indicates that the fundamental properties of low-mass stars can be altered in the presence of strong magnetic activity (e.g., Morales et al. 2008; López-Morales 2007; Ribas 2006). In particular, observations of active, low-mass eclipsing binary (EB) stars have found the empirically measured stellar radii (\(R\)) to be inflated by \(\approx10\%\), and the empirically measured stellar effective temperatures (\(T_{\text{eff}}\)) to be suppressed by \(\approx5\%\), relative to the predictions of standard theoretical stellar evolution models, which better match the properties of inactive objects (see Coughlin et al. 2011; Kraus et al. 2011; Morales et al. 2010; Stassun et al. 2009, and references therein). Resolving these discrepancies will be critical to the ongoing development of accurate theoretical stellar models (see Stassun et al. 2010). Accurate estimates of stellar radii are especially important in the context of searches for transiting exoplanets, which rely upon the assumed stellar radius/density to infer the planet radius/density.

Activity effects also lead to errors in object masses (\(M\)) when these are derived from \(T_{\text{eff}}\). A particularly salient example is 2M0535–05, an EB in the Orion Nebula Cluster (age \(\approx1 \text{ Myr}\)) comprising two brown dwarfs (Stassun et al. 2006, 2007). The primary and secondary brown dwarf (BD) components of 2M0535–05 have dynamically measured masses of 60±3 and 39±2 M\textsubscript{Jup}, respectively, and \(T_{\text{eff}}\) ratio of \(T_1/T_2 = 0.952\pm0.004\) (Gómez Maqueo Chew et al. 2009). That is, the system exhibits a reversal of the usual \(M-T_{\text{eff}}\) relation, such that the primary component is cooler than its companion. Figure 1 shows the 2M0535–05 system on the Hertzsprung-Russell (H-R) diagram. The secondary BD’s \(T_{\text{eff}}\) and bolometric luminosity (\(L_{\text{bol}}\), calculated directly from the empirically measured \(T_{\text{eff}}\) and \(R\)) place it at a position that is consistent with that predicted by the model isochrone. In contrast, the primary is far displaced from its expected position, and so appears to have a mass of only \(\sim25\ M_{\text{Jup}}\)—more than a factor of 2 lower than its true mass—on the basis of its low \(T_{\text{eff}}\). Reiners et al. (2007) used spectrally resolved H\textalpha measurements to show that, whereas the secondary BD in 2M0535–05 is chromospherically quiet, the primary BD is highly chromospherically active, perhaps a consequence of its rapid rotation.

Since magnetic activity seems to alter the fundamental properties of both stars and BDs, it would be valuable to have an easily observable metric with which to quantitatively assess the degree to which a given object’s \(T_{\text{eff}}\) has been suppressed and its radius inflated. Here we present such an empirical metric by relating the degree of \(T_{\text{eff}}\) suppression and radius inflation to the strength of H\textalpha emission, a commonly used and readily observable tracer of chromospheric activity (Scholz et al. 2007; Berger 2006).

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2 Methods and Data Used

We use two different samples and approaches to empirically determine a relationship between $T_{\text{eff}}$ suppression, $R$ inflation, and the level of activity as measured from H$\alpha$.

First we use the large set of nearby field M dwarfs with well measured spectral types and H$\alpha$ equivalent widths (EWs) from the PMSU catalog (Reid et al. 1995; Hawley et al. 1996). Following Morales et al. (2008), we restrict ourselves to the sample of 746 stars with distances determined directly from trigonometric parallaxes. Fig. 2 shows the estimated $T_{\text{eff}}$ and $R$ of the PMSU sample stars as a function of $M$. Strongly chromospherically active stars—defined as those with H$\alpha$ in emission—show a clear displacement to lower $T_{\text{eff}}$ and to larger $R$ relative to both the theoretical isochrone and to the non-active stars, whereas non-active stars more closely track the isochrone. From these $T_{\text{eff}}$ and $R$ offsets, and the observed H$\alpha$ emission, we derive linear relationships between $\Delta T_{\text{eff}}$, $\Delta R$, and $\log L_{\text{H}\alpha}/L_{\text{bol}}$ (see Fig. 3). The relationships are statistically significant with $>90\%$ confidence.

The second approach uses the much smaller sample of stars in EBs that have directly measured masses, radii, and reliable $T_{\text{eff}}$, but for which we must use X-ray flux as a proxy for H$\alpha$. We use the small set of low-mass EBs with accurately measured $M$, $R$, $T_{\text{eff}}$, and X-ray luminosities ($L_X$) from López-Morales (2007). The sample includes 11 individual stars in 7 EB systems spanning the range $T_{\text{eff}}=3125$–$5300$ K and $M=0.21$–$0.96$ M$\odot$. We begin with the correlation of $\Delta R$ vs. $L_X/L_{\text{bol}}$ already demonstrated in that work, which we rederived using the fundamental stellar data compiled in López-Morales (2007) and the same 3 Gyr isochrone of Baraffe et al. (1998) as above.

Fig. 1 H-R diagram for the primary and secondary BD components of the EB 2M0535–05 in the ~1-Myr Orion Nebula Cluster (Stassun et al. 2006, 2007). The measured $T_{\text{eff}}$ and $L_{\text{bol}}$ for both BDs are represented as blue symbols. Measurement uncertainties in $T_{\text{eff}}$ and $L_{\text{bol}}$ are represented by the error bars at upper right. The dynamically measured masses of the primary and secondary are represented as red bars on the 1-Myr theoretical isochrone of Baraffe et al. (1998). The measured $L_{\text{H}\alpha}/L_{\text{bol}}$ for the two components are indicated next to the blue symbols. The active primary appears far cooler than expected, and therefore appears to be much younger than the secondary and to have a mass of only $\approx 27$ M$\text{Jup}$ based on its observed $T_{\text{eff}}$, a factor of 2 lower than its true mass. Shifting the position of the active primary (arrow) using our empirically calibrated H$\alpha$-based relations brings the primary into much closer agreement with its theoretically expected position in the HR diagram (black symbol); this is where the active primary would be if it were not active.

Fig. 2 $T_{\text{eff}}$ vs. Mass (top) and Radius vs. Mass (bottom) for M-dwarfs with trigonometric distances and H$\alpha$ measurements from the PMSU catalog. Active objects (H$\alpha$ in emission) are filled symbols. Solid curve is a 3 Gyr isochrone (Baraffe et al. 1998). Dashed curve is a polynomial fit to the non-active objects. H$\alpha$-active dwarfs are significantly displaced to lower $T_{\text{eff}}$ and larger radii compared to both the isochrone and to the non-active dwarfs.
so we also derive the relationship $\Delta T_{\text{eff}}$ vs. $L_X/L_{\text{bol}}$. Next we use the empirical $L_X/L_{\text{bol}}$ vs. $L_{\text{H}\alpha}/L_{\text{bol}}$ relationships of Scholz et al. (2007) and Delfosse et al. (1998) convert the above from relationships on $L_X/L_{\text{bol}}$ into relationships on $L_{\text{H}\alpha}/L_{\text{bol}}$. The resulting relationships between $\Delta T_{\text{eff}}$, $\Delta R$, and $\log L_{\text{H}\alpha}/L_{\text{bol}}$ (Fig. 3) are statistically significant with $>95\%$ confidence.

![Fig. 3](image_url)

Fig. 3 $T_{\text{eff}}$ suppression (top) and radius inflation (bottom) as a function of fractional $\text{H}\alpha$ luminosity for both field M-dwarfs (filled symbols) and low-mass eclipsing binaries (error bars). Linear fit relations to both sets are dashed lines. The final averaged best-fit relation the solid line. See text for the linear fit coefficients.

3 Empirical Relations Linking Radius Inflation and $T_{\text{eff}}$ Suppression to $\text{H}\alpha$ Emission

Combining the results from the field M dwarfs and EBs, we obtain the following final relations (in percent units):

$$\frac{\Delta T_{\text{eff}}}{T_{\text{eff}}} = (-4.71 \pm 2.33) \times (\log L_{\text{H}\alpha}/L_{\text{bol}} + 4) + (-4.4 \pm 0.6)$$

$$\frac{\Delta R}{R} = (15.37 \pm 2.91) \times (\log L_{\text{H}\alpha}/L_{\text{bol}} + 4) + (7.1 \pm 0.6).$$

As an example of how the apparent mass of an object can be altered by activity, we calculate how the observed H-R diagram positions of the two BDs in 2M0535$-$05 are altered by the above relations. In effect, we are seeing how the 2M0535$-$05 system would appear in the H-R diagram were the system completely inactive. We use the $L_{\text{H}\alpha}/L_{\text{bol}}$ measurements of Reiners et al. (2007) shown in Fig. 1. We find that the primary BD has been displaced by $\Delta T_{\text{eff}} = -6.9 \pm 1.4\%$ and $\Delta R = 15.2 \pm 1.7\%$, and the secondary BD by at most $\Delta T_{\text{eff}} = -3.0 \pm 0.9\%$ and $\Delta R < 2.5 \pm 1.1\%$ (implying nearly constant $L_{\text{bol}}$ for both). Shifting the position of the primary BD accordingly (Fig. 1) shows that, if it were inactive, it would be in excellent agreement with the theoretically expected position for its known mass.

4 Impact on Inferred Initial Mass Functions

The vast majority of masses for stars and BDs in young clusters can only be determined by comparison with theoretical evolutionary tracks in H-R diagrams, using either $L_{\text{bol}}$ or $T_{\text{eff}}$ or both (e.g., Scholz et al. 2012). Therefore, if there is indeed a relation between magnetic activity and $R$ inflation / $T_{\text{eff}}$ suppression, this will also affect estimates of stellar and substellar masses derived from $T_{\text{eff}}$, especially at young ages when activity levels are high. Here we examine the two ways of estimating masses—$T_{\text{eff}}$ and $L_{\text{bol}}$—that are commonly used in the literature and investigate the impact of magnetic activity on the derived masses.

First we use $T_{\text{eff}}$ to estimate masses from model isochrones at 1 Myr. At each model mass, we consider a range of activity levels and apply offsets to the model $T_{\text{eff}}$ based on our empirical relations above. We then use these $T_{\text{eff}}$ values to estimate the masses that would be inferred from the isochrone. As expected, this procedure leads to a systematic underestimation of the masses. At high levels of activity, the effect can be substantial. For $L_{\text{H}\alpha}/L_{\text{bol}} = -3.3$, which corresponds to the saturation limit in young low-mass stars and in young associations (Scholz et al. 2007), the mass estimates are a factor of $\sim 2$ lower than for objects with low levels of magnetic activity ($\log L_{\text{H}\alpha}/L_{\text{bol}} < -4.5$). Note that because the mass--$T_{\text{eff}}$ relationship is less steep at older ages, the underestimation of mass is less severe at older ages ($> 100$ Myr).

In the second test case, we use $L_{\text{bol}}$ derived from $K$-band absolute magnitudes to derive masses. In this case the influence of magnetic activity is introduced by the $T_{\text{eff}}$ dependence of the bolometric correction, since $L_{\text{bol}}$ is (as discussed above) practically not affected. We compute spectral types from the suppressed values of $T_{\text{eff}}$, and then compute $K$-band bolometric corrections from the spectral types, and we combine these with the model $K$-band absolute magnitudes to find $L_{\text{bol}}$. Finally, we estimated masses from the model isochrone and $L_{\text{bol}}$. This second method still leads to an underestimate of the masses, but the effect is much smaller than when directly estimating masses from $T_{\text{eff}}$. The change of the bolometric corrections with increasing magnetic activity is quite small (at most 10\%), resulting in relatively minor changes of a few percent in the mass estimate.
An important application of $T_{\text{eff}}$-based mass estimates is the determination of initial mass functions (IMFs) for young clusters. M-dwarfs with ages from 10 to 100 Myr exhibit H$\alpha$ emission in the range $\log L_{H\alpha}/L_{\text{bol}} = -4.2$ to $-3.3$ (Scholz et al. 2007). Thus, our analysis implies that objects inferred to be BDs from $T_{\text{eff}}$-based (or spectral type based) mass estimates could actually be low-mass stars since masses will be underestimated by up to a factor of 2.

We further evaluated the impact of this effect on measurements of the slope of the IMF, $\alpha$ (in $dN/dM \propto M^{-\alpha}$). For this purpose, we assume a measured slope of $\alpha = 0.6$ (see Scholz et al. 2012), calculate the IMF based on that slope for $M < 0.6 M_\odot$, correct the masses for a given level of H$\alpha$ emission using our relations above, and re-determine the slope $\alpha$. If we start with $\log L_{H\alpha}/L_{\text{bol}} = -4.0$ for BDs and $-3.5$ for low-mass stars (Barrado et al. 2003), the masses have to be corrected by factors of 1.3–1.7 for BDs, and by 2.2–2.5 for low-mass stars. As a result, the slope changes from $\alpha = 0.6$ to $\alpha = 0.5$. In general, we expect that $\alpha$ will be underestimated by $\gtrsim 0.1$, if the masses are estimated from $T_{\text{eff}}$ and activity is not taken into account. In addition, the peak mass of the IMF would be underestimated by up to a factor of 2.

## 5 Discussion

It remains unclear what is the underlying physical mechanism driving the correlations between $\Delta T_{\text{eff}}$, $\Delta R$, and $L_{H\alpha}$. Chabrier et al. (2007) and MacDonald & Mullan (2009) have suggested that a sufficiently strong field could suppress convection, inhibit heat transfer, and thus inflate (and cool) the stellar surface. Since such a field would also likely result in chromospheric activity, one might therefore expect the correlations with H$\alpha$ emission that we have derived.

Browning (2008) has shown in global numerical models that fully convective stars can host large kG strength fields. However, such fields alone appear to be too weak to produce the radius inflation and $T_{\text{eff}}$ suppression observed in 2M0535–05 (MacDonald & Mullan 2009). Chabrier et al. (2007) also suggest that fully convective objects should be less affected by the same convective inefficiencies invoked to explain radius discrepancies at higher masses. It is possible that a combination of rotation and magnetic activity contribute to both inflation/suppression and H$\alpha$ emission in such a way as to produce our empirical relation without a causal correspondence between H$\alpha$ and the magnetic field.

An alternative explanation for $T_{\text{eff}}$ suppression is a spot covered surface. Since spot coverage is also controlled by magnetic fields, a correlation with H$\alpha$ might still exist. However, Mohanty et al. (2010) and Mohanty & Stassun (2012) have now shown from a spectral fine-analysis of the 2M0535–05 system, observed at high resolving power during both primary and secondary eclipses, that such a large-spot scenario is strongly disfavored as an explanation for the $T_{\text{eff}}$ suppression of the primary BD in 2M0535–05. Thus, while the $T_{\text{eff}}$ suppression mechanism produces a clear correlation with chromospheric H$\alpha$ activity as we have shown here, it evidently does not in all cases effect this correlation directly through surface spots.

## 6 Conclusions

We have shown that there exists a correlation between the strength of H$\alpha$ emission in active M-dwarfs, and the degree to which their $T_{\text{eff}}$ are suppressed and radii inflated compared with inactive objects and theoretical evolutionary models. Our relationships above should prove directly useful for a variety of applications in which accurate estimates of masses and radii are needed for low-mass stars and BDs, and should assist in correcting inferred initial mass functions at young ages.

While promising, the correlations we have derived contain significant scatter, and they are currently limited by the lack of a single sample of stars with both H$\alpha$ and direct radius measurements. We therefore encourage researchers to publish H$\alpha$ measurements, as this is usually available from the spectra used to determine EB radial velocities.

Finally, the relations we have determined already indicate quite clearly that the radius inflation and temperature suppression mechanism operates in such a way that the temperature suppression and radius inflation almost exactly cancel in terms of their effect on the bolometric luminosity. Moreover, the relations between activity, $T_{\text{eff}}$ suppression, and radius inflation do not appear to manifest any obvious discontinuity across the fully convective transition (see also Stassun et al. 2010). These are important, fundamental clues to the physical nature of these effects, and should help to constrain theoretical models that are being developed to explain these phenomena (e.g., Chabrier et al. 2007; MacDonald & Mullan 2009).

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