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THE IMPACT OF CHROMOSPHERIC ACTIVITY ON OBSERVED INITIAL MASS FUNCTIONS

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ABSTRACT

Using recently established empirical calibrations for the impact of chromospheric activity on the radii, effective temperatures, and estimated masses of active low-mass stars and brown dwarfs, we reassess the shape of the initial mass function (IMF) across the stellar/substellar boundary in the Upper Sco star-forming region (age $\sim$ 5–10 Myr). We adjust the observed effective temperatures to warmer values using the observed strength of the chromospheric Hα emission, and redetermine the estimated masses of objects using pre-main-sequence evolutionary tracks in the H-R diagram. The effect of the activity-adjusted temperatures is to shift the objects to higher masses by 3%–100%. While the slope of the resulting IMF at substellar masses is not strongly changed, the peak of the IMF does shift from $\approx$0.06 to $\approx$0.11 $M_\odot$. Moreover, for objects with masses $\lesssim 0.2\ M_\odot$, the ratio of brown dwarfs to stars changes from $\sim$80% to $\sim$33%. These results suggest that activity corrections are essential for studies of the substellar mass function, if the masses are estimated from spectral types or from effective temperatures.

Key words: brown dwarfs – stars: activity – stars: fundamental parameters – stars: low-mass – stars: luminosity function, mass function

Online-only material: color figures

1. INTRODUCTION

A fundamental question in the study of star formation is the mass spectrum of stars produced in young star clusters—the initial mass function (IMF). The IMF encodes the physics from the star formation process, sets the initial conditions for stellar population modeling, and thus informs models of galactic evolution. Empirical IMFs serve as crucial touchstones for many aspects of stellar and galactic astrophysics.

The origin of the IMF and its dependence on environmental factors remains an active area of research (Offner et al. 2013). Substellar objects specifically may provide crucial insight into the IMF as a whole. Consensus is emerging that objects below the deuterium-burning limit ($\sim$13 $M_{\rm Jup}$; Baraffe et al. 1998) can form by the same process as their stellar counterparts (Chabrier et al. 2014). In this unified picture of star formation, the formation of low-mass objects requires nonlinear density fluctuations generated by turbulence. Two other prominent theories for brown dwarf (BD) formation are ejection from their gas reservoir due to three-body interactions, and disk fragmentation around a more massive star due to gravitational instability (Reipurth & Clarke 2001; Bate 2000). Current observational evidence—relatively massive BD disks (Ricci et al. 2014), the continuity of the IMF across the substellar boundary, the discovery of a young BD binary, and a pre-BD in isolation (Luhman et al. 2009; André et al. 2012), as well as the orbital properties of close binaries (Dupuy & Liu 2011)—seems to favor a unified turbulent fragmentation theory.

In the turbulent fragmentation paradigm, turbulence and self-gravity generate a range of density perturbations, which in conjunction with subfragmentation, produce the full range of stellar masses. Because the BDs sample the tail of the distribution, it is possible that their abundance is more sensitive to changes in environment than the IMF as a whole. Indeed, there is some evidence for different populations of low-mass objects from cluster to cluster (Scholz et al. 2013), whereas the evidence for a varying IMF in the Milky Way is absent (see, e.g., Bastian et al. 2010 for a review). As we show in this paper, some of this variation might be due to chromospheric activity contaminating mass determination at the substellar boundary. In contrast, massive elliptical galaxies do show evidence for a bottom heavy IMF (van Dokkum & Conroy 2011); however, it is unlikely that a change in the BD-to-star ratio would be detectable given the uncertainties in the overall mass-to-light ratio.

A first step toward understanding the origins of possible IMF variations is a robust calculation of young cluster IMFs. Determining the masses of objects near the substellar boundary in these regions is crucial because it provides a direct probe of the star formation process. More importantly, young clusters allow us to probe further down the mass function because substellar objects are still relatively bright at young ages.

Empirically determining the IMFs of young clusters is usually done in one of two ways: one can estimate the luminosity function and then convert to a mass function using a theoretical *M*–*L* relationship (e.g., Muench et al. 2003), or one can estimate the masses of the individual stars in the cluster by comparing their position in the H-R diagram with a theoretical isochrone, and then build up the aggregate IMF from those individual masses (e.g., Luhman et al. 2003). In the latter case, the masses can be estimated from effective temperatures ($T_{\rm eff}$) or bolometric luminosities ($L_{\rm bol}$) or a combination of the two. The distribution of stellar masses is usually found to peak between 0.1–0.5 $M_\odot$. In recent years, the ratio of stars to BDs in individual clusters has frequently been used as a simple, quantitative metric to parameterize the IMF in the low-mass regime (e.g., Andersen et al. 2008; Luhman et al. 2003; Scholz et al. 2012), specifically suited to test the various proposed formation scenarios for BDs (see Scholz et al. 2013).

Importantly, stellar masses inferred from $T_{\rm eff}$ measurements can be significantly underestimated if the effects of magnetic activity are not taken into account. There is emerging consensus in the literature that magnetic activity inflates the radii and suppresses the temperatures of low-mass stars (e.g., López-Morales 2007; Morales et al. 2008, 2010; MacDonald & Mullan 2009; Stassun et al. 2012). An active star will present a lower $T_{\rm eff}$ than expected for its mass; the stellar mass inferred from that lower $T_{\rm eff}$ will in turn be lower than the true mass. In Stassun et al. (2012), we used mass, radius, and $T_{\rm eff}$ measurements for a benchmark sample of active field dwarfs and eclipsing binaries to derive empirical relationships between the strength of magnetic activity (as measured by the strength of the Hα chromospheric emission) and the degree of radius inflation and $T_{\rm eff}$ suppression. We found, for example, that a low-mass star near the H-burning limit at an age of a few million years with an Hα-to-bolometric luminosity ratio of $\log L_{\rm H\alpha}/L_{\rm bol} = -3.5$ (i.e., near the chromospheric "saturation" value of -3.3) will have its $T_{\rm eff}$ decreased by $\approx$7% (or $\sim$200 K), and thus its $T_{\rm eff}$-inferred mass will be a factor of $\sim$2 lower than the true mass (see Figure 7 in Stassun et al. 2012).

In this paper, we perform an initial assessment of the impact of such chromospheric effects on the inferred shape of the bottom of the IMF of a young cluster when the stellar masses are determined from observed $T_{\rm eff}$ measurements. We use Upper Sco as our first test region for this experiment (see Preibisch & Hans 1999; Preibisch et al. 2001, 2002; Ardila et al. 2000; Martin et al. 2004; and see Preibisch & Mamajek 2008 for a review of the Upper Sco region). Being young (5–10 Myr; see Slesnick et al. 2008; Pecaut et al. 2012), the region is amenable to a complete census study of activity's effects on the inferred masses of low-mass stars and BDs at an age where they are still likely to be magnetically active while no longer being strongly contaminated by signatures of disk accretion. Moreover, $T_{\rm eff}$ and Hα equivalent width (EW) measurements are available for the low-mass objects in this region (Slesnick et al. 2008; Lodieu et al. 2011), allowing their masses and chromospheric activity levels to be determined.

To be clear, it is not our aim in this paper to determine an "absolute" IMF for Upper Sco. The observational determination of IMFs is notoriously complicated by potential observational biases and systematic effects due to, e.g., sample completeness and contamination, differential reddening, mass segregation, unresolved binarity, etc. These issues are beyond the scope of this paper. Rather, our aim is to explore the impact of activity on an observed IMF independent of these other observational issues, thus providing an assessment of the differential effect of activity specifically.

In Section 2 we summarize the data from the literature that we use as well as the relations that we employ to convert the observed chromospheric activity measures into estimated stellar mass corrections. Section 3 presents our main result that the ratio of apparent BDs to stars in a young cluster is significantly altered by these corrections. We conclude with a discussion of some implications and limitations of this work in Section 4.

2. DATA AND METHODS

2.1. Study Sample

Our sample of young, low-mass stars is taken from the study of the young ($\sim$5–10 Myr) Upper Sco star-forming region of Slesnick et al. (2008). The sample is based on a large-scale photometric multi-band survey in optical and near-infrared (IR) bands. Slesnick et al. (2008) present spectroscopy for 243 candidate members and confirm 145 as bona fide members of the star-forming association. Combining spectra and photometry, the authors determine luminosities, $T_{\rm eff}$, as well as Hα EWs, and also provide an estimate of the object masses and ages based on the position of objects in the H-R diagram. Based on their analysis, the age of the Upper Sco members is consistent with formation in a single burst 5 Myr ago. The mass function presented in their paper does not turn over until below 0.05 $M_\odot$, suggesting a possible overabundance of very low-mass stars and BDs in Upper Sco compared with other regions.

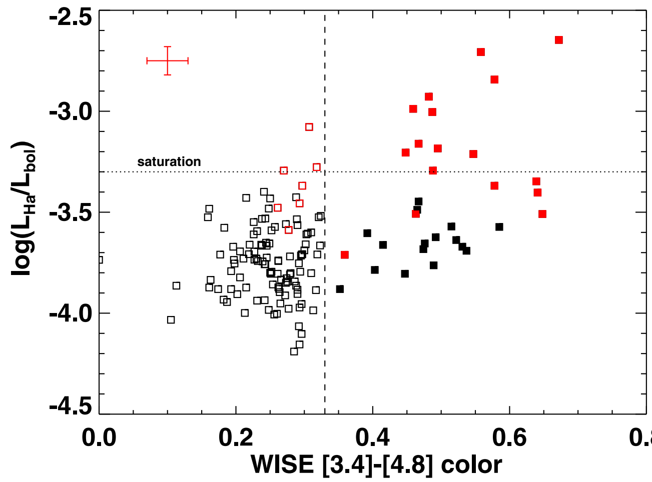

Figure 1. Sample of Slesnick et al. (2008) in the $L_{\rm H\alpha}/L_{\rm bol}$ vs. *WISE* [3.4]$-$[4.8] plane. Stars with Hα emission EW indicative of active accretion (red symbols) are removed from our study. Error bars in the upper left represent typical measurement uncertainties. The vertical line indicates the [3.4]$-$[4.8] color above which stars possess significant excess IR emission indicative of disks (solid symbols); these objects are also eliminated from our study. The horizontal line indicates the maximum ("saturated") level of $L_{\rm H\alpha}/L_{\rm bol}$ expected from chromospheric activity. Most of the stars with excessive Hα emission (red) are in the upper right quadrant, as expected for stars actively accreting from disks, whereas the majority of the sample is in the lower left quadrant as expected for naked non-accreting stars.

(A color version of this figure is available in the online journal.)

The Slesnick et al. (2008) sample is ideal for our purposes because (1) the low-mass population of the region was characterized with reportedly good completeness from $\sim$0.2 $M_\odot$ to well below the nominal H-burning limit of $\sim$0.08 $M_\odot$ (i.e., the IMF is well sampled near the expected peak of the stellar mass distribution and below, (2) the stars are young enough to be highly magnetically active but old enough that the fraction of stars with massive disks and high accretion rates is relatively low, and (3) the Slesnick et al. (2008) analysis included $T_{\rm eff}$-inferred stellar masses and reported measurements of the Hα emission for all of the sources.

To measure the strength of chromospheric activity, we take the Hα EWs reported by Slesnick et al. (2008) and convert these to $L_{\rm H\alpha}/L_{\rm bol}$ in the same manner as described in Stassun et al. (2012). In short, we scale the EWs to Hα luminosities by multiplying with continuum fluxes at the wavelength of Hα taken from the AMES–Dusty models (Allard et al. 2000) for low-gravity, solar metallicity objects ($\log g = 4.0$) with $T_{\rm eff}$ from 2400 to 4000 K. The models provide fluxes for a unit area of stellar surface; therefore we also multiply with $4\pi R^2$, where R was determined from L and $T_{\rm eff}$. This method gives $L_{\rm H\alpha}$ for each object, without any assumptions about distance or age.

The Upper Sco study sample of Slesnick et al. (2008) is shown in Figure 1 in the $L_{\rm H\alpha}/L_{\rm bol}$ versus *WISE* [3.4]–[4.8] plane. A trend of increasing $L_{\rm H\alpha}/L_{\rm bol}$ with increasing *WISE* color is apparent, and is due to the presence of strong accretion-induced Hα emission in objects with massive disks as inferred from excess IR emission in the *WISE* colors. Since our empirical relations for correcting the $T_{\rm eff}$ due to activity assume that the Hα emission is caused by chromospheric activity only, we must eliminate stars in the sample whose Hα emission is potentially contaminated by accretion. To that end, we remove stars that satisfy one or both of the following criteria: (1) Hα emission stronger than 20 Å EW, corresponding to the maximum emission observed in young mid-late M stars (see Figure 4 in Slesnick et al. 2008, and references therein), and (2) *WISE* [3.4]−[4.8] color larger than 0.33, corresponding to significant excess IR emission over that expected from bare photospheric colors in young mid-late M stars (see, e.g., Dawson et al. 2013).

Application of these cuts removes 40 stars (in Figure 1 these are the red symbols and all objects to the right of the vertical line), leaving 105 stars in our study sample. Note that none of these 105 sample stars possess $L_{\rm H\alpha}/L_{\rm bol}$ above the nominal chromospheric "saturation" limit of log $L_{\rm H\alpha}/L_{\rm bol} \approx -3.3$ (horizontal line in Figure 1), suggesting that the retained sample is indeed clean of active accretors.

Note that the removed set (red points and filled points in Figure 1) is larger than (but inclusive of) the set identified as accretors by Slesnick et al. (2008) because here we have conservatively also flagged objects that show clear signatures of massive disks from the *WISE* IR data that were not available at the time of the Slesnick et al. (2008) study. This allows for the possibility of objects that may not have been observed to be actively accreting at the epoch when the Hα spectra were obtained but that may be affected by accretion at other times nonetheless. Note also that our removal of the reddest objects in the *WISE* passbands does not imply removal of the lowest mass objects, as the *WISE* colors are primarily probing the presence of circumstellar disks, not the photospheric $T_{\rm eff}$. We have checked that the removed set does not represent a distinct region of the IMF; a two-sided Kolmogorov–Smirnov test of the masses of the removed set versus the masses of the retained set gives a probability of 32% that they are drawn from the same parent sample.

2.2. *Stellar Masses and Empirical Activity Corrections*

To ascertain the effect of the observed activity on the inferred masses of the sample stars, we use the empirical relation between $L_{\rm H\alpha}/L_{\rm bol}$ and $T_{\rm eff}$ suppression determined by Stassun et al. (2012). Specifically, we adjust the observed $T_{\rm eff}$ upward according to Equation (1) in Stassun et al. (2012):

$$\Delta T_{\rm eff}/T_{\rm eff} = m_T \times (\log L_{H\alpha}/L_{\rm bol} + 4) + b_T, \qquad (1)$$

where the relation fit coefficients from Table 1 in Stassun et al. (2012) are $m_T = -4.71 \pm 2.33$ and $b_T = -4.4 \pm 0.6$, in percentages.

For consistency with the methods employed by Slesnick et al. (2008), we adopt their reported luminosities as is. We also adopt their reported spectroscopic $T_{\rm eff}$ determinations and then adjust them using Equation (1) above.

We infer the adjusted masses of the stars by interpolating in $T_{\rm eff}$ and L using the same pre-main-sequence stellar evolutionary models of D'Antona & Mazzitelli (1997) as adopted by Slesnick et al. (2008). Note that the empirical corrections of Stassun et al. (2012) do not depend on any particular choice of pre-main-sequence models, because the corrections depend only on the observed $T_{\rm eff}$ and Hα emission. However, the masses inferred from the $T_{\rm eff}$ and L certainly do depend on the choice of models, hence our use here of the same models originally adopted by

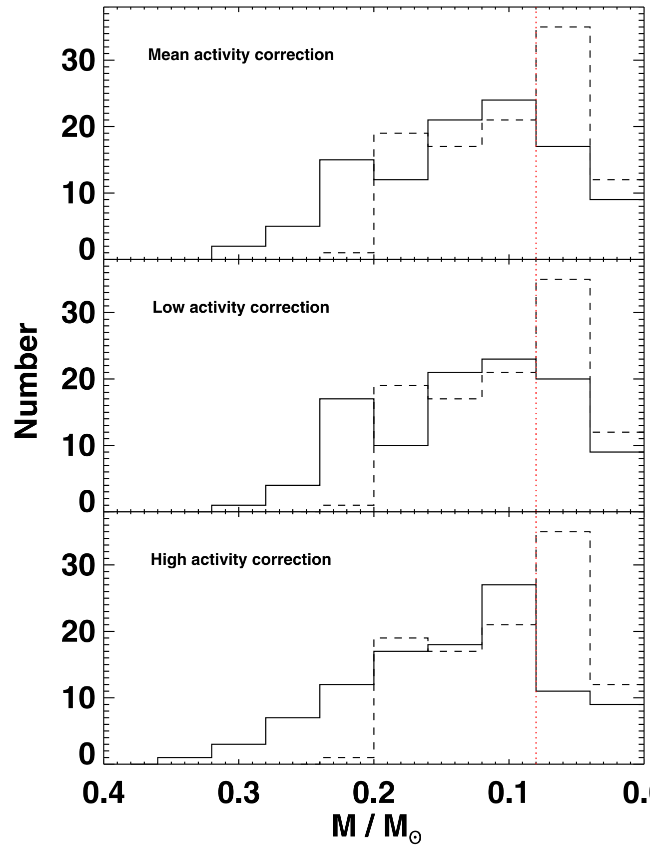

Figure 2. Initial mass function of Upper Sco stars from Slesnick et al. (2008) before (dashed histograms) and after application of activity corrections (solid histograms) according to Equation (1). The top panel uses the mean coefficients in Equation (1), whereas the middle and bottom panels use the 1σ low and high coefficients, respectively. The vertical line in each panel denotes the nominal BD mass limit of 0.08 $M_\odot$. The ratio of BDs to stars is lower in the activity-corrected IMFs at very high statistical significance (see the text).

(A color version of this figure is available in the online journal.)

Slesnick et al. (2008) in order to compare the adjusted masses to the originally reported ones. Finally, to ensure an accurate comparison between the adjusted masses determined here and the masses originally inferred by Slesnick et al. (2008), we checked that we were able to reproduce the original masses from Slesnick et al. (2008) using their originally reported $T_{\rm eff}$ and L. In all cases we reproduced their originally reported masses to within 1%, implying that we are effectively adopting the same interpolation method on the D'Antona & Mazzitelli (1997) evolutionary tracks.

3. RESULTS

The result of adjusting the masses of the study sample stars according to the observed Hα emission is shown in Figure 2. The masses are binned by 0.04 $M_\odot$, and in each panel the original masses from Slesnick et al. (2008) are represented by the solid histogram. For comparison, the activity-adjusted masses are represented as dashed histograms. Because the activity correction coefficients in Equation (1) have associated uncertainties, we show in the different panels of Figure 2 the activity-adjusted mass histograms that result from adopting the coefficients at their mean values (top panel) or at their 1σ low or high values (middle and bottom panels). Visually, the original IMF from Slesnick et al. (2008) appears to be shifted to systematically lower masses, as expected since the activity corrections act systematically to adjust the $T_{\rm eff}$ to higher values corresponding to higher masses. Considering the sample on an object-by-object basis, the smallest change in mass in 3% while the largest change in mass is 102%.

If we quantify the shift in the overall sample by comparing the modal values of the distributions in Figure 2, we find the following modal values for the mean correction, low correction, and high correction cases, respectively (in units of $M_\odot$): 0.111 ± 0.007, 0.104 ± 0.006, and 0.119 ± 0.007. In comparison, the modal value of the uncorrected distribution is $0.056 \pm 0.004\, M_\odot$. In other words, the activity-corrected modal mass is consistently higher than the uncorrected modal mass, and the difference is in all cases statistically significant at $>6\sigma$. In addition, a Wilcoxon rank-sum test yields a probability of $<10^{-5}$ in all cases for the null hypothesis of no difference in the sample medians before and after application of the activity correction.

However, the intrinsic breadth of the IMF may make shifts in the IMF peak difficult to quantify with the modal value; indeed, the IMF appears to be broadly "flat" in the vicinity of the peak (Slesnick et al. 2008; see Figure 2). Thus a number of previous studies have instead used the ratio of BDs to stars (or vice versa) as an alternative metric for characterizing the IMF (Luhman et al. 2003; Andersen et al. 2008; Scholz et al. 2012). In the case of the IMFs shown in Figure 2, the BD-to-star ratio for the mean correction, low correction, and high correction cases, respectively, are 0.33 ± 0.07, 0.38 ± 0.08, and 0.24 ± 0.06, where we define BDs as objects with inferred masses $<0.08\, M_\odot$. In comparison, the BD-to-star ratio for the uncorrected distribution is 0.81 ± 0.16. The uncertainties in the above ratios are based on simple Poisson errors based on the numbers of objects in the sample above and below $0.08\, M_\odot$. By this simple statistical treatment, the activity-corrected and -uncorrected IMFs differ in their BD-to-star ratios at the level of $\sim 3\sigma$. However, using a proper statistical test for differences in two sample proportions[6] (Newcombe 1998), we find a probability of $<10^{-6}$ in all cases for the null hypothesis that the proportions are the same before and after application of the activity correction.

4. DISCUSSION AND CONCLUSIONS

In our earlier work (Stassun et al. 2012), we discussed the fact that we saw no obvious discontinuity in our $T_{\rm eff}$ suppression relations at the fully convective mass boundary ($M \sim 0.3\, M_\odot$). Indeed, our empirical correction seemed to solve the $T_{\rm eff}$ reversal problem for the fully convective, young BD eclipsing binary 2M0535−05. Our study sample in this current work comprises low-mass stars and BDs that have likely not begun hydrogen fusion yet, e.g., Burrows et al. (2001) shows that the core temperature of a $0.2\, M_\odot$ star does not reach the critical value of 3×10^6 K until ≈ 11 Myr. In that sense, these young stars are more like the BD eclipsing binary than field stars of similar temperature. One key feature of $T_{\rm eff}$ suppression in field stars is that $L_{\rm bol}$ does not change with activity because the energy output is purely set by fusion reaction rate in the core. Given that we do not yet fully understand the mechanism behind $T_{\rm eff}$ suppression, it is possible that the empirical relation derived in the field would not apply to pre-main-sequence stars of similar $T_{\rm eff}$.

Our correction may resolve an issue raised by the analysis in Slesnick et al. (2008). Their results suggest that Upper Sco "contains relatively higher numbers of very low-mass stars and BDs compared with other star-forming regions." The slope of the low-mass IMF derived by Slesnick et al. (2008) is higher than usual ($\alpha = -1.13$ compared with 0.6 in most other regions, Scholz et al. 2012). While the mass distribution begins to turn over around $0.1\, M_\odot$ in other regions, Slesnick et al. (2008) report a secondary peak at $0.05\, M_\odot$. All this would indicate an overabundance of substellar objects in Upper Sco, which is not confirmed by other groups (Dawson et al. 2011). Slesnick et al. (2008) speculate that this overabundance may be related to the presence of OB stars in Upper Sco. We have shown above that after applying the correction, the peak of the mass function shifts to $0.1\, M_\odot$ or higher, and the secondary peak disappears. The star-to-BD ratio increases as well, and is now consistent with values for other regions (see Scholz et al. 2013 for a review), which have been derived without using $T_{\rm eff}$. Thus, after taking into account the effect of magnetic activity on the estimated masses, the low-mass IMF in Upper Sco no longer appears abnormal.

Our current work has not accounted for possible contamination by unresolved binary stars; however, we expect these to have a minimal impact on our correction for the mass–radius anomaly. Generically, unidentified binaries can confuse determination of stellar properties because of mismatches between luminosity, effective temperature, and $\log g$. Close, tidally interacting binaries are also known to persist as chromospherically active and to show enhanced Hα emission. However, stars in this mass regime have a lower total binary fraction than higher mass stars, closer to 30% (Duchêne & Kraus 2013). More importantly, the parameter space in which to "hide" a companion is small. Companions close enough to induce activity are statistically biased toward more equal masses, making them likely to show up as double lined, spectroscopic binaries (Reid & Gizis 1997). For wider systems, nearly equal mass binaries—the easiest to detect—produce the most severe errors in determining stellar properties: these systems would show higher luminosities at a given $T_{\rm eff}$. Thus one would infer a larger radius, but not an unusually high $L_{\rm H\alpha}/L_{\rm bol}$. These systems would only degrade the correlation we identify here.

We have demonstrated that the mass distribution in the very low-mass regime is significantly altered by the effects of magnetic activity. If masses are estimated from $T_{\rm eff}$ they can be systematically underestimated, which would influence the derived IMF and especially the star-to-BD ratio. When masses are estimated from luminosity, this issue is avoided, however other uncertainties arise. During the pre-main-sequence contraction stars drop sharply in luminosity, and so the estimated masses depend strongly on the assumed age, which is typically uncertain by several Myr. Luminosities are also affected by uncertainties in extinction and distance. For comparison, a 10% error in a cluster distance manifests as a 20% error in luminosity, which in turn biases masses by roughly 10%–20% at the substellar boundary, and by up to 50% below the substellar boundary where deuterium-burning effects become particularly important. Similarly, a change of 2 Myr ($\approx$20%) in assumed age for a region like Upper Sco can translate to 20%–50% change in mass. Ideally IMF measurements for young clusters should be estimated by multiple techniques to combat these uncertainties.

To our knowledge, the Upper Sco data set published by Slesnick et al. (2008) is the largest sample of young low-mass objects covering a large range in $T_{\rm eff}$ and Hα measurements for every object (see Lodieu et al. 2011 for measurements of additional Upper Sco members). This makes it possible to estimate masses from $T_{\rm eff}$ while correcting for the influence of magnetic activity. To extend this type of analysis and test the IMF in diverse regions, it would be desirable to obtain activity

[6] We use the chi-square test for equal proportions as implemented in the *R* statistics package.

measurements (e.g., Hα EWs) for large samples of young very low-mass objects in other star-forming regions.

An ancillary impact of accurate mass determinations in young clusters is the validation of atmosphere models for comparison with young exoplanets, as there remains a need to understand how spectral class maps to mass and age in isolated objects in order to make comparison models for massive exoplanets. Most importantly, measuring the tail of the IMF in young clusters is vital for our understanding of star formation, and in particular the role of turbulence in producing cluster–cluster variations. If changes to the IMF are most dramatic at lower masses, accurate measurements in young clusters are most important. Our work here suggests that unmodeled physics such as magnetic activity can substantially influence the low-mass end of the IMF.

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