An Improved Activity-Age Relation for Solar-Type Stars Younger than the Sun

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ABSTRACT

The strong anti-correlation between chromospheric activity and age for solar-type dwarfs (late-F through K types) has led to common use of the Ca H & K emission index (R'_{HK}) as an empirical age estimator. Despite their broad utility, existing R'_{HK} vs. age relations are inconsistent with modern astrophysical interpretation, often giving implausible ages at both high and low activity levels. We provide a refined calibration of the R'_{HK} vs. age relation for stars having near-solar metallicity with ages younger than the Sun (<4.5 Gyr). The new activity-age calibration is consistent with: (1) the evolution of activity among solar-type stars in clusters of known age, (2) the "gyrochronological" rotation period evolution of solar-type stars proposed by Barnes, (3) activity vs. kinematic age for field solar-type stars, and (4) the evolution of fractional X-ray luminosity among solar-type stars, as measured by surveys with ROSAT and Chandra. Both R'_{HK} and fractional X-ray luminosity (L_X/L_{bol}) scale remarkably well with empirical Rossby number for solar-type stars with activity below saturated levels (L_X/L_{bol} < -4.2, $\log(R'_{HK})$ < -4.3). Indeed, fractional X-ray luminosity appears to have comparable age-discerning power to R'_{HK}. The non-zero slope in $\log(R'_{HK})$ vs. B-V color observed in clusters can be accounted for when the Barnes rotational evolution equations are combined with the observed correlation between Rossby number and chromospheric activity. The empirical scatter in the R'_{HK} values among clusters samples with assumed common ages suggests minimum accuracy of the order ***% in activity-derived ages of solar-type stars aged between the Pleiades and the Sun (∼0.1-4.5 Gyr**). At younger ages, corresponding to higher activity levels (R'_{HK} > -4.3), R'_{HK} alone does not distinguish $\sim10^6$-10^7 yr pre-MS stars from $\sim10^8$ yr ZAMS stars, and alternative age-dating techniques (i.e. isochronal ages) are clearly preferable. Despite these limitations, and given the difficulty of age-dating main sequence stars through other methods, the revised activity vs. age relation is a useful independent estimator of age for the study of evolutionary phenomena associated with solar-type stars. ** SOME OF THESE THINGS MIGHT NOT BE TRUE WHEN THE PAPER IS DONE, AND WILL HAVE TO BE CHANGED! **

Subject headings:

1. Introduction

Age is, arguably, the most difficult basic stellar quantity to measure for low-mass field stars (see e.g. Mamajek et al. 2007). Yet, the temporal evolution of phenomena such as stellar activity, surface abundances, and circumstellar matter is of current interest and within observational means for nearby field stars, and obviously requires accurate stellar ages. Our particular motivation for improving field star age estimates stems from our interest in circumstellar disk evolution as executed via the *Spitzer Space Telescope* Formation and Evolution of Planetary Systems

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(FEPS)[1] Legacy Science program which is surveying solar-type stars between ∼3 Myr and ∼3 Gyr (Meyer et al. 2004, 2006; Carpenter et al. 2007; Hillenbrand et al. 2007) .

The most theoretically grounded age estimator is the Hertzsprung-Russell diagram which can be employed in stellar clusters for which main sequence turn-off and/or turn-on ages are typically available. Field stars, however, are generally main sequence objects and, by definition, lack co-eval accompanying stellar populations that might enable age dating via standard H-R diagram techniques. Historically, a popular age estimator for field stars of roughly solar mass has been the R'_{HK} index which measures chromospheric emission in the cores of the broad photospheric Ca II H & K absorption lines, normalized to the underlying photospheric spectrum. The R'_{HK} index is calculated from the Mt. Wilson band-ratio measurement of the Ca H & K emission line strength (the "S-index" S_{MW}; Vaughan et al. 1978; Vaughan & Preston 1980). For discussion of how to measure S_{MW} and R'_{HK}, as well as the history of studies using this index, we refer the reader to papers by Wright et al. (2004); Henry et al. (1996); Baliunas et al. (1995, 1996); Noyes et al. (1984, and references therein). Our simple goal for this study is to provide a R'_{HK} vs. age relation for the common situation when one is presented with measurement of R'_{HK} and $(B-V)_{\circ}$ (possibly derived from a spectral type or another color) for a solar-type and solar metallicity dwarf.

The activity-age data pair of highest quality is that for the Sun. The solar age is presumed coincident with that of the oldest portions of meteorites (the Ca-Al-rich inclusions; 4.5672 ± 0.0006 Gyr; Amelin et al. 2002) However, the Sun and presumably most other stars exhibit activity cycles (with period 11 years in the case of the Sun) as well as longer term variations (e.g. the so-called Maunder minimum in the case of the Sun). Over the period 1966-1993, covering mostly solar cycles 20, 21, and 22, Baliunas et al. (1995) estimated the solar Mt. Wilson S-index to be $\overline{S_{\odot}}$ = 0.179. Over the period 1994-2006, mostly solar cycle 23, Hall et al. (2007) measured $\overline{S_{\odot}}$ = 0.170. Using a mean solar S-value which is approximately weighted by the span of measurements ($\overline{S_{\odot}}$ = 0.176; for ∼1966-2006) and a mean solar color of $B-V$ = 0.65 (Cox 2000), and using the equations from Noyes et al. (1984), we estimate the mean solar activity to be $\log R'_{HK} = -4.91$. Estimated variations on time scales up to a few percent of the solar age are 0.15 in $\log R'_{HK}$ (** DON'T UNDERSTAND THIS SENTENCE**)

Using the Sun as one anchor point, we can look to open clusters with ages derived from other methods (e.g. the H-R diagram) in order to populate and activity-age calibration. There are a such few R'_{HK} vs. age relations in the literature which have been used in age-dating field stars, most notably Soderblom et al. (1991), Donahue (1993), and Lachaume et al. (1999). As seen in **Fig. 1**, the three curves are alarmingly inconsistent with one another. That there are problems with all three calibrations can be easily demonstrated. For the most recent calibration (Lachaume et al. 1999), the solar R'_{HK} value (-4.91) would infer a solar age of 7.2 Gyr, which is clearly in error. The other two calibrations apparently used the Sun as one of their anchor points, but with a different R'_{HK} value. For the calibrations of Soderblom et al. (1991) and Donahue (1993), one derives ages of 4.1 and 4.0 Gyr, respectively.

At younger ages, the existing calibrations lead to implausible ages. For example, given the observed activity levels in the ∼5-15 Myr Sco-Cen OB association ($\log R'_{HK} \simeq -4.05$; §**), the Soderblom et al. (1991) curve (if extrapolated to stars younger than the youngest anchor in their calibration: the ∼0.5 Gyr-old Ursa Major group) predicts ages that are too old by an order of magnitude. The activity-age calibration of Donahue (1993) is the most popular in recent studies (e.g. Wright et al. 2004), but for $\log R'_{HK} \simeq -4.05$, it predicts a stellar age of *one hour*. Given the paucity (though not complete absence) of young stars in the previous calibrations, we should not be too surprised at the lack of agreement with other age-dating methods at the high-activity end of the relation.

Clearly, an improved activity-age calibration is needed. Further, we would like to understand and quantify the limitations of such a relationship and hence its usefulness for practical application. We focus this paper on refining the age-activity relation for *solar-type stars that are younger than the Sun (stronger in chromospheric activity) and near solar in metallicity*. By "solar-type", we restrict our discussion to stars with $0.45 < (B-V)_{\circ} < 0.90$ mag, which approximately covers the color range over which the Noyes et al. (1984) relation for the photospheric contribution to the S-index is applicable (∼F5-K2), as well as the color range blanketed by recent activity surveys (e.g. Henry et al. 1996; Wright et al. 2004). By "solar metallicity" we mean within 0.15 dex of the

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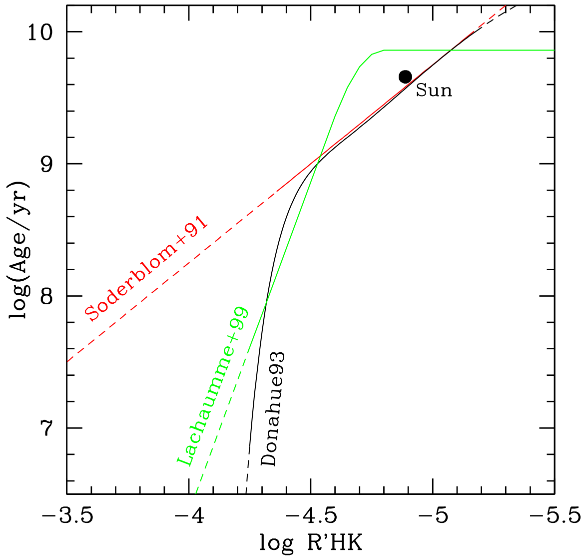

Fig. 1.— Three oft-cited R'_{HK} vs. age calibration curves, with the mean solar R_{HK} value of -4.91 (§1). Dashed portions indicate extrapolation of the relation beyond the activity range probed by the three studies. The *solid* error bars for the Sun reflect the range of solar activity during Cycles 20-22, where the *dashed* extension shows the activity minimum predicted during the Maunder Minimum (**?**).

solar [Fe/H]. There are four recently appreciated facts that make our investigation timely:

(1) There are many stars with measured R'_{HK} values that belong to age-dated young stellar aggregates (e.g. Sco-Cen, β Pic, etc.) that can broaden and strengthen the activity-age calibrations relative to several decades ago.

(2) The ages of well-studied nearby open clusters have been updated over the past decade. The most noticeable difference relative to traditionally accepted age values is the systematic shift towards older ages based on the Li-depletion boundary age estimation method (e.g. Stauffer, Schultz, & Kirkpatrick 1998; Barrado y Navascués, et al. 2004).

(3) The nearest young open clusters and stellar aggregates which anchor any activity-age relation all appear to have near-solar metallicity (r.m.s. $\simeq$ 0.1 dex in [Fe/H]; Twarog, Ashman, & Anthony-Twarog (1997), including T Tauri stars in the nearest star-forming regions (Padgett 1996). Recent analysis of the California-Carnegie Planet Search Project sample by J. Wright (private communication) suggests that there are metallicity effects which strongly bias age estimates based on R'_{HK}, most severely so for stars older than the Sun.

(4) Interest in circumstellar disk evolution has increased dramatically. The availability of relevant infrared data e.g. from *Spitzer* observations begs for a robust stellar age estimator in order to probe the collisional and radiative evolution of debris disks and the connection of such phenomena to exo-solar planetary system dynamics.

2. Data

2.1. Cluster Membership and Ages

References for the stellar membership and the ages of the clusters and associations used as calibrators in our quantification of the activity-age relationship are provided in **Table 1**. The cluster ages are discussed at length in Hillenbrand et al. (2007), and we adopt their age scale in this study. **achem !!! there is some merit to putting some of that info here. we might consider best economies.** We considered only those possible cluster members having R'_{HK} measurements as given below. Kinematic membership of individual stars to their assigned groups was scrutinized with modern astrometric data (i.e. *Hipparcos*, Tycho-2, and UCAC2 catalogs) either by the authors or through examination of recently published kinematic studies (e.g. de Zeeuw et al. 1999; Makarov 2006), or both.

We briefly review the stellar groups and references for their memberships and ages. Members of Upper Sco were taken from Preibisch & Zinnecker (1999) and Walter et al. (1994), and we adopt the mean group age (5 Myr) from Preibisch et al. (2002). Memberships and mean ages for the β Pic and Tuc-Hor moving groups (12 and 30 Myr ages, respectively) were taken from **?**, and HD 105 was added as a Tuc-Hor member following Mamajek et al. (2004). Members of Lower Cen-Cru and Upper Cen-Lup were taken from de Zeeuw et al. (1999) and Mamajek et al. (2002), and mean group ages were adopted from Mamajek et al. (2002). In Tuc-Hor, only stars demonstrated by Mamajek et al. (2004) to be near and comoving with the β Tuc nucleus were retained for our activity-age calibration. The α Per members have been confirmed kinematically by Makarov (2006) for all of the cluster candidates except Cl Melotte 20 696 and AP 93. We find that the UCAC2 proper motions for both of these stars are statistically consistent with membership, and include them in our α Per sample.

For the Pleiades, all of the R'_{HK} measurements of candidate members from Duncan et al. (1991), Soderblom et al. (1993), and White, Gabor, & Hillenbrand (2007), were considered. We independently tested the kinematic membership of each of these stars to the Pleiades using Tycho-2 or UCAC2 proper motions and the group proper motion from Robichon et al. (1999). All of the objects have motions within 2σ of the Pleiades mean motion (although #571 is a marginal case, but supporting evidence suggests that this is probably a bona fide member). Deacon & Hambly (2004) independently assign high membership probability to the Pleiades for stars #102, 129, 173, 296, 314, 514, 923, 1776, 1015, 1207, 3097.

The membership and mean age (500 Myr) for the Ursa Major cluster were taken from King et al. (2003), and only stars with "Y" or "Y?" membership assingments from King et al. were included. The primary source of membership assignment and age (625 Myr) for the Hyades is Perryman et al. (1998). Upon closer examination, we rejected the membership of a few of the Perryman et al. Hyades candidates. To test the kinematic membership of the candidates to the Hyades cluster, we use the convergent point solution from **?**. We reject the likely interloper HIP 25639 due to its distance (Hipparcos $d \simeq 86$ pc, compared to 46 pc for the Hyades nucleus), large peculiar velocity ($\sim$7 km/s), and remarkable inactivity ($\log R'_{HK}$ = -5.38; Paulson et al. 2002). Hence, rather than being a chromospherically "dead" Hyad, HIP 25639 is probably an old field dwarf. HIP 19386 ** NEED CLOSER LOOK AT HYADS! **

In summary, we believe that the cluster membership assignments in Table 1 are quite reliable. Any interlopers among the samples that we may not have caught are small in number, and hence will have negligible impact on our findings.

2.2. Ca II H & K Data

We use a standard metric of stellar chromospheric activity: the R'_{HK} index derived from S-values in the tradition of the Mt. Wilson HK project. The R'_{HK} index approximates the ratio of chromospheric luminosity in Ca II H & K line cores compared to the stellar bolometric luminosity (Noyes et al. 1984). The ratio is derived from measured S-values converted to the Mount Wilson system, S_{MW} from which the underlying stellar photospheric contribution is then subtracted, following Noyes et al. (1984). Typical errors due to measurement uncertainty and then calibration to the standard system are typically 0.05-0.1 dex.

Given the ubiquity of the R'_{HK} index in the literature, and the uniformity in its calculation and calibration by previous authors, we make no attempt either to improve upon the R'_{HK} index, nor to correct for other effects (i.e. metallicity, gravity, etc.). R'_{HK} values were taken from many sources, including the large surveys of Henry et al. (1996), Baliunas et al. (1996), Wright et al. (2004), Gray et al. (2003), and Gray et al. (2006), the smaller focussed surveys of young stars by Soderblom et al. (1993), Soderblom et al. (1998), Paulson et al. (2002), White, Gabor, & Hillenbrand (2007). S-values from Duncan et al. (1991) were converted to R'_{HK} following Noyes et al. (1984). Systematics between the surveys are addressed by several of the more recent authors and should be minimal since most surveys attempt to calibrate to the Mount Wilson system.

The members of the stellar groups listed in Table **4 ??** were queried in the above catalogs of R'_{HK} measurements. Although many of the surveys contain a mix of field and nearby open cluster members, we consider only the latter at present. Our intention is to apply our results to the former.

3. Analysis

With established membership lists and R'_{HK} values assembled from a few large, homogeneous spectroscopic surveys, we proceed in this section with a series of tests that establish our ability to derive a meaningful activity-age relationship. We investigate various second parameter effects, e.g. color/temperature/mass, surface gravity, and composition. We focus on color dependencies by testing the R'_{HK} diagnostic versus binary pairs having the same age/composition but substantial temperature differences (§3.1.1) and versus kinematic groups having different ages (§3.1.2). In §3.3, we derive a preliminary empirical activity-age relation based on cluster and solar $\log R'_{HK}$ data. In §3.3, we tie the $\log R'_{HK}$ data to stellar rotation rates via the Rossby number, and attempt to independently derive an activity-age relation based on the "gyrochronology" rotation evolution equations of **?**. In §3.3, we demonstrate that kinematic ages of samples of solar-type field stars manifest evolution in activity vs. age consistent with what is seen for the cluster population. In §3.4, we explore the correlation between fractional X-ray luminosity and Ca H&K activity for solar-type stars, and demonstrate that $\log(L_X/L_{bol}$ can be used to derive age estimates.

3.1. R'_{HK} Systematics

Although the R'_{HK} index is used to directly estimate the ages of stars, there is some evidence that R'_{HK} varies as a function both of age and color (or mass). We test whether there are spectral dependencies of R'_{HK} which if present could systematically impact stellar age estimates depending on the uniformity of the samples between the different associations and clusters. We first examine the evidence for these systematic effects empirically within the data, but in §** we explore the possible cause of these systematic effects from mass-dependent rotation evolution.

Such color/temperature/mass dependencies of the R'_{HK} index versus age have been discussed before. Typically R'_{HK} is plotted versus $B{-}V$, perhaps the most common color index classically available for large samples of stars.

Specifically, Soderblom et al. (1991) found **blah for halo stars, blah for Hyades.** Paulson et al. (2002) **found blah for Hyades**. **not entirely sure how to fix the last clause**

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3.1.1. Color-Separated Binaries

We identified 23 binary systems in the previously mentioned R'_{HK} databases, where the photospheric $B{-}V$ colors of the components differed by >0.05 mag, and both components had $B{-}V$ colors between 0.45 and $\approx$0.9 (where the photospheric correction is well characterized; Noyes et al. 1984). These systems are listed in **Table 2** and plotted in Fig. 2. The reddening towards these stars is small, given their spectral types and $B{-}V$ colors. Any interstellar reddening should effect both components, and not affect any measurements of the mean slope. DWARFS?

In the course of searching for binaries with R'_{HK} data, we found a pair with R'_{HK} data from Henry et al. (1996) at 36" separation (HD 44105 & 44120). We find that these stars constitute an optical pair, and were omitted from our sample. The stars clearly do not constitute a physical binary due to their mismatch in *Hipparcos* astrometry and their color-magnitude positions with respect to each other (the F3/F5V star HD 44105 is 1.3 mag fainter than the G1V star HD 44120). *** Fig 3 **. A statistical analysis of the 24 individual slopes ($m = \Delta\log R'_{HK}/\Delta(B{-}V)$) showed that one system was statistically deviant (HD 137763; rejected by Chauvenet's criterion; Bevington & Robinson 1992), and that the mean slope was $m = 0.21 \pm 0.30$. The true median of the slope is $m = 0.39^{+0.50}_{-0.38}$ (Gott et al. 2001). While the binary data alone are statistically consistent with zero slope in $\Delta\log R'_{HK}/\Delta(B{-}V)$, there is some hint that the slope is slightly positive.

3.1.2. Stellar Kinematic Groups

We also tried to constrain the slope m using stars in kinematic groups. The colors and $\log R'_{HK}$ values for members of several kinematic groups are plotted in Fig. **??**. To improve the statistics for a "post-T Tauri" bin, we combined the UCL and LCC groups, which are approximately coeval (Mamajek et al. 2002), and whose individual R'_{HK} measurements were similar. The individual slopes for each group were measured by calculating the ordinary least squares bisector Isobe et al. (OLS bisector 1990) and slope uncertainty for 10000 bootstrap simulations of the data are listed in **Table 4**. The measured slopes for the samples with more than 10 data points (i.e. Hyades, Pleiades, UMa, α Per), are all positive, and consistent with a weighted mean slope of $m = 1.39 \pm 0.16$. The weighted mean slope for all of the groups is 1.05 ± 0.12.

3.1.3. *Conclusions on Color Effects*

In short, we have no evidence for a color effect among binaries §3.1.1, no evidence among very old stars (Soderblom et al. 1991), and no evidence looking at the median values as a function of color. However, there is evidence that a positive slope of $m \simeq 1$ exists for the young clusters. A result of this trend is that one should expect the presence of of higher mass (older) F-stars to bias any R'_{HK} -color slope to lower values.

Since the focus of our study is on the youngest stars (<4 Gyr), and the young clusters clearly demonstrate a color effect, for now we take the approach of empirically "color correcting" the $\log R'_{HK}$ values to a standard color. The median $(B-V)_\circ$ color for the stars with $(B-V)_\circ \in [0.4, 0.9]$ is 0.65, which coincidently is the color of the Sun ($(B-V)_\circ = 0.65$; Cox 2000).

is this what we are still doing ??

3.2. Activity-Age Calibration Using Cluster Stars

** PLOT R'HK HISTOGRAMS FOR EACH CLUSTER **

** characterize mean/median/dispersion vs age

** demonstrate robustness to separating cluster samples by author **

** PLOT ALL CLUSTER DATA ON R'HK VS. AGE AND FIT POLYNOMIAL***

** be clear about the range of applicability of derived age-activity relationship **

3.3. Combining Gyrochronology and the Rossby Number: An Independent Means of Creating an Activity-Age Calibration

Thus far we have attempted to calibrate the $\log R'_{HK}$ vs. age relation empirically using stars of "known" age. In this section, we will demonstrate that one can derive an age vs. activity calibration by combining the empirical "gyrochronology" rotational evolution equations of **?** with the observed correlation between Rossby number and chromospheric activity $\log R'_{HK}$ demonstrated by Noyes et al. (1984). We will discuss the results of **?** and Noyes et al. (1984), update the activity vs. Rossby number relation of Noyes et al. (1984), and combine these relations into an activity-age relation to be compared against our previously relation based on cluster stars.

In the course of their evolution, solar-type stars lose angular momentum through stellar winds. This inexorable lose of angular momentum leads to a steady slowdown in rotation rates, first quantified by **?** as period $\propto$ age$^{-0.5}$ ** CHECK**. Detailed surveys of solar-type stars in open clusters over the past two decades showed that the evolution in rotation period has a heavy color-dependence (i.e. mass-dependence) ** REFS** . **?** combined the existing literature and derived a color-dependent version of the Skumanich law which he dubs "gyrochronology". Barnes finds that the majority of stars follow what he calls the interface rotational sequence:

** GYRO EQUATION **

The Barnes gyrochronology relation is calibrated to the Sun and **.

** ROSSBY NUMBER DISCUSSION

In their classic chromospheric activity study, Noyes et al. (1984) attempt to understand the evolution of $\log R'_{HK}$ in terms of the stellar dynamo. Stellar activity as quantified by $\log R'_{HK}$ should be driven by the strength of the stellar dynamo, which theoretically should be proportional to the Rossby number to the **POWER** power. The Rossby number ($R_o = P/\tau_c$) is the stellar rotation period P divided by an estimate of the convective turnover time τ_c. Some assumptions go into calculating this number. First, stars are not rigid rotators (indeed the Sun's rotation ranges from 25 days near the equator to $\sim$32 days near the poles, so any estimate of the rotation rate of an unresolved stellar disk via chromospheric activity or starspot modulation will simply be some latitudnal mean that may vary with time (**REF**). Second, the Rossby number is dependent on a convective turnover time that is either based directly on stellar interior models (e.g. **?**) or informed by the models but empirically calibrated (e.g. Noyes et al. 1984). Multiple studies have attempted to quantify the convective turnover time for solar-type main sequence stars (Noyes et al. 1984; **?**; **?**) and pre-main sequence stars ** REF**. A recent study by **?** **CHECK** shows that the Noyes et al. (1984) color vs. convective turnover time relation still produces the tightest correlation between activity and Rossby number, even compared to modern stellar models using Mixing Length Theory (MLT) and Full Turbulence Spectrum (FTS) treatments of convection. In light of their results, we adopt the Noyes et al. (1984) convective turnover time relation as a function of $B-V$ color.

** PLOT R_O vs. LOGR'HK

3.4. Consistency of an Activity-Age Relation With Other Age and Activity Indicators

3.4.1. Gyrochronlogy Ages

3.4.2. Fractional X-ray Luminosity

? demonstrated that fraction X-ray luminosity and $\log R'_{HK}$ are well-correlated, suggesting that coronal and chromospheric emission line losses are physically connected.

3.4.3. Kinematic Ages of Field Stars

3.5. A Final Age-Activity Calibration

Basically make two relations, one dependent only on cluster ages vs. activity, and another that includes gyrochron ages. (In case gyrochron age relation changes).

4. Discussion

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4.1. The "Classical" vs. LDB Age Scales

Over the past decade, a number of new age estimates have been derived for nearby populous clusters via the Li-depletion boundary (LDB) method (e.g. **?**) ** THEORY **. The ages estimated for the Pleiades, α Persei, and IC 2391 clusters via this method are systematically higher than those previously derived Barrado y Navascués, et al. (2004). The LDB method is observationally challenging, physically elegant, and the problem with the classical MS turn-off ages can be interpreted as inadequate modeling of mixing between radiative-convective interfaces, as suggested by recent 3D hydrodynamical modelling (e.g.) **YOUNG?**. However, there are observational discrepencies which suggest that the LDB age scale could be at best somewhat more difficult to model than previously done, and at worst, systematically over-estimating stellar ages.

The first example is the discrepency between the expansion age of the β Pic Moving Group ($\approx$12 Myr Ortega et al. 2002), and the Li depletion pattern of its M-type members (Jensen et al., 2007, in prep.). The mid-M-type members of the group appear to have depleted ** orders of magnitude more Li than predicted by any of the suite of published models. The kinematic age appears to be well-constrained, in the author's opinion (see a preliminary age estimate for the group by Mamajek & Feigelson 2001), despite previous criticism of the kinematic age for another well-studied group (TW Hya association; **?**). So we are skeptical that the kinematic age could be in error by more than tens of percent, whereas the Li depletion data from Jensen et al. would seem to suggest a group age of $\sim$30 Myr ***.

4.2. Ramifications of the Activity-Age Calibration on the Local Star-Formation History

4.3. Activity Ages for Solar-Type Dwarfs Within 25 pc

** WE'LL SEE IF THERE IS TIME** As a service to the community, we use our new activity-age calibration to derive age estimates for solar-type main sequence stars in the solar neighborhood (specifically within 25 pc). To produce a parent sample, we queried the Hipparcos catalog for stars with $B-V \in [0.45,0.9]$, parallaxes of $\varpi \geq 40$ mas and $\sigma_{\varpi} < 5$ mas (i.s. S/N > 8). We made a B-V vs. M_V diagram, and clipped several obvious interlopers (e.g. HIP 10529, 60970, 108467, 21000), the lone G giant (Capella)

4.4. Activity Ages for Exoplanet Host Stars

** WE'LL SEE IF THERE IS TIME** In their review on extrasolar planets, **?** lists 148 stars known to have exoplanets as of 2006. In **Table ??**, we compile all of the published $\log R'_{HK}$ values for exoplanet host stars (and calculated a few values when only S-values were published). Using our revised activity-age relation, we estimate ages for those stars in our $(B-V)_{\circ}$ color range of study, and list lower limits when the star is less active than the Sun ($\log R'_{HK} <$ -4.91). To compliment the $T_{\rm eff}$ and $(B-V)_{\circ}$ data for these objects, we also list the spectral type, with the MK type catalogs of Gray et al. and Houk et al. preferentially listed when available.

4.5. Activity Ages for Stars with Debris Disks

5. Summary

The goal of this study was to provide the community with a well-calibrated conversion between activity and age for stars younger than the Sun.

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TABLE 1
ADOPTED CLUSTER INFORMATION

(1) Group/Star Name	(2) Age Myr	(3) Age Ref.	(4) Memb. Ref.
Upper Sco	5	P02	W94,P99
β Pic	12	O02	Z04
Upper Cen-Lup	16	M02	Z99,M02
Lower Cen-Cru	16	M02	Z99,M02
Tuc-Hor	30	M04	M04
α Per	85	B04	M06,here-alfper
Pleiades	130	B04	D91,here-alfper
Ursa Major	500	K03	K03
Hyades	625	P98	P98
Sun	4567	A02	...

NOTE.—P98 = Perryman et al. (1998)

TABLE 2
COLOR-SEPARATED PAIRS OF SOLAR-TYPE STARS WITH LOG R'_{HK} MEASUREMENTS

(1) Name	(2) (B-V)	(3) Ref.	(4) log R'_{HK}	(5) Ref.	(6) Name	(7) (B-V)	(8) Ref.	(9) log R'_{HK}	(10) Ref.
HD 531B	0.67	1	-4.28	2	HD 531A	0.75	1	-4.39	2
HD 5190	0.52	1	-4.96	3	HD 5208	0.68	1	-5.13	3
HD 6872A	0.47	1	-4.86	2	HD 6872B	0.54	1	-4.96	2
HD 7439	0.45	1	-4.75	4	HD 7438	0.81	1	-4.67	2
HD 13357A	0.67	1	-4.74	2*	HD 13357B	0.72	1	-4.61	2*
HD 14082A	0.52	1	-4.41	2	HD 14082B	0.62	1	-4.37	2
HD 23439A	0.76	5	-4.94	2	HD 23439B	0.89	5	-5.22	4
HD 26923	0.57	1	-4.50	6	HD 26913	0.68	1	-4.39	6
HD 53705	0.62	1	-4.93	3	HD 53706	0.78	1	-5.01	3
HD 59099	0.49	1	-4.72	3*	HD 59100	0.63	1	-4.98	3
HD 73668A	0.61	1	-4.88	2	HD 73668B	0.81	1	-4.66	2
HD 103432	0.71	1	-4.82	2	HD 103431	0.76	1	-4.73	7*
HD 116442	0.78	1	-4.94	2	HD 116443	0.87	1	-4.94	2
HD 134331	0.62	1	-4.82	3	HD 134330	0.72	1	-4.82	3
HD 134439	0.77	1	-4.78	2	HD 134440	0.85	1	-4.85	2
HD 135101A	0.68	1	-5.11	2	HD 135101B	0.74	1	-5.01	4
HD 137763	0.79	1	-4.97	2	HD 137778	0.87	1	-4.37	2
HD 142661	0.55	1	-4.94	4*	HD 142661B	0.81	1	-4.58	4*
HD 144087	0.75	1	-4.66	2	HD 144088	0.85	1	-4.60	2
HD 219175A	0.54	1	-4.99	7*	HD 219175B	0.65	1	-4.89	2

NOTE.—References: (1) Perryman & ESA (1997), (2) Wright et al. (2004), (3) Henry et al. (1996), (4) Gray et al. (2003), (5) Mermilliod (1991), (6) Baliunas et al. (1996), (7) Duncan et al. (1991). "*" implies that the published S_{MW} value from the cited survey was converted to log R'_{HK} by the author following Noyes et al. (1984).

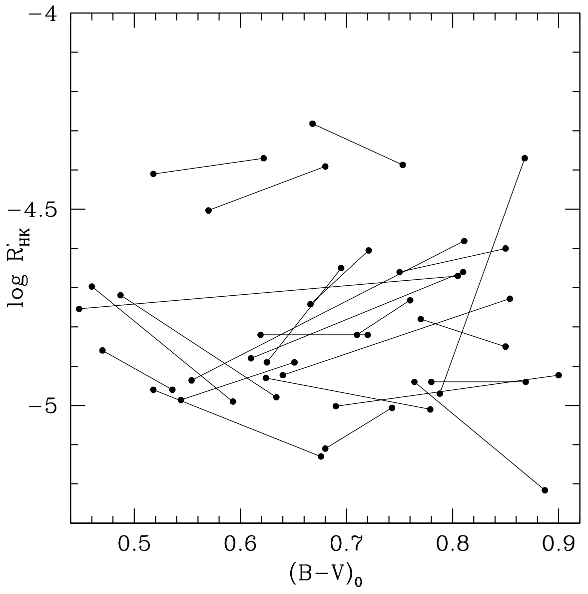


Fig. 2.— Color versus activity for 23 non-identical (Δ(B-V) $\geq$ 0.05) stellar binaries (see §3.1.1).

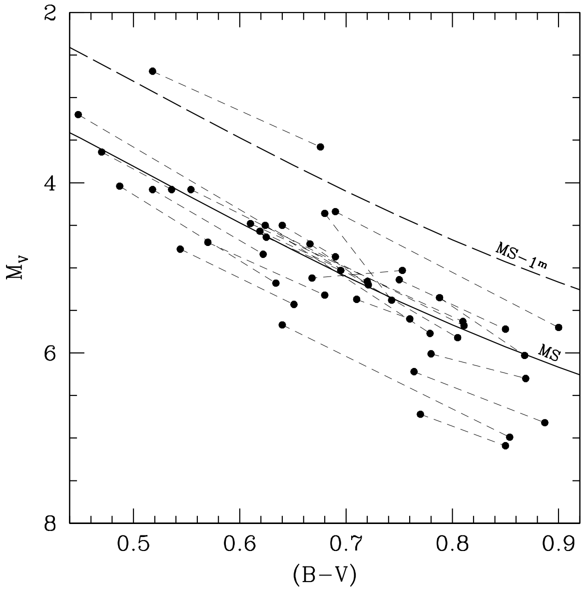


Fig. 3.— Color vs. absolute magnitude for 23 non-identical (Δ(B-V) $\geq$ 0.05) stellar binaries (see §3.1.1).

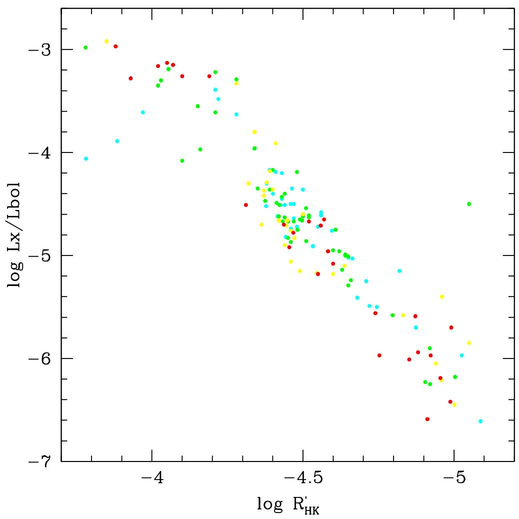
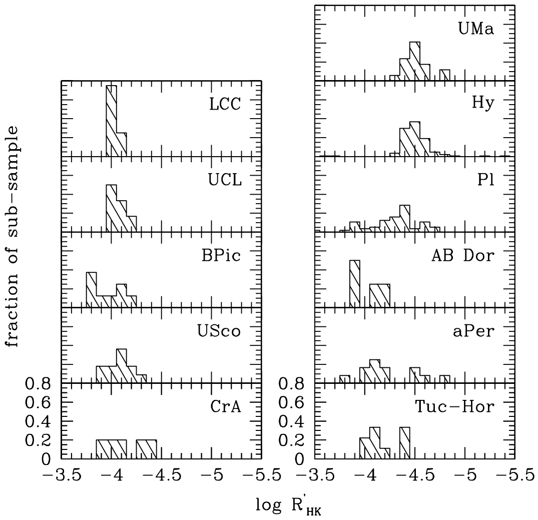


Fig. 4.—

TABLE 3
CLUSTER AND SOLAR LOG R'_{HK} VALUES

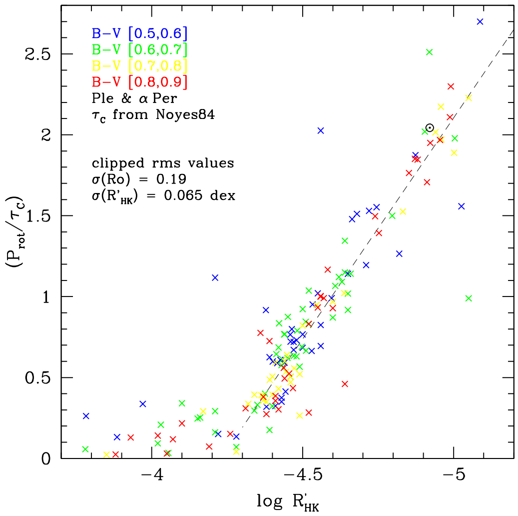
(1) Group Name	(2) Age Myr	(3) Median $\log R'_{HK}$	(4) unc.	(4) N	(6) 68% CL	(7) slope m	(8) unc.
USco	5	-4.05	0.03	9	0.13	-1.01	0.89
β Pic	12	-4.03	0.13	6	0.19	1.33	0.22
UCL+LCC	16	-4.04	0.02	10	0.07	-0.67	0.32
Tuc-Hor	30	-4.16	0.13	8	0.16	3.88	3.31
α Per	90	-4.14	0.13	12	0.28	3.14	1.07
Pleiades	125	-4.33	0.04	54	0.26	1.54	0.22
UMa	500	-4.48	0.03	17	0.09	1.10	0.27
Hyades	625	-4.47	0.01	108	0.10	1.23	0.44
Sun	4567	-4.91	...	...	....	....	...

NOTE.—Columns: (1) name of group, (2) age, (3) median $\log R'_{HK}$, (4) standard error of median (Gott et al. 2001), (5) number of star-author data points per bin, (6) 68% confidence intervals on $\log R'_{HK}$, (7) OLS bisector slope $m = \Delta \log R'_{HK}/\Delta B{-}V$, (8) uncertainty in slope from bootstrap simulations



LCC
UCL
BPic
USco
CrA
UMa
Hy
Pl
AB Dor
aPer
Tuc−Hor
fraction of sub−sample
log R'HK

Fig. 5.—



B−V [0.5,0.6]
B−V [0.6,0.7]
B−V [0.7,0.8]
B−V [0.8,0.9]
Ple & α Per
τc from Noyes84
clipped rms values
σ(Ro) = 0.19
σ(R'HK) = 0.065 dex
(Prot/τc)
log R'HK

Fig. 6.—

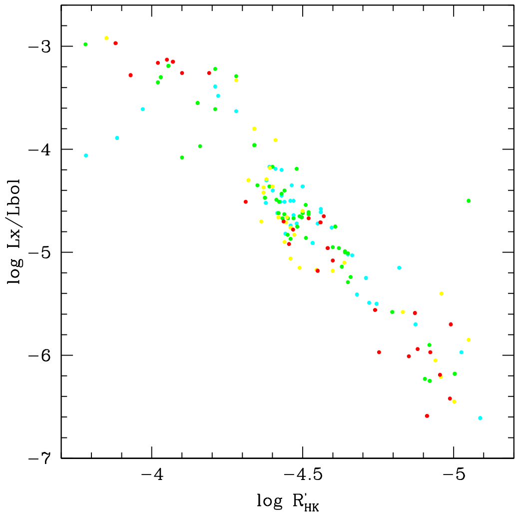


Fig. 8.—

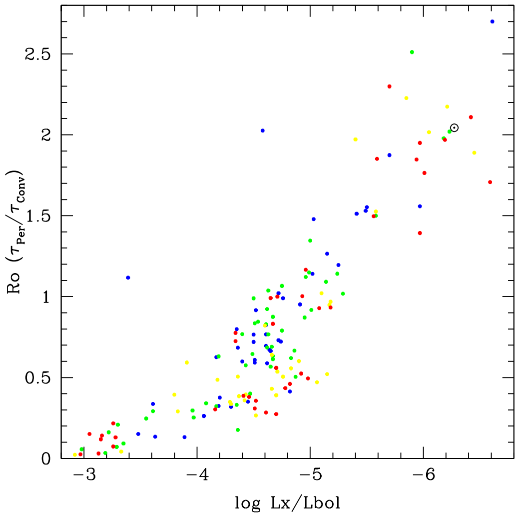


Fig. 7.—

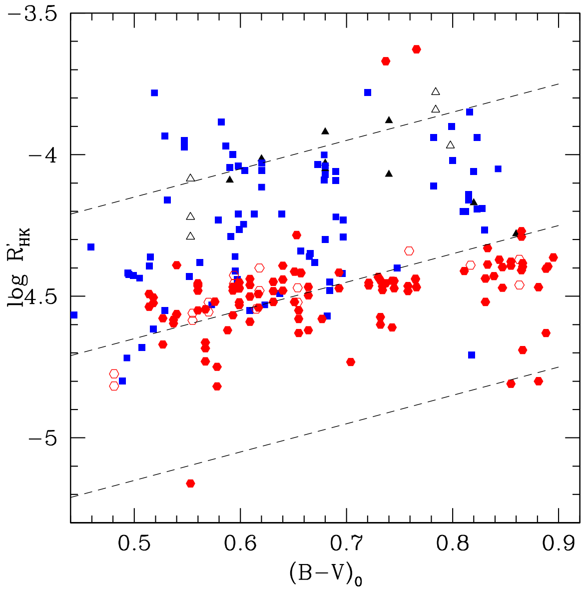


Fig. 9.— $(B-V)_{\circ}$ vs. $\log R'_{HK}$ for members of stellar clusters or associations in Table 4. I'll list the shape/color codes later. The dashed lines are for m = 1, if we were do "color-correction".

TABLE 4

MEMBERS OF STELLAR AGGREGATES WITH LOG R'_{HK} MEASUREMENTS

(1) Astrometric Name	(2) SIMBAD Name	(3) HD Name	(4) $B-V$ mag	(5) Ref.	(6) $E(B-V)$ mag	(7) Ref.	(8) $(B-V)_\circ$ mag	(9) Ref.	(10) $\log R'_{HK}$ dex	(11) N_{obs}	(12) Ref.	(13) Group
TYC 6779-305-1	V1149 Sco	HD 143006	0.75	1	0.07	1,2	0.68	2	-4.03	4	3	US
TYC 6215-184-1	ScoPMS 214	...	1.24	4	0.30	4,5	0.82	4,2	-4.17	1	6	US
TYC 6779-1372-1	ScoPMS 5	HD 142361	0.71	1	0.10	4,2	0.62	4,2	-4.01	2	6	US
2UCAC 22492947	PZ99 J161329.3-231106	...	...	...	0.60	5,7	0.86	2,7	-4.28	1	6	US
TYC 6785-476-1	PZ99 J154106.7-265626	...	0.92	8	0.50	7	0.74	2,7	-3.88	1	6	US
TYC 6793-501-1	ScoPMS 60	HD 146516	0.79	4	0.20	4,5	0.59	2,4	-4.09	1	6	US
TYC 6208-1543-1	PZ99 J160158.2-200811	...	1.10	1	0.30	7	0.68	2,7	-3.92	1	6	US
TYC 6793-1406-1	PZ99 J161618.0-233947	...	0.64	1	0.40	5,7	0.74	2,7	-4.07	1	6	US
TYC 6779-305-1	V1149 Sco	HD 143006	0.75	1	0.07	1,2	0.68	2	-4.05	1	6	US
HIP 84586	V824 Ara	HD 155555	0.80	1	0.00	9	0.80	1,9	-3.97	...	10	β Pic
HIP 92680	PZ Tel	HD 174429	0.78	1	0.00	9	0.78	1,9	-3.78	1	11	β Pic
HIP 92680	PZ Tel	HD 174429	0.78	1	0.00	9	0.78	1,9	-3.84	...	12	β Pic
HIP 25486	HR 1817	HD 35850	0.55	1	0.00	9	0.55	1,9	-4.08	...	10	β Pic
HIP 25486	HR 1817	HD 35850	0.55	1	0.00	9	0.55	1,9	-4.22	5	3	β Pic
HIP 25486	HR 1817	HD 35850	0.55	1	0.00	9	0.55	1,9	-4.29	1	6	β Pic
TYC 7822-158 1	MML 63	...	0.87	13	0.23	14	0.80	2,14	-4.02	1	6	UCL
HIP 76673	MML 69	HD 139498	0.75	1	0.09	14	0.68	2,14	-4.04	1	6	UCL
TYC 7331-782 1	MML 70	...	0.95	14	0.15	14	0.82	2,14	-4.06	1	6	UCL
TYC 7333-1260 1	MML 74	HD 143358	0.73	14	0.05	14	0.59	2,14	-4.04	2	6	UCL
TYC 7319-749 1	MML 58	...	0.88	13	0.14	14	0.81	2,14	-4.20	2	6	UCL
TYC 7310-2431 1	MML 52	...	0.97	14	0.05	14	0.62	2,14	-4.12	2	6	UCL
HIP 59764	SAO 251810	HD 106506	0.60	1	0.06	15	0.55	1,15	-3.95	1	11	LCC
HIP 59764	SAO 251810	HD 106506	0.60	1	0.06	15	0.55	1,15	-3.97	...	12	LCC
HIP 66941	SAO 252423	HD 119022	0.74	1	0.12	14	0.62	1,14	-4.03	...	11	LCC
HIP 66941	SAO 252423	HD 119022	0.74	1	0.12	14	0.62	1,14	-4.06	...	12	LCC
HIP 490	SAO 214961	HD 105	0.59	1	0.00	9	0.59	1,9	-4.36	1	11	Tuc
HIP 490	SAO 214961	HD 105	0.59	1	0.00	9	0.59	1,9	-4.41	7	3	Tuc
HIP 1481	SAO 248159	HD 1466	0.54	1	0.00	9	0.67	1,9	-4.36	1	11	Tuc
HIP 105388	SAO 246975	HD 202917	0.69	1	0.00	9	0.69	1,9	-4.06	1	11	Tuc
HIP 105388	SAO 246975	HD 202917	0.69	1	0.00	9	0.69	1,9	-4.09	...	12	Tuc
HIP 105388	SAO 246975	HD 202917	0.69	1	0.00	9	0.69	1,9	-4.22	4	3	Tuc
HIP 116748A	DS Tuc A	HD 222259A	0.68	1	0.00	9	0.68	1,9	-4.00	...	12	Tuc
HIP 116748A	DS Tuc A	HD 222259A	0.68	1	0.00	9	0.68	1,9	-4.09	1	11	Tuc
TYC 3320-545-1	Cl Melotte 20 699	...	0.70	16	0.10	17	0.60	16,17	-4.05	2	6	α Per
2UCAC 47800056	Cl* Melotte 20 AP 93	...	0.94	18	0.10	17	0.84	17,18	-4.05	1	6	α Per
TYC 3320-1283-1	Cl Melotte 20 622	...	0.82	19	0.10	17	0.72	17,19	-3.78	1	6	α Per
TYC 3321-1655-1	Cl Melotte 20 1101	...	0.69	20	0.10	17	0.59	17,19	-4.00	1	6	α Per
TYC 3315-1080-1	Cl Melotte 20 373	...	0.77	20	0.10	17	0.67	20,17	-4.04	2	6	α Per
2UCAC 47964793	Cl Melotte 20 696	...	0.74	19	0.10	17	0.64	17,19	-4.21	1	6	α Per
TYC 3319-306-1	Cl Melotte 20 350	...	0.69	19	0.10	17	0.60	17,19	-4.04	1	6	α Per
TYC 3320-583-1	Cl Melotte 20 935	...	0.63	19	0.10	17	0.53	17,19	-4.16	1	6	α Per
TYC 3319-306-1	Cl Melotte 20 350	...	0.69	19	0.10	17	0.60	17,19	-4.21	1	6	α Per
TYC 3319-589-1	Cl Melotte 20 389	...	0.67	16	0.10	17	0.57	16,17	-4.53	1	6	α Per
TYC 3320-2239-1	Cl Melotte 20 767	...	0.61	19	0.10	17	0.52	17,19	-4.62	2	6	α Per
TYC 3325-753-1	Cl Melotte 20 1234	...	0.72	16	0.10	17	0.62	16,17	-4.53	1	6	α Per
TYC 3320-423-1	Cl Melotte 20 750	...	0.59	19	0.10	17	0.49	17,19	-4.80	1	6	α Per
TYC 1799-1037-1	Cl Melotte 22 164	HD 23158	0.49	19	0.03	19,21	0.46	21	-4.33	2	23	Pleiades
TYC 1799-1224-1	Cl Melotte 22 233	HD 23195	0.53	19	0.03	19,21	0.49	21	-4.72	2	23	Pleiades
TYC 1800-1632-1	Cl Melotte 22 1726	HD 23713	0.54	19	0.04	19,21	0.51	21	-4.44	2	23	Pleiades
TYC 1804-2140-1	Cl Melotte 22 1776	HD 282958	0.72	19	0.04	19,21	0.68	21	-4.07	1	21	Pleiades
TYC 1799-978-1	Cl Melotte 22 745	HD 282969	0.52	19	0.03	19,21	0.50	21	-4.43	1	23	Pleiades
2UCAC 39967447	Cl Melotte 22 2106	...	0.86	19	0.04	19,21	0.82	21	-4.19	2	23	Pleiades
2UCAC 39967452	Cl Melotte 22 2126	...	0.85	19	0.04	19,21	0.81	21	-4.14	2	23	Pleiades
2UCAC 39967452	Cl Melotte 22 2126	...	0.85	19	0.04	19,21	0.81	21	-4.16	1	21	Pleiades
2UCAC 40300217	Cl Melotte 22 2027	...	0.86	19	0.04	19,21	0.82	21	-4.71	1	23	Pleiades
GSC 1799-960	Cl Melotte 22 625	...	1.17	19	0.36	19,21	0.82	21	-3.85	1	21	Pleiades

TABLE 4—*Continued*

(1) Astrometric Name	(2) SIMBAD Name	(3) HD Name	(4) $B-V$ mag	(5) Ref.	(6) E(B-V) mag	(7) Ref.	(8) $(B-V)_{\circ}$ mag	(9) Ref.	(10) $\log R'_{HK}$ dex	(11) N_{obs}	(12) Ref.	(13) Group
TYC 1799-1268-1	Cl Melotte 22 129	...	0.88	19	0.05	19,21	0.83	21	-4.27	1	23	Pleiades
TYC 1799-963-1	Cl Melotte 22 296	...	0.84	19	0.04	19,21	0.80	21	-3.90	1	21	Pleiades
TYC 1799-974-1	Cl Melotte 22 708	...	0.61	19	0.03	19,21	0.58	21	-3.88	2	23	Pleiades
TYC 1800-1091-1	Cl Melotte 22 2147	...	0.81	19	0.03	19,21	0.78	21	-4.11	2	23	Pleiades
TYC 1800-1616-1	Cl Melotte 22 1215	...	0.64	19	0.04	19,21	0.60	21	-4.26	1	23	Pleiades
TYC 1800-1620-1	Cl Melotte 22 1117	...	0.72	19	0.04	19,21	0.68	21	-4.57	2	23	Pleiades
TYC 1800-1683-1	Cl Melotte 22 1613	...	0.54	19	0.05	19,21	0.49	21	-4.42	1	23	Pleiades
TYC 1800-1716-1	Cl Melotte 22 1856	...	0.56	19	0.04	19,21	0.51	21	-4.39	1	23	Pleiades
TYC 1800-1852-1	Cl Melotte 22 1797	...	0.56	19	0.04	19,21	0.52	21	-4.36	1	23	Pleiades
TYC 1800-1917-1	Cl Melotte 22 923	...	0.62	19	0.04	19,21	0.58	21	-4.23	2	23	Pleiades
TYC 1803-156-1	Cl Melotte 22 727	...	0.55	19	0.03	19,21	0.52	21	-3.78	4	23	Pleiades
TYC 1803-542-1	Cl Melotte 22 405	...	0.54	19	0.04	19,21	0.49	21	-4.42	3	23	Pleiades
TYC 1803-808-1	Cl Melotte 22 489	...	0.63	19	0.10	19,21	0.53	21	-3.94	2	23	Pleiades
TYC 1803-944-1	Cl Melotte 22 739	...	0.62	19	0.04	19,21	0.59	21	-3.97	1	21	Pleiades
TYC 1804-2129-1	Cl Melotte 22 996	...	0.65	19	0.04	19,21	0.60	21	-4.25	3	23	Pleiades
TYC 1804-2205-1	Cl Melotte 22 1207	...	0.63	19	0.04	19,21	0.59	21	-4.29	1	23	Pleiades
2UCAC 39967447	Cl Melotte 22 2106	...	0.86	19	0.04	19,21	0.82	21	-3.94	1	6	Pleiades
TYC 1800-1091-1	Cl Melotte 22 2147	...	0.81	19	0.03	19,21	0.78	21	-3.94	1	6	Pleiades
TYC 1803-1351-1	Cl Melotte 22 173	...	0.85	19	0.04	19,21	0.81	21	-4.20	1	6	Pleiades
TYC 1804-1179-1	Cl Melotte 22 2278	...	0.87	19	0.04	19,21	0.83	21	-4.19	1	6	Pleiades
TYC 1803-1156-1	Cl Melotte 22 571	...	0.78	19	0.03	19,21	0.75	21	-4.40	1	6	Pleiades
TYC 1804-2140-1	Cl Melotte 22 1776	...	0.72	19	0.04	19,21	0.68	21	-4.30	1	6	Pleiades
TYC 1800-1526-1	Cl Melotte 22 2786	...	0.61	19	0.04	19,21	0.56	21	-4.38	1	6	Pleiades
TYC 1813-126-1	Cl* Melotte 22 PELS 191	...	0.71	1	0.04	1,21	0.67	21	-4.38	1	6	Pleiades
TYC 1803-574-1	Cl Melotte 22 314	...	0.66	19	0.04	19,21	0.61	21	-4.21	1	6	Pleiades
TYC 1800-471-1	Cl Melotte 22 2506	...	0.60	19	0.05	19,21	0.55	21	-4.43	1	6	Pleiades
TYC 1803-1061-1	Cl Melotte 22 514	...	0.70	19	0.04	19,21	0.66	21	-4.34	1	6	Pleiades
TYC 1799-102-1	Cl Melotte 22 120	...	0.71	19	0.04	19,21	0.67	21	-4.35	1	6	Pleiades
TYC 1800-1415-1	Cl Melotte 22 3179	...	0.57	19	0.03	19,21	0.53	21	-4.55	1	6	Pleiades
TYC 1804-1400-1	Cl Melotte 22 3097	...	0.74	19	0.04	19,21	0.70	21	-4.23	1	6	Pleiades
TYC 1799-118-1	Cl Melotte 22 102	...	0.72	19	0.04	19,21	0.68	21	-4.45	1	6	Pleiades
TYC 1800-1774-1	Cl Melotte 22 1182	...	0.64	19	0.04	19,21	0.60	21	-4.44	1	6	Pleiades
TYC 1804-1400-1	Cl Melotte 22 3097	...	0.74	19	0.04	19,21	0.70	21	-4.29	1	6	Pleiades
TYC 1799-118-1	Cl Melotte 22 102	...	0.72	19	0.04	19,21	0.68	21	-4.48	1	6	Pleiades
TYC 1800-1627-1	Cl Melotte 22 1200	...	0.54	19	0.03	19,21	0.51	21	-4.68	1	6	Pleiades
TYC 1803-818-1	Cl Melotte 22 250	...	0.69	19	0.05	19,21	0.64	21	-4.49	1	6	Pleiades
TYC 1803-818-1	Cl Melotte 22 250	...	0.69	19	0.05	19,21	0.64	21	-4.49	1	6	Pleiades
TYC 1804-2366-1	Cl Melotte 22 1015	...	0.65	19	0.04	19,21	0.61	21	-4.55	1	6	Pleiades
TYC 1804-305-1	Cl Melotte 22 2644	...	0.74	19	0.04	22	0.70	19,22	-4.42	1	6	Pleiades
TYC 1803-8-1	Cl Melotte 22 174	...	0.85	19	0.04	19,21	0.81	21	-3.48	1	6	Pleiades
HIP 15310	Cl Melotte 25 2	HD 20439	0.62	1	0.00	24	0.62	1,24	-4.49	3	23	Hyad
HIP 19786	Cl Melotte 25 18	HD 26767	0.64	1	0.00	24	0.64	1,24	-4.39	2	23	Hyad
HIP 14976	SAO 56256	HD 19902	0.73	1	0.00	24	0.73	1,24	-4.60	1	3	Hyad
HIP 15304	Cl Melotte 25 1	HD 20430	0.57	1	0.00	24	0.57	1,24	-4.66	3	23	Hyad
HIP 19148	Cl Melotte 25 10	HD 25825	0.59	1	0.00	24	0.59	1,24	-4.48	13	3	Hyad
HIP 19148	Cl Melotte 25 10	HD 25825	0.59	1	0.00	24	0.59	1,24	-4.57	3	23	Hyad
HIP 19793	Cl Melotte 25 15	HD 26736	0.66	1	0.00	24	0.66	1,24	-4.42	24	23	Hyad
HIP 19781	Cl Melotte 25 17	HD 26756	0.69	1	0.00	24	0.69	1,24	-4.47	27	23	Hyad
HIP 19786	Cl Melotte 25 18	HD 26767	0.64	1	0.00	24	0.64	1,24	-4.48	9	3	Hyad
HIP 19796	Cl Melotte 25 19	HD 26784	0.51	1	0.00	24	0.51	1,24	-4.49	1	23	Hyad
HIP 20130	Cl Melotte 25 26	HD 27250	0.74	1	0.00	24	0.74	1,24	-4.47	12	23	Hyad
HIP 20146	Cl Melotte 25 27	HD 27282	0.72	1	0.00	24	0.72	1,24	-4.45	45	23	Hyad
HIP 20237	Cl Melotte 25 31	HD 27406	0.56	1	0.00	24	0.56	1,24	-4.48	161	23	Hyad
HIP 20480	Cl Melotte 25 42	HD 27732	0.76	1	0.00	24	0.76	1,24	-4.48	10	23	Hyad
HIP 20492	Cl Melotte 25 46	HD 27771	0.85	1	0.00	24	0.85	1,24	-4.81	1	23	Hyad
HIP 20557	Cl Melotte 25 48	HD 27808	0.52	1	0.00	24	0.52	1,24	-4.52	183	23	Hyad
TYC 1265-569-1	Cl Melotte 25 49	HD 27835	0.60	1	0.00	24	0.60	1,24	-4.53	12	23	Hyad

TABLE 4—*Continued*

(1) Astrometric Name	(2) SIMBAD Name	(3) HD Name	(4) $B-V$ mag	(5) Ref.	(6) E(B-V) mag	(7) Ref.	(8) $(B-V)_\circ$ mag	(9) Ref.	(10) $\log R'_{HK}$ dex	(11) N_{obs}	(12) Ref.	(13) Group
HIP 20577	Cl Melotte 25 52	HD 27859	0.60	1	0.00	24	0.60	1,24	-4.45	102	23	Hyad
HIP 20719	Cl Melotte 25 63	HD 28068	0.65	1	0.00	24	0.65	1,24	-4.41	81	23	Hyad
HIP 20741	Cl Melotte 25 64	HD 28099	0.66	1	0.00	24	0.66	1,24	-4.50	81	23	Hyad
HIP 20815	Cl Melotte 25 65	HD 28205	0.54	1	0.00	24	0.54	1,24	-4.60	144	23	Hyad
HIP 20826	Cl Melotte 25 66	HD 28237	0.56	1	0.00	24	0.56	1,24	-4.46	2	23	Hyad
HIP 20826	Cl Melotte 25 66	HD 28237	0.56	1	0.00	24	0.56	1,24	-4.48	5	3	Hyad
HIP 20899	Cl Melotte 25 73	HD 28344	0.61	1	0.00	24	0.61	1,24	-4.44	33	23	Hyad
HIP 20899	Cl Melotte 25 73	HD 28344	0.61	1	0.00	24	0.61	1,24	-4.46	7	3	Hyad
HIP 20949	Cl Melotte 25 76	HD 283704	0.77	1	0.00	24	0.77	1,24	-3.63	1	23	Hyad
HIP 20978	Cl Melotte 25 180	HD 28462	0.86	1	0.00	24	0.86	1,24	-4.27	9	23	Hyad
HIP 20951	Cl Melotte 25 79	HD 285733	0.83	1	0.00	24	0.83	1,24	-4.44	12	23	Hyad
HIP 21280	Cl Melotte 25 96	HD 285931	0.85	1	0.00	24	0.85	1,24	-4.40	18	23	Hyad
HIP 21099	Cl Melotte 25 87	HD 28593	0.73	1	0.00	24	0.73	1,24	-4.46	21	23	Hyad
HIP 21112	Cl Melotte 25 88	HD 28635	0.54	1	0.00	24	0.54	1,24	-4.56	33	23	Hyad
TYC 1266-1012-1	Cl Melotte 25 91	HD 28783	0.88	19	0.00	24	0.88	19,24	-4.47	3	23	Hyad
TYC 1266-1286-1	Cl Melotte 25 92	HD 28805	0.74	19	0.00	24	0.74	19,24	-4.45	18	23	Hyad
HIP 21317	Cl Melotte 25 97	HD 28992	0.63	1	0.00	24	0.63	1,24	-4.48	60	23	Hyad
TYC 1266-1175-1	Cl Melotte 25 99	HD 29159	0.87	19	0.00	24	0.87	19,24	-4.40	9	23	Hyad
HIP 21637	Cl Melotte 25 105	HD 29419	0.58	1	0.00	24	0.58	1,24	-2.91	1	23	Hyad
HIP 21654	Cl Melotte 25 106	HD 29461	0.66	1	0.00	24	0.66	1,24	-4.55	15	3	Hyad
HIP 22380	Cl Melotte 25 116	HD 30505	0.83	1	0.00	24	0.83	1,24	-4.39	7	23	Hyad
HIP 22422	Cl Melotte 25 118	HD 30589	0.58	1	0.00	24	0.58	1,24	-4.75	1	23	Hyad
HIP 23069	Cl Melotte 25 127	HD 31609	0.74	1	0.00	24	0.74	1,24	-3.67	1	23	Hyad
HIP 19098	Cl* Melotte 25 PELS 10	HD 285367	0.89	1	0.00	24	0.89	1,24	-4.39	8	25	Hyad
HIP 24923	SAO 94471	HD 242780	0.77	1	0.00	24	0.77	1,24	-4.44	6	25	Hyad
HIP 23750	Cl* Melotte 25 S 140	HD 240648	0.73	1	0.00	24	0.73	1,24	-4.43	7	25	Hyad
HIP 20480	Cl Melotte 25 42	HD 27732	0.76	1	0.00	24	0.76	1,24	-4.46	8	25	Hyad
TYC 1266-1286-1	Cl Melotte 25 92	HD 28805	0.73	1	0.00	24	0.73	1,24	-4.44	7	25	Hyad
HIP 18327	Cl Melotte 25 7	HD 258252	0.90	1	0.00	24	0.90	1,24	-4.36	8	25	Hyad
HIP 20492	Cl Melotte 25 46	HD 27771	0.85	1	0.00	24	0.85	1,24	-4.39	8	25	Hyad
HIP 16529	Cl Melotte 25 4	...	0.84	1	0.00	24	0.84	1,24	-4.37	9	25	Hyad
HIP 20130	Cl Melotte 25 26	HD 27250	0.74	1	0.00	24	0.74	1,24	-4.45	8	25	Hyad
HIP 20850	Cl Melotte 25 178	HD 28258	0.84	1	0.00	24	0.84	1,24	-4.43	9	25	Hyad
HIP 15310	Cl Melotte 25 2	HD 20439	0.62	1	0.00	24	0.62	1,24	-4.54	13	25	Hyad
TYC 1266-1175-1	Cl Melotte 25 99	HD 29159	0.87	19	0.00	24	0.87	19,24	-4.38	8	25	Hyad
HIP 19261B	Cl Melotte 25 12	HD 26015B	0.65	1	0.00	24	0.65	1,24	-4.28	8	25	Hyad
HIP 20741	Cl Melotte 25 64	HD 20899	0.66	1	0.00	24	0.66	1,24	-4.47	9	25	Hyad
HIP 20949	Cl Melotte 25 76	HD 283704	0.77	1	0.00	24	0.77	1,24	-4.47	10	25	Hyad
HIP 13806	Cl Melotte 25 153	...	0.85	1	0.00	24	0.85	1,24	-4.38	18	25	Hyad
HIP 20557	Cl Melotte 25 48	HD 27808	0.52	1	0.00	24	0.52	1,24	-4.50	8	25	Hyad
HIP 19786	Cl Melotte 25 18	HD 26767	0.64	1	0.00	24	0.64	1,24	-4.44	15	25	Hyad
HIP 10672	SAO 110453	HD 14127	0.57	1	0.00	24	0.57	1,24	-4.55	12	25	Hyad
HIP 20951	Cl Melotte 25 79	HD 285773	0.83	1	0.00	24	0.83	1,24	-4.44	9	25	Hyad
HIP 19148	Cl Melotte 25 10	HD 25825	0.59	1	0.00	24	0.59	1,24	-4.47	8	25	Hyad
HIP 21317	Cl Melotte 25 97	HD 28892	0.63	1	0.00	24	0.63	1,24	-4.45	8	25	Hyad
TYC 1266-149-1	Cl Melotte 25 93	HD 28878	0.89	19	0.00	24	0.89	19,24	-4.40	8	25	Hyad
HIP 23069	Cl Melotte 25 127	HD 31609	0.74	1	0.00	24	0.74	1,24	-4.45	7	25	Hyad
HIP 19796	Cl Melotte 25 19	HD 26784	0.51	1	0.00	24	0.51	1,24	-4.54	11	25	Hyad
HIP 14976	SAO 56256	HD 19902	0.73	1	0.00	24	0.73	1,24	-4.57	10	25	Hyad
HIP 19781	Cl Melotte 25 17	HD 26756	0.69	1	0.00	24	0.69	1,24	-4.42	21	25	Hyad
HIP 20577	Cl Melotte 25 52	HD 27859	0.60	1	0.00	24	0.60	1,24	-4.47	9	25	Hyad
HIP 23498	Cl Melotte 25 187	HD 32347	0.77	1	0.00	24	0.77	1,24	-4.44	7	25	Hyad
HIP 20978	Cl Melotte 25 180	HD 28462	0.86	1	0.00	24	0.86	1,24	-4.41	7	25	Hyad
HIP 20815	Cl Melotte 25 65	HD 28205	0.54	1	0.00	24	0.54	1,24	-4.58	8	25	Hyad
HIP 13600	SAO 93184	...	0.70	1	0.00	24	0.70	1,24	-4.73	10	25	Hyad
HIP 15304	Cl Melotte 25 1	HD 20430	0.57	1	0.00	24	0.57	1,24	-4.68	13	25	Hyad
HIP 19793	Cl Melotte 25 15	HD 26736	0.66	1	0.00	24	0.66	1,24	-4.42	17	25	Hyad

TABLE 4—*Continued*

(1) Astrometric Name	(2) SIMBAD Name	(3) HD Name	(4) $B-V$ mag	(5) Ref.	(6) E(B-V) mag	(7) Ref.	(8) $(B-V)_\circ$ mag	(9) Ref.	(10) $\log R'_{HK}$ dex	(11) N_{obs}	(12) Ref.	(13) Group
HIP 20826	Cl Melotte 25 66	HD 28237	0.56	1	0.00	24	0.56	1,24	-4.46	8	25	Hyad
HIP 21741	Cl Melotte 25 109	HD 284574	0.81	1	0.00	24	0.81	1,24	-4.41	7	25	Hyad
HIP 20146	Cl Melotte 25 27	HD 27282	0.72	1	0.00	24	0.72	1,24	-4.46	9	25	Hyad
HIP 22422	Cl Melotte 25 118	HD 30589	0.58	1	0.00	24	0.58	1,24	-4.82	10	25	Hyad
HIP 22380	Cl Melotte 25 116	HD 30505	0.83	1	0.00	24	0.83	1,24	-4.33	9	25	Hyad
HIP 20899	Cl Melotte 25 73	HD 28344	0.61	1	0.00	24	0.61	1,24	-4.50	10	25	Hyad
HIP 22566	Cl Melotte 25 143	HD 30809	0.53	1	0.00	24	0.53	1,24	-4.58	7	25	Hyad
HIP 21099	Cl Melotte 25 87	HD 28593	0.73	1	0.00	24	0.73	1,24	-4.48	9	25	Hyad
TYC 1265-569-1	Cl Melotte 25 49	HD 27835	0.60	1	0.00	24	0.60	1,24	-4.52	8	25	Hyad
HIP 21112	Cl Melotte 25 88	HD 28635	0.54	1	0.00	24	0.54	1,24	-4.56	10	25	Hyad
HIP 20237	Cl Melotte 25 31	HD 27406	0.56	1	0.00	24	0.56	1,24	-4.45	8	25	Hyad
HIP 20978	Cl Melotte 25 180	HD 28462	0.86	1	0.00	24	0.86	1,24	-4.29	1	6	Hyad
HIP 21637	Cl Melotte 25 105	HD 29419	0.58	1	0.00	24	0.58	1,24	-4.52	8	25	Hyad
HIP 21280	Cl Melotte 25 96	HD 285931	0.85	1	0.00	24	0.85	1,24	-4.47	1	6	Hyad
HIP 20951	Cl Melotte 25 79	HD 285733	0.83	1	0.00	24	0.83	1,24	-4.52	1	6	Hyad
HIP 21112	Cl Melotte 25 88	HD 28635	0.54	1	0.00	24	0.54	1,24	-4.39	1	6	Hyad
TYC 1266-1012-1	Cl Melotte 25 91	HD 28783	0.88	19	0.00	24	0.88	19,24	-4.80	1	6	Hyad
TYC 1266-149-1	Cl Melotte 25 93	HD 28878	0.89	19	0.00	24	0.89	19,24	-4.63	1	6	Hyad
TYC 1266-1175-1	Cl Melotte 25 99	HD 29159	0.87	19	0.00	24	0.87	19,24	-4.69	1	6	Hyad
HIP 19386	SAO 111629	HD 26257	0.55	1	0.00	24	0.55	1,24	-5.16	9	25	Hyad
HIP 20577	Cl Melotte 25 52	HD 27859	0.60	1	0.00	24	0.60	1,24	-4.47	1	6	Hyad
HIP 20719	Cl Melotte 25 63	HD 28068	0.65	1	0.00	24	0.65	1,24	-4.52	1	6	Hyad
TYC 1266-1286-1	Cl Melotte 25 92	HD 28805	0.74	19	0.00	24	0.74	19,24	-4.61	1	6	Hyad
HIP 20441	Cl Melotte 25 39	HD 27685	0.68	1	0.00	24	0.68	1,24	-4.58	1	6	Hyad
HIP 20741	Cl Melotte 25 64	HD 28099	0.66	1	0.00	24	0.66	1,24	-4.62	1	6	Hyad
HIP 20826	Cl Melotte 25 66	HD 28237	0.56	1	0.00	24	0.56	1,24	-4.55	1	6	Hyad
HIP 20899	Cl Melotte 25 73	HD 28344	0.61	1	0.00	24	0.61	1,24	-4.59	1	6	Hyad
HIP 21317	Cl Melotte 25 97	HD 28992	0.63	1	0.00	24	0.63	1,24	-4.52	1	6	Hyad
HIP 21654	Cl Melotte 25 106	HD 29461	0.66	1	0.00	24	0.66	1,24	-4.58	1	6	Hyad
HIP 22203	Cl Melotte 25 142	HD 30246	0.67	1	0.00	24	0.66	1,24	-4.63	1	6	Hyad
TYC 1265-569-1	Cl Melotte 25 49	HD 27835	0.59	19	0.00	24	0.59	19,24	-4.62	1	6	Hyad
HIP 25639	SAO 58077	HD 35768	0.56	1	0.00	24	0.56	1,24	-5.38	6	25	Hyad
HIP 22566	Cl Melotte 25 143	HD 30809	0.53	1	0.00	24	0.53	1,24	-4.67	1	6	Hyad
HIP 15304	Cl Melotte 25 1	HD 20430	0.57	1	0.00	24	0.57	1,24	-4.73	1	6	Hyad
HIP 8486	GJ 9061B	HD 11131	0.65	1	0.00	9	0.65	1,9	-4.47	4	11	UMa
HIP 8486	GJ 9061B	HD 11131	0.65	1	0.00	9	0.65	1,9	-4.52	...	31	UMa
HIP 19859	HR 1322	HD 26923	0.57	1	0.00	9	0.57	1,9	-4.55	...	31	UMa
HIP 19859	HR 1322	HD 26923	0.57	1	0.00	9	0.57	1,9	-4.52	...	31	UMa
HIP 21276	GJ 3295	HD 28495	0.76	1	0.00	9	0.76	1,9	-4.34	6	3	UMa
HIP 27072	HR 1983	HD 38393	0.48	1	0.00	9	0.48	1,9	-4.77	3	11	UMa
HIP 27072	HR 1983	HD 38393	0.48	1	0.00	9	0.48	1,9	-4.82	...	31	UMa
HIP 27913	HR 2047	HD 39587	0.59	1	0.00	9	0.59	1,9	-4.46	...	31	UMa
HIP 27913	HR 2047	HD 39587	0.59	1	0.00	9	0.59	1,9	-4.43	...	31	UMa
HIP 36704	HR 8883	HD 59747	0.86	1	0.00	9	0.86	1,9	-4.37	1	3	UMa
HIP 36704	HR 8883	HD 59747	0.86	1	0.00	9	0.86	1,9	-4.46	...	31	UMa
HIP 42438	HR 3391	HD 72905	0.62	1	0.00	9	0.62	1,9	-4.40	3	3	UMa
HIP 42438	HR 3391	HD 72905	0.62	1	0.00	9	0.62	1,9	-4.48	1	6	UMa
HIP 80686	HR 6098	HD 147584	0.56	1	0.00	9	0.56	1,9	-4.56	1	11	UMa
HIP 80686	HR 6098	HD 147584	0.56	1	0.00	9	0.56	1,9	-4.58	...	31	UMa
HIP 88694	HR 6748	HD 165185	0.61	1	0.00	9	0.61	1,9	-4.54	...	31	UMa
HIP 115312	HR 8883	HD 220096	0.82	1	0.00	9	0.82	1,9	-4.39	1	3	UMa

NOTE.—References and notes: (1) Perryman & ESA (1997), (2) unreddened $B-V$ color appropriate for spectral type given by other reference, (3) Wright et al. (2004), (4) Walter et al. (1994), (5) I have assumed A_V/E(B-V) = 3.1 in converting a A_V value to E(B-V), (6) White, Gabor, & Hillenbrand (2007), (7) Preibisch & Zinnecker (1999), (8) Høg et al. (2000) (converted to Johnson using Mamajek et al. (2006), (9) star is within 75 pc and presumed to have no reddening, (10) Gray et al. (2006), (11) Henry et al. (1996), (12) Soderblom et al. (1998), (13) Wichmann et al. (1997), (14) Mamajek et al. (2002), (15) Nordström et al. (2004), (16) Prosser (1992), (17) Crawford & Barnes (1974), (18) Messina (2001), (19) Mermilliod (1991), (20) Stauffer et al. (1989), (21) Soderblom et al. (1993), (22) Stauffer & Hartmann (1987), (23) Duncan et al. (1991), converted to to $\log R'_{HK}$

following Noyes et al. (1984), (24) Taylor (2006), (25) Paulson et al. (2002), (26) Upgren et al. (1985), (27) Reid (1992), (28) Weis & Upgren (1982), (29) van Altena (1969), (30) Weis & Hanson (1988), (31) Gray et al. (2003)