Alkali-Activity Correlations in Open Clusters

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Received __________________; accepted __________________

to appear in *The Astronomical Journal*, December 2004

ABSTRACT

We present a census of correlations between activity measures and neutral resonance lines of the alkali elements Li I and K I in open clusters and star forming regions. The majority of very young associations and star formation regions show no evidence of Li-activity correlations, perhaps because their chromospheric activity indicators have a dominant origin in accretion processes with implied disk clearing timescales in the range of a few $\times 10^6$ to $\sim 4\times 10^7$ years. Alkali-alkali and/or -activity correlations are newly noted within IC 2391, M34, and perhaps Blanco 1 and NGC 6475. Global x-ray luminosities are not as robust indicators as traditional optical indicators of alkali-activity correlations, nor are Li I-K I relations. Intracluster alkali-activity correlations are *not* global, but are seen only within different intracluster subsamples, evincing rich behavior. Li- and K-activity correlations appear to go hand-in-hand, likely suggesting at least some part of intracluster Li variance is not due to real differential Li depletion. While up to $\sim$90% of the star-to-star variance in Li I and K I within such a subsample can be related to that in optical chromospheric emission, significant Li dispersion above observational scatter may remain even after accounting for this. We suggest, e.g., that *at least* 3 independent mechanisms (including a possible intra-cluster age spread) influence the distribution in the M 34 Li-$T_{\rm eff}$ plane. We argue that Li-activity correlations are not illusory manifestations of a physical Li-rotation connection. While an unexpected correlation between Li, chromospheric emission, and the λ6455 Ca I feature in cool M 34 dwarfs indicates the role of "activity" is played by spots/plages, we note that the alkali-"activity" correlations are qualitatively opposite in sign to other abundance anomalies being rapidly delineated in active, young, cool stars.

Subject headings: line: formation – Open clusters and associations – stars: abundances, activity, late-type

1. Introduction

The key prediction of standard stellar models (SSMs) that photospheric Li astration is uniquely a function of mass, chemical composition, and age has encountered significant observational challenges. Statistically significant star-to-star Li abundance spreads have been reported in numerous open clusters spanning a large range in age (e.g., IC 2602, 35-50 Myr, Randich et al. 2001; Pleiades, 100 Myr, Duncan & Jones 1983; M34, 220 Myr, Jones et al. 1997; Hyades, 650 Myr, Thorburn et al. 1993; and M67, 4.5 Gyr, Pasquini et al. 1997, Jones et al. 1999). Existing work indicates that such scatter seems predominantly–perhaps exclusively–confined to K dwarfs (48) with the exception of G dwarfs in M67.

The observed steepening decline in the Li-$T_{\rm eff}$ relation for progressively older clusters, relative overabundance of Li in short-period tidally-locked binaries in clusters of intermediate-to-old age, and intracluster Li scatter all suggest the need to augment SSMs with main-sequence Li depletion mechanisms. Such refined models, however, seem ill-equipped to explain intracluster Li spreads in ZAMS- or PMS-aged clusters. Other refinements that might account for Li scatter in young clusters include star-to-star composition differences (53), the effects of magnetic fields (84), and allowance for intracluster age spreads (e.g., Soderblom et al. 1993a).

A relation between relative Li content and chromospheric activity level in the Pleiades was inferred by Soderblom et al. (1993a); using cumulative x-ray luminosity distributions for samples of differing relative Li content, Favata et al. (19) suggested the existence of a Li/x-ray luminosity connection in the Pleiades. Recent investigations, however, have suggested that some portion of intracluster Li scatter is merely illusory (e.g., Jeffries 1999). King et al. (37) have shown that the majority of Pleiades stars showing enhanced Li abundances (relative to neighbors in the cluster H-R diagram) indeed do have the largest measures of chromospheric emission. Specifically, there is a significant correlation between star-to-star Li abundance excess/deficit and star-to-star chromospheric emission excess/deficit– both quantities being measured relative to mean cluster relations. Based on preliminary work with Li in the dual young clusters NGC 2451 A and B, Margheim et al. (40) suggested that at least some portion of a Pleiades Li-rotation connection stems from v sin i-dependent measurement errors.

Also troubling is a correlation in the Pleiades between differential line strengths of λ7699 K I and differential chromospheric emission values (King et al. 2000, and suspected by Soderblom et al. 1993a for Pleiads with $B-V\leq0.9$). Randich (2001; hereafter R01) reports that active stars with $0.75\leq(B-V)_0\leq1$ in the young IC 2602 cluster show significant dispersion in their λ7699 K I equivalent widths, and that these line strengths are significantly enhanced over inactive field star values (82). Moreover, these K I excesses/deficits were found to correlate with stellar x-ray luminosity, thus suggesting a relation with stellar activity in this young cluster too. An important additional finding of R01 is the lack of K I dispersion in IC 2602 outside the above color range; this contrasts with the significant λ6707 Li I dispersions for $(B-V)>1$.

Since K is immune from stellar depletion processes, there is great benefit in theoretical work suggesting the λ7699 K I feature can be used as an excellent “proxy” to investigate the details of λ6707 Li I line formation (79). Such work (e.g., Houdebine & Doyle 1995) and the above observations suggest that significant Li scatter in young clusters might arise from differential NTLE effects related to stellar activity differences (or the effects of a surrounding chromosphere on photospheric structure; Stuik et al. 1997). "NLTE effects" likely describes a number of distinct, though intricately inter-related, processes that make modeling the Li I and K I features difficult; besides (79) and Houdebine & Doyle (27), two other notable explorations of alkali resonance line formation are Bruls et al. (7) and Carlsson et al. (8), who review previous work and lay out considerable ground work of their own.

Inasmuch as additional observational progress seems needed to better understand Li I line formation in cool dwarfs (the key to which may indeed be first understanding K I line formation, as stressed by Carlsson et al. and Stuik et al.), here we investigate the relation between the Li I and K I line strengths and activity in open clusters and young star forming regions or associations having meaningful sample sizes and datasets with which to do so. The objects we consider provide a potentially important age baseline. While we anticipated that the dispersions in chromospheric emission (and projected rotational velocity) and Li are smaller in many of these aggregates than in the Pleiades, an interesting question is if the dispersions remain correlated. We also sought evidence of the troubling correlation between K I line strength and activity in additional environments. Finally, we wished to utilize the growing body of open cluster abundance and activity data to explore the universality of Li-K-activity correlations by searching for intercluster and/or intracluster differences in them.

2. Data, Analysis, and Results

To supplement our own (65) and extant data for M34, we searched the literature for additional stellar aggregates of $\geq$15 – 20 objects having: both Li and activity measurements that that were not simply upper limits; membership evaluated (or re-evaluated by us as needed) through a variety of means (photometry, radial velocities, proper motions, rotational velocity or activity itself); and self-consistent temperature or photometric color estimates. Known double-lined binaries have usually been excluded since continuum dilution of the spectral lines is generally ill-constrained. With these data in hand for a particular aggregate, we detrend the various measurements (Li, activity, potassium) as a function of color or temperature using polynomial fitting as in King et al. (37). We stress that the goal of such a procedure is not to derive formal mean relations between these quantities, but simply to remove the global intracluster mass-dependence (and/or perhaps NLTE effects; Schuler et al. 2003) of chromospheric/coronal emission and Li depletion (by whatever mechanism) so that star-to-star scatter at a given color/mass/$T_{\rm eff}$ can be isolated. For each stellar aggregate, all available Li or K or activity[1]. data was used in the fitting regardless of whether present in the combined Li-activity or Li-K sample.

An example of this fitting procedure is shown in Figure 1 for Li abundances, Hα flux measurements, and K I equivalent widths for our M34 sample described below. The observed minus fit deviations above or below each stellar aggregates' mass-dependent baseline (which the polynomial fits are meant to represent) are hereafter referred to as "differential" or "residual" values, and labeled with the symbol Δ in the figures. Two important notes are as follows. First, we have altered the sign convention in a few original sources to consistently ensure here that larger positive activity residuals represent enhanced relative emission, while larger positive Li or K residuals represent relative abundance enhancements (i.e., stronger line absorption). Second, residual or differential values involving Li, K, or Hα equivalent widths (as well as the linear unnormalized x-ray fluxes for Lupus) are normalized by the (absolute value of) the fitted values themselves in order

[1]The chromospheric activity measures, log R, are the logarithmic ratio of emission line (either Ca II H&K, Hα, or Ca II infrared triplet) flux at the stellar surface to the bolometric flux; i.e., $\log R = \log{(F_L/\sigma T_{\rm eff}^4)}$

to represent fractional abundances or chromospheric fluxes[2].

In looking at possible correlations between these fractional abundances, line strengths, activity measures, etc., we found it important to consider the basic statistical methodology. In particular, because a) an outlying point or two with extremely large activity measure (not uncommon in the very very young systems) might spuriously mask or introduce significant correlations between residual activity and Li as assessed with the traditional linear correlation coefficient, and b) the adequacy of assuming a linear relation between the Li and activity residuals is unclear, we computed rank correlation (i.e., Spearman) coefficients for our datasets. The reader wishing to skip the details of the sample selection, data description, and individual statistical results may wish to jump to §3 for a discussion of the results.

2.1. Very young associations and star formation regions

Li and activity data for 9 very young (few Myr) aggregates were available. Model dependent ages, which generally ignore the possibility of few Myr age spreads, are taken from the same references and given in parentheses following the aggregate's name along with the number of objects having intersecting Li and activity data. Li and Hα equivalent widths for the Chameleon star forming region ($\sim$5 Myr; 51 objects) were taken from Covino et al. (11); $(B-V)$ photometry is taken from Alcalá et al. (1). Li and Hα equivalent widths and $T_{\rm eff}$ estimates for PMS stars in the Upper Scorpius OB Association ($\sim$5 Myr; 166 objects) were taken from Preibisch et al. (55). Dolan & Mathieu (1999, 2001) provide $(R-I)$ colors and Li and Hα equivalent widths for the λ Ori star forming region ($\sim$7 Myr; 256 objects). $(R-I)$ colors, Li equivalent widths, and Hα-to-bolometric luminosity ratios in the σ Ori

[2]For example, $\Delta EW({\rm H}\alpha) = [EW({\rm H}\alpha_{\rm obs}) - EW({\rm H}\alpha_{\rm fit})]/|EW({\rm H}\alpha_{\rm fit})|$

PMS cluster (∼3 Myr; 27 objects) come from Zapatero Osorio et al. (92). Mamajek, Meyer, & Liebert (39) provide photometric temperatures and Li and Hα equivalent widths of PMS stars in the Upper Cen-Lup (∼17 Myr; 63 objects) and Lower Cen-Crux (∼16 Myr; 47 objects) subgroups of the Sco-Cen OB association. $(B-V)$ colors and Li abundances provided by Soderblom et al. (69) and King (38), and x-ray-to-bolometric luminosity ratios from Flaccomio et al. (21) are utilized for NGC 2264 (5-10 Myr; 12 objects). Wichmann et al. (1996,2000) provide $(B-V)$ colors, ROSAT-based x-ray and bolometric luminosities, and Li and Hα line strengths for PMS stars in the Taurus-Auriga T Tauri association (5-10 Myr; 31 objects). Two samples were taken for the Lupus star forming region (≤10 Myr; 56 and 46 objects). Spectral-type-based $T_{\rm eff}$ estimates and Li and Hα equivalent widths from Wichmann et al.(1997a,1999) comprise the first sample. The second sample consists of Li equivalent width, ROSAT-based X-ray fluxes, and spectral types from Wichmann et al. (90); we calculated $T_{\rm eff}$ values from the spectral types in the same manner as Wichmann et al. (88).

The residual Li values are plotted versus the residual chromospheric/coronal emission measures in Figures 2 and 3; a few points lying outside the bounds of these (and subsequent) plots have been omitted for clarity, but still included in the statistical analyses. The Spearman coefficient for Upper Sco is significant at the 99.3% confidence level. As the referee has stressed, while this correlation is significant, it is not a clean one– indeed, only some 22% of the variance in Li equivalent widths is associated with that of the Hα differences. Independent, higher resolution measurements would be desirable in order to eliminate the possibility of effects such as correlated measurement errors in Li and Hα. Inspection of Figures 2 and 3 suggests that stars with low residual Li in λ Ori and Upper Cen-Lup tend to be stars with low residual activity; these aggregates' Spearman coefficients are significant at the 83% and 97% confidence levels respectively. None of the other aggregates evince significant correlations. Fig. 2

Fig. 3

2.2. The Young Clusters IC 2391, IC 2602, and α Persei

The clusters IC 2391, IC 2602, and α Persei may all be coeval at $\sim$50 Myr, though the estimated ages range from 35-50 Myr for the former two clusters (e.g. Barrado Y Navascués, Stauffer & Patten 1999), and 50-70 Myr for α Per (e.g., Prosser 1992); consistent comparison clearly indicates these clusters are no more than 50-75% of the Pleiades age (e.g., the color-magnitude diagrams from Pinsonneault et al. 1998). Li abundances, Hα and λ7699 K I equivalent widths, and $T_{\rm eff}$ values for IC 2391 and 2602 members were taken from Randich et al. (58), Stauffer et al. (74), and Randich (59) respectively. $L_X/L_{\rm Bol}$ ratios were taken from Stauffer et al. (74) and supplemented by x-ray data from Simon & Patten (67) and Randich et al. (60); when needed, bolometric luminosities were calculated using the distance moduli inferred from Figure 4 of Stauffer et al. (74) and the bolometric corrections of Johnson (32). Membership information, lithium abundances, photometric colors, $T_{\rm eff}$ values, and x-ray luminosities for α Per stars were taken from the studies of Prosser (56), Stauffer et al. (76), Balachandran, Lambert & Stauffer (1988; updated as needed in Balachandran, Lambert & Stauffer 1996), Randich et al. (61), Prosser et al. (57), and Randich et al. (62). Figures 4 and 5 show the residual Li abundances versus residual chromospheric/coronal emission measurements. Randich et al. (58) noted color-dependent behavior in the dispersions of the λ7699 K I line in IC 2602. We thus divided all our samples into two bins with a cut near $(B-V)_0\sim$1.0. Fig. 4
Fig. 5

For the cool objects in IC 2391, the Spearman coefficient indicates a correlation between residual Li and Hα-based activity at the 99.7% confidence level; no statement can be made regarding trends with x-ray-based activity residuals given the fewer points with near-zero spread in residual activity. The correlation coefficient suggests some 97% of the variance in Li scatter in the cool stars is related to that in Hα. The Spearman coefficient for the warm IC 2391 stars indicates a correlation between residual Li and Hα is significant at a marginal 93.9% confidence level; the correlation coefficient here suggests 50% of the global variance in Li abundance is associated with that of the Hα line strength. No significant correlation between residual Li abundances and x-ray luminosities is seen, however.

The IC 2602 results are starkly different. For the cool cluster stars, no significant correlation is seen between residual Li abundance and either Hα line strength or x-ray luminosity. Rather, the Spearman coefficient for the warm IC 2602 stars indicates a correlation between residual Li abundance and Hα line strength significant at the 99.997% confidence level. For these stars, 64% of the variance in Li abundance is associated with that in Hα line strength. In contrast to IC 2391, these results seem confirmed by the x-ray luminosities, whose residuals are correlated with those in Li abundance at the 98.9% confidence level according to the Spearman coefficient. The strength of the correlation is modest, however, with 54Since it is unclear why errors in the x-ray luminosities might be correlated with those in Li abundances, the relationship is perhaps best viewed, then, as a probabilistic one or one component of a multivariate correlation.

As inspection of Figure 5 indicates, no significant correlation exists between residual Li abundances and x-ray luminosities for either the warm or cool stars in α Per. Considerable caution is warranted, though, in concluding there is no Li-activity relation for this cluster. As the results in Figure 4 indicate for both IC 2391 and IC 2602, x-ray luminosities apparently are not a robust means for inferring Li-Hα-based activity relations.

Correlations between residual λ7699 K I line strengths and residual activity indicators are of keen interest since their existence rules out stellar depletion mechanisms and/or age spreads (possibly manifested via chromospheric/coronal emission spreads) as the source of the Li-activity connection. Figure 6 indicates that, just as for Li, such a correlation is indeed seen for K I in warm IC 2602 stars. The Spearman coefficient is significant at the 99.8% and 95.0% confidence levels in the ΔEW(K)-ΔEW(Hα) and ΔEW(K)-$\Delta\log L_{\rm X}/L_{\rm Bol}$ planes. The correlation coefficient suggests that 73% and 53% of the variance in K I equivalent width is associated with that in Hα line strength and x-ray luminosity, respectively. Two additional notes are worth mentioning. First, as with Li in IC 2602 and IC 2391, x-ray emission seems to be a less robust tracer of K-activity relations. Second, comparison of Figures 4 and 6 indicates the dispersion in fractional K I equivalent width pales in comparison to that of Li abundance– particularly in the cool stars. Fig. 6

2.3. ZAMS Clusters: NGC 2516, Blanco 1, and the Pleiades

Given the canonical Pleiades age of 100 Myr (Meynet et al. 1993), self-consistently inferred ages of 140 Myr (Meynet et al. 1993; Pinsonneault et al. 1998) suggest NGC 2516 is slightly older. Estimates for Blanco 1 suggest ages both slightly below (85) and above (46) the Pleiades value; one can probably reasonably conclude the cluster is Pleiades age plus or minus 20%. Li abundances and photometry of Blanco 1 members are taken from Table 1 of Jeffries & James (30). Hα equivalent widths were taken from Panagi & O'dell, M. A. (46) & Panagi et al. (47), who also present Li measurements. We have not utilized the latter data since Li equivalent widths for stars in common with Jeffries & James (30) are discordant; we suspect that resolution differences may play a role in this, but the possibility of intrinsic variability (50) remains an intriguing open question worthy of future study. Blanco 1 x-ray luminosities are taken from **(author?)** (Micela et al. 1999). Li abundances, $T_{\rm eff}$ values, and x-ray luminosities for NGC 2516 are taken from Jeffries, James & Thurston (31). Li abundances, K I equivalent widths, photometry, and optical activity measures for the Pleiades are identical to those described in King et al. (37)[3]. These were supplemented by

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[3]For consistency with the IC 2391/2602 and M34 data, the average of their $(B-V)_0$- and $(V-I)_0$-based $T_{\rm eff}$ and (concomitantly) detrended Li abundances are employed here.

x-ray luminosity ratios (with respect to bolometric) from Stauffer et al. (75) and Micela et al. (1999b, 1996); when needed, bolometric luminosities were calculated using the distance modulus of 5.63 from Pinsonneault (54) and the bolometric corrections of Johnson (32).

Figure 7 plots residual Li abundance versus both residual x-ray luminosity and Hα equivalent width for Blanco 1. The Spearman coefficient is significant at only the 85% confidence level for the residual Li/x-ray data. For the Li-Hα data, significance is at the 92.2% confidence level; the linear correlation coefficient is significant at the 99.6% confidence level (and suggests 69% of the observed variance in Blanco 1 Li abundances is associated with that in Hα equivalent widths). While the Li-Hα results are ambiguous, the difference between them and the Li-xray results is analogous to that seen for IC 2391 and 2602.

Figure 8 shows residual Li abundances versus residual x-ray luminosity ratios for NGC 2516 stars. No trend is visible, and this is confirmed by both the linear correlation and Spearman coefficients; the latter is significant at only the 82% confidence level, and the former suggests that only 38% of the variance in NGC 2516 Li abundance is associated with that in x-ray luminosity. Again, as the results for IC 2391, 2602, and (now) Blanco 1 suggest, concluding there is no Li-"activity" relation in NGC 2516 on the basis of x-ray data is premature. Measurements of the usual optical chromospheric emission indicators in NGC 2516 would be of considerable interest. Fig. 7

Fig. 8

The Pleiades exhibit a rich diversity of behavior in Li-activity and K-activity relations, as well as differences with activity indicator and stellar subset ("warm" versus "cool"). Figure 9 compares Li abundances and residual fractional K I equivalent widths versus residual activity measures for Pleiades dwarfs, which are again segregated into "warm" and "cool" objects as above (which we were unable to do for Blanco 1 and NGC 2516). For both warm and cool stars, all trends between both residual Li abundance or residual K I equivalent width and all three residual activity indicators are highly significant (at confidence levels ranging from 97.9% to 99.997% according to the Spearman coefficients) except for three cases: residual Li abundance versus residual Hα flux for cool Pleiads (a marginal 82.8% confidence level); residual Li abundance versus residual x-ray luminosity for cool Pleiads (41.5% confidence level); and residual K I equivalent width versus residual Ca II infrared triplet flux for cool Pleiads (75.3% confidence level). The ordinary linear correlation coefficients confirm these patterns, and suggest intimate Li-activity and, more importantly, K-activity relations in the Pleiades. For example, 52% and 61% of the variance in Li abundance is related to that in Ca II infrared triplet flux for cool and warm Pleiads, respectively; 68% and 75% of the variance in residual K I equivalent width is related to that in Ca II flux in warm Pleiads, and to that in Hα flux in cool Pleiads, respectively. Fig. 9

While there is strong evidence of Li-activity and K-activity correlations in the Pleiades, a distinct question is to what extent there exist correlations between Li and K. This is addressed in Figure 10 which plots the residual Li abundances versus the residual fractional K I equivalent widths. Intriguingly, the cool stars show no significant correlation; only $\leq$6% of the variance in Li abundance is associated with that in K I equivalent width. In contrast, the Spearman coefficient indicates a correlation at the 99.0% confidence level for the warm Pleiads; some 42% of the variance in Li abundance is associated with that in K I line strength for these objects. Fig. 10

2.4. Intermediate Age, Post-ZAMS Clusters: NGC 6475, M 34, and the Hyades

The clusters NGC 6475 (220 Myr; Meynet et al. 1993) and M 34 (180-250 Myr; Meynet et al. 1993, Jones et al. 1997) are perched in age between the $\sim$100 Myr old Pleiades and the $\sim$650 Myr old Hyades (e.g., Perryman et al. 1998). James & Jeffries (28) provide photometry, Li equivalent widths, and Hα, Ca II infrared triplet, and x-ray flux ratios for NGC 6475; we have derived Li abundances from these data using an updated version of the LTE analysis package MOOG (68), Kurucz (1992; private communication) model atmospheres, and $T_{\rm eff}$ values calculated from equation (3) of Soderblom et al. (72); results are given in Table 1. M34 photometry, Li abundances, and Hα and Ca II infrared triplet chromospheric flux ratios are taken from (34) and Soderblom et al. (70); we have ignored stars with $(B-V)_0 \leq 0.47$ in order to avoid Li gap stars, whose abundances may be significantly altered by processes having no relation with activity. Equivalent widths of the λ7699 K I line were measured in the course of our M34 abundance study (65) and are presented in Table 2. Ca II K-based flux ratios for Hyades dwarfs were taken from the recent work of Paulson et al. (51). Hyades Li abundances are taken from Balachandran (4), and culled of SB2 and short-period tidally locked binaries. Tab. 1 Tab. 2

The NGC 6475 results are contained in Figure 11, which shows differences and similarities with the analogous Pleiades results in Figure 9. Unlike the Pleiades, the residual Li abundance of warm objects in NGC 6475 show no correlation with residual Ca II, Hα, or x-ray flux ratios. On the other hand, while the cool objects are too few for a meaningful statistical comparison, their residual Li abundances seem consistent with those in the Pleiades in showing a correlation with residual Ca II emission, perhaps residual Hα emission, but not residual x-ray emission. Fig. 11

The residual Li abundances and K I equivalent widths are shown versus residual chromospheric fluxes for M 34 in Figure 12. The results are consistent with the qualitative ones for NGC 6475 showing both similarities and contrasts with those for the Pleiades. In particular, in contrast to the Pleiades, the Spearman coefficients indicate that warm M34 objects evince no significant correlation between either residual Li abundance or residual K I equivalent width and residual activity. The cool M34 dwarfs, however, do exhibit significant correlations (at the 94.0-98.8% confidence level) between either residual Li abundance or residual K I line strength and residual activity; indeed, 87.4% (88.0%) of the variance in Li abundance (K I equivalent width) is associated with that in Ca II (Hα) emission. Fig. 12

Like the Pleiades, there is clear evidence of Li-activity and K-activity correlations in M34– though not in the warm dwarfs. Again, a distinct question is the existence of a correlation between Li and K. Residual Li abundances and K I line strengths are plotted in Figure 13. The results are in stark contrast to the Pleiades'. In M34, the warm dwarfs do not exhibit a significant Li-K correlation (76% confidence level), though the variance in Li abundance associated with that in K I line strength (40%) is similar to the warm Pleiads. Rather, it is the cool M34 objects which seem to demonstrate a correlation between Li and K residuals (93.1% confidence level); some 70% of the variance in Li abundance is associated with that in K I equivalent width in cool M34 dwarfs. Fig. 13

The Hyades residual Li abundances are plotted versus residual Ca II K-based emission flux ratios in Figure 14. These stars do not show evidence of a significant correlation between residual Li and residual activity. The Spearman coefficient suggests the inverse trend in Figure 14 is significant at only the 59% confidence level; only some 18% of the variance in Li abundance is associated with that in K-line emission. Fig. 14

3. Discussion

A qualitative summary of the possible correlations for the various stellar aggregates is presented in Table 3. In most cases, the statistics are reasonably unambiguous as to whether a significant correlation exists. A "Y?" entry in Table 3 denotes cases where the observed scatter might be approached by the star-to-star uncertainties when the latter are not especially well defined; as the referee notes, a concern in such cases is that one may simply be looking at a correlation between errors. We also use "Y?" to denote cases where the correlation is statistically significant but not markedly strong (generally $\leq$50% of the variance in one variable is associated with that in the other variable). This could arise from correlations that are multivariate in nature. From the experience of first using the likely errant Hyades abundances of Thorburn et al. (81), we noted that significant correlations of low strength can also arise from errors in the details of the Li computation. Such cases should be viewed with caution and an eye towards future observational clarification. A "?" entry indicates cases where an interestingly high but not significant correlation is found or where additional data are needed to definitively address the existence or not of correlations.

Tab. 3

3.1. Li and Activity in Very Young Stars: Implications for Disks/Accretion?

The majority of very young systems in Figures 2 and 3 do not exhibit correlations between residual Li abundances and residual x-ray or Hα emission. These results (or those for Hα anyway, see below) are in contrast with the correlations found in older clusters. While veiling associated with increased Hα emission could, in principle, dilute Li absorption line strengths (the correct sense to mask the trend in the Li-Hα residuals seen in older systems), few of the objects in our very young systems have Hα equivalent widths ($\geq$few Å) needed to significantly afflict the Li equivalent widths (78).

Instead, we conjecture the absence of a correlation between the Li and Hα residuals in most of our very young systems is due to the Hα emission not having a chromospheric origin (as in our older clusters), but an origin in circumstellar accretion processes (25). Whether the same is true of x-ray emission is the subject of considerable debate (e.g., Flaccomio, Micela & Sciortino 2003; Kastner et al. 2003; Feigelson et al. 2003), but we rely upon x-ray data alone for only one of our very young systems. In this scenario, Hα emission at older ages would be dominated by a chromospheric component given subsequent dissipation of circumstellar material. This raises the possibility of using the existence of correlations between residual Li and canonical activity measures as a probe of the timescale for dissipation of circumstellar material. Taken at face value, our results would suggest that this timescale is at least a few $\times 10^6$ yr for most of the very young stars considered here, and no more than $\sim 4\times 10^7$ yr (the age of IC 2602 and 2391 where Li-activity correlations can be seen). This range of ages is not inconsistent with the timescale for inner disk dissipation estimated from the L-band excess survey of Haisch, Lada & Lada (24).

3.2. X-rays versus Other Activity Proxies

The cool stars in NGC 6475 (Figure 11) and the Pleiades (Figure 9), and the warm stars in Blanco 1 (Figure 7) and IC 2391 (Figure 4) are all cases that suggest that x-rays are not as robust indicators of residual Li-residual "activity" correlations as are Hα and/or Ca II. Indeed, there is only a sole unambiguously positive result ('Y') in the Li-xray column of Table 3. The warm IC 2602 and Pleiades stars exhibit significant residual Li-Hα (and -Ca II) correlations *and* residual Li-L_X correlations. However, the *magnitude* of the residual Li-L_X correlations (measured by the amount of variance in Li attributable to that in L_X) is smaller than those of the residual Li-Hα and residual Li-Ca II correlations in warm IC 2602 and Pleiades dwarfs.

The reason for this may be straightforward. Because the x-ray emission is believed to be coronal in nature, it must be that coronal conditions do not influence the details of neutral alkali line formation in our stars where alkali "formation depths" (an inherently ill-defined term, particularly in NLTE) can be in the upper photosphere, in reasonable proximity (e.g., Stuik et al. 1997, Bruls et al. 1992) to the chromospheric formation heights of the cores of the Hα and Ca II lines (e.g., Vernazza, Avrett & Loeser 1981)[4]. In the more rigorous framework of Stuik et al. (1997), the alkali line formation is *not* influenced directly by the presence of an overlying or surrounding chromosphere, but rather by the effects of manifestations of "activity" (spots and plages) on conditions in the underlying or surrounding photosphere. Possible observational evidence of this scenario from M 34 data is presented in §3.6. Our results suggest the activity-based effects on photospheric stratification which control alkali line formation are better traced by chromospheric Hα and Ca II emission than by coronal x-ray emission.

As noted by the referee and stressed by Soderblom et al. (71), "coronal activity", "chromospheric emission", and "spots or plages" may be broadly connected and lumped under the broad umbrella of activity, but are nevertheless distinct phenomena. Indeed, x-ray luminosity is likely a global property, but spots and plages reflect local conditions. Analogously, the theoretical work discussed in the introduction also stresses the important difference between the global presence of a chromosphere and its effect on local conditions affecting alkali line formation.

The practical consequences of this are three-fold. First, Li-activity correlations are best probed using Hα and Ca II emission rather than x-rays. Second, as the referee notes, since such emission is known to demonstrate rotational modulation (as do spots and plages) this may provide the best support for the theoretical expectation (e.g., Stuik et al. 1997) that the alkali lines do not sense the global chromosphere, but are instead influenced by local inhomogeneities. Third, concluding there is no relation between Li-activity residuals in α Per (Figure 5) and NGC 2516 (Figure 8), would be premature since only x-ray data are readily available for these clusters. Hα and/or Ca II data are needed to better explore the

[4]Of course, the precise formation height of the Li line is controlled in part by the Li abundance, which, unlike K, likely declines as a function of stellar mass and age.

intriguing issue of inter-cluster differences in residual Li-activity correlations.

3.3. Correlation of Li and Activity Residuals

A review of the statistical results in the preceding section suggests there is good evidence for correlations between Li and activity residuals in clusters other than α Per and NGC 2516. The source of these correlations will be discussed below. Here, though, we note that there is a rich behavior in these correlations including interesting intra- and inter-cluster differences. The examples below are discussed according to temperature subclass and age, but we caution the reader against inferring that there exist well-defined age- or temperature subclass-based patterns in the correlation differences– in the absence of larger and more homogeneous cluster star abundance samples, inspection of Table 3 indicates otherwise.

First, warm stars in the young clusters IC 2602 and the Pleiades demonstrate significant positive correlations between residual Li abundance and Hα emission strength; such a correlation may possibly be present in IC 2391 and Blanco 1 as well, but this can not be claimed with high confidence on the basis of extant data. However, warm stars in all the older clusters (NGC 6475, M34, and the Hyades for which there is only Ca II K-line data) do not; this behavior persists when looking at Ca II infrared triplet data for the Pleiades, NGC 6475, and M34.

Second, residual Li abundances of cool stars in IC 2391, the Pleiades, NGC 6475, and M34 show striking correlations with residual Hα and/or Ca II infrared triplet emission; however, the 7 cool older Hyades stars in our sample do not show evidence of such a correlation (the significance is at only the 66% confidence level). Third, the results from Figure 4 indicate that cool stars in the very young cluster IC 2391 show a significant correlation between residual Li and residual Hα emission strength, but those in the twin cluster IC 2602 do not (see also R01). This raises the intriguing possibility, which needs additional investigation with larger sample sizes, that the Li scatter in the cool stars of these two very young otherwise similar clusters has different origins.

Fourth, the cool Pleiads (Figure 9) show a progression in the significance and size of the correlation between residual Li abundances and residual emission as one proceeds from the Ca II infrared triplet, to Hα, and finally to x-rays. The same behavior might be seen in NGC 6475 (Figure 11), but more data are clearly warranted here. We note that our Pleiades Li-L_X results are at odds with the conclusions of Favata et al. (19), who compared the cumulative distributions of x-ray flux for Pleiades G dwarfs and K dwarfs in "high" and "low" Li samples to conclude there was an Li-X-ray connection for cool Pleiads, but not warm ones. Our results– which search specifically for Li-x-ray correlations in similarly defined cool and warm Pleiades samples– run counter to these results; we find it is the warm Pleiads which evince an Li-x-ray correlation, while cool Pleiads do not.

3.4. Potassium and Activity

Table 3 indicates that K is measured in six cluster subgroups, four of which show K-activity correlations and Li-activity correlations; the two subgroups that show no K-activity correlations also demonstrate no Li-activity correlations. The limited evidence thus far indicates that Li- and K-activity correlations go hand-in-hand (though see below concerning the cool Pleiads). As we conclude elsehwere, this most likely suggests that at least some (perhaps substantial) part of cluster star Li variance does not arise from differential physical Li depletion, but from errors in our treatment of alkali line formation. Additional details and notes of interest concerning potassium and activity in our sample are discussed below.

The behavior of potassium with activity mimics that of lithium in IC 2602. Residual K line strengths are correlated with both residual x-ray luminosity (as noted by R01) and residual Hα line strength for warm IC 2602 stars. The cool stars do not evince any such correlation, but the number with K I measurements and their limited range in residual activity are both small. However, an important Li-K difference stressed by R01 can be seen here again in our Figures 4 and 6; the scatter in K grossly pales in comparison to the scatter in Li in cool IC 2602 stars– this is true even when focusing on the intersection of cool stars in Figures 4 and 6. As noted by R01, this provides strong evidence that, at least in some clusters, there is a mechanism to induce Li scatter in cool dwarfs that is not related to activity *per se*. The situation can be clearly seen in Figure 15, which shows residual Li abundances plotted against residual fractional K I line strengths. The trend for the warm stars is significant at the 99.7% confidence level while no trend exists between residual Li and K I for the cool dwarfs. Fig. 15

Figure 9 confirms that residual K I line strength, like Li abundance, is correlated with residual activity measures for warm Pleiads. Interesting behavior is seen for the cool Pleiads, however. As one moves from the Ca II infrared triplet, to Hα, to x-rays, the correlation between residual K I equivalent widths and residual activity measures grows stronger. This is opposite to the behavior demonstrated by Li. We conjecture that this reflects the confluence of stellar stratification, differences in the depletion of Li versus K, and the details of line formation. Since cool Pleiads have undergone Li but not K depletion, we expect the line "formation heights" of the more abundant stronger K I lines are larger than those for the Li I line. The dichotomy of trends in cool Pleiads seen in Figure 9 would be qualitatively explained, then, if the "formation heights" of Ca II, Hα, and x-ray emission represented an analogously vertically stratified sequence. As the referee notes, a (perhaps simpler) alternative explanation is that, for the cool Pleiads anyway, the variance in Li (unlike K) may be dominated by the strong ongoing action of physical Li depletion processes, dwarfing a Li-activity covariance contribution whose analog remains a dominant source of the K residuals.

The Δlog N(Li) versus ΔEW(K) relations for the Pleiades (Figure 10) evince similar behavior as for IC 2602– it is only the warm stars that show a significant correlation. The lack of a significant correlation between residual Li and K in cool Pleiads is important since the results in Figure 9 demonstrate that both residual Li and residual K line strength are significantly correlated with some form of chromospheric emission. This suggests that searching for correlated Li and K residuals may *not* be a robust way to infer activity effects on either or both.

Potassium results for M34 are shown in Figure 12. Two features of note can be seen here. First, the behavior of residual K mimics that of residual Li in that only the cool M34 dwarfs demonstrate a significant correlation between residual K I line strength and both residual Hα and Ca II emission. Second, the lack of a residual K-activity correlation in the warm M34 dwarfs is in stark contrast to that present in the younger IC 2602 and Pleiades clusters; these (possibly age-related) inter-cluster differences mimic those seen for Li in warm dwarfs. Figure 13 shows the Li residuals versus those in K I line strength in M34. Again, two notes are made. First, in contrast to the Pleiades results (Figure 10), it is only the cool M34 dwarfs that demonstrate a (marginally) significant correlation. Second, the residual Li-K correlation for warm M34 dwarfs is at the 76.6% confidence level– considerably larger than the confidence levels (which range from 19.5% to 37.8%) of correlations between either residual Li or K and either residual Hα or Ca II emission; given the marginal 76.6% confidence level, we can only speculate that correlated measurement errors in the Li and K line strengths may play a role in the warm M34 dwarfs.

3.5. Li- and K-Activity Relations: Implications, Origins, and the Role of Rotation

Assuming the Li-activity relations we have encountered are causal and lead to spurious Li abundance measurements, their significant impact is a substantial reduction in the star-to-star Li scatter in open clusters. However, we find such a reduction does not eliminate star-to-star scatter. Using the correlation coefficients to attribute specific percentages of observed Li variance to the effects of activity variance, one can derive refined estimates of the star-to-star Li scatter with the presumed illusory effects of activity removed. In M34, e.g., using the residual Li-Hα results in Figure 12, the original 0.55 dex standard deviation in cool star Li abundances is brought into near exact agreement with that for the warm stars (originally 0.25 dex) at a refined estimate of 0.21 dex. Using the Pleiades Ca II-based results in Figure 9, the original star-to-star scatter of 0.50 dex in cool Pleiades is reduced to 0.34 dex. Using the Hα-based results in Figure 4, Li abundance scatter in the cool and warm IC 2391 objects (originally 0.46 and 0.17 dex) is reduced to $\sim$0.10 dex. Similarly, scatter in the warm IC 2602 objects drops from 0.21 dex to 0.12 dex.

While the refined scatter in warm and cool IC 2391 and warm IC 2602 stars is consistent with observational error, the refined scatter in cool M34 and Pleiades dwarfs suggests intrinsic scatter of $\geq$0.15 $-$ 0.20 dex over and above that due to observational uncertainty; Randich (59) argue strongly for signficant intrinsic Li scatter in cool IC 2602 stars. Thus, while there remains evidence for genuine intrinsic scatter in the cool dwarfs of some clusters, the possibility of illusory dispersion related to activity needs to be accounted for to reliably estimate intrinsic Li dispersions. Accurate estimates are needed to explore issues such as the possible (complex) evolution and convergence of Li abundance scatter in clusters of different ages and metallicity suggested by Jones et al. (34).

While we reach different findings, Favata et al. (19) suggest that Li-activity relations in cool Pleiades dwarfs (and presumably elsewhere) might simply reflect a Li-rotation relation. I.e., the Li-activity connection is not causal, but an illusory one itself that simply reflects the relation between rotation and activity– whatever that relation might be. In such a picture, rotation itself might, e.g., influence the physical depletion of Li in the star; any connection to activity is indirect. This view contrasts with the picture assumed above where the influence of chromospheric/coronal emission is assumed to influence the apparent strength of the λ6707 Li I line, not the true abundance, and any connection to rotation is indirect. As discussed by Jones et al. (34), a causal Li-rotation connection that leads to more or less vigorous physical depletion of Li may be complex– perhaps having both a component due to the effect of rotation on stellar structure (and therefore standard PMS burning) in very young stars (41), and another component arising from the influence of angular momentum loss on Li depletion on the main-sequence (9).

We believe, however, there is good reason to believe the Li-activity relation is *not* an indirect reflection of the causal influence of rotation on Li depletion. While the ability of rotation to significantly alter stellar structure sufficiently to induce a direct Li-rotation correlation in young stars has been questioned (37), stronger evidence is the existence of K-activity relations in the Pleiades (Figure 9), IC 2602 (Figure 6), and M34 (Figure 12) that are analogous to the respective Li-activity correlations. Presumably K is *not* being physically depleted in these stars regardless of how rotation is affecting the stellar structure.

At the same time, we noted (as did Randich 2001) that a Li-activity correlation fails to explain the Li scatter in cool IC 2602 stars, and falls short of explaining the scatter in Li in cool Pleiads and M34 dwarfs. Moreover, data like that in Figure 6d of King et al. (37), which shows an anti-correlation between residual Li abundance and rotational period in cool Pleiads significant at the 92.4% level, make the idea of a connection between Li scatter and rotation difficult to dispel. If not a direct effect of rotation, then a remaining possibility is that Li dispersion is introduced by systematic measurement errors due to blending associated with large projected rotational velocity as suggested by Margheim et al. (40).

The Li-rotation picture is captured in Figure 16 for M34, the Pleiades, and IC 2391 and 2602. The top panels display residual Li abundances for cool M34 dwarfs versus projected rotational velocity[5]. The residuals in the right-hand panel are residuals of residuals– the remaining scatter after Δlog N(Li) variations are removed from using an average of linear least square fits to the Δlog N(Li)-Hα and -Ca II trends in Figure 12. The middle row of Figure 16 is an analogous plot for cool Pleiads in Figure 9. Li residuals from Figure 4 are plotted versus v sin$i$ for cool IC 2602 and IC 2391 stars in the bottom row of Figure 16. Fig. 16

A significant (98.3% confidence level) correlation exists between residual Li and projected rotation in M34. This mimics the Li-activity trend, and thus raises the possibility that Li-activity relations are an illusory manifestation of Li-rotation correlations resulting from rotation-dependent measurement errors; indeed, the activity-detrended Li residuals in M34 show no correlation with rotational velocity, providing no evidence that independent effects due to activity and rotation are operating. While an illusory Li-activity relation in M34 is possible, and the effects of rotation on line measurements may be operating, it is not clear that this is the sole cause of Li scatter in the other clusters in Figure 16. Large Li residuals are seen at all projected rotational velocity in the Pleiades. And no residual Li-rotation patterns whatsoever are clear for IC 2602 and IC 2391. Rather, dispersion in

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[5]While rotational period information is available for many objects discussed here, it is projected rotational velocity which is the salient culprit being addressed. Moreover, the consistency and evolution of the rotational distributions in the various clusters is inconsequential as regards the effects of a cluster's actual current distribution of projected rotational velocities on the simple measurement of Li.

cool IC 2391 stars seems entirely removed by an association with activity, and neither activity nor rotation seem to play a role in the dispersion of Li abundances in cool IC 2602 stars. Additionally, the way fractional K I line strength residuals mimic the behavior of Li with activity would require that similar blending effects deleteriously afflict the K I line measurements as well; whether this is plausible is not yet clear.

3.6. The Nature of the Activity Dependence

Three important questions are whether the alkali-activity relations are a) illusory themselves, b) an indirect resultant of other relations, and c) connected to anomalous abundances recently found in cool stars. As the referee notes, different colors may produce different rankings of alkali and emission residuals. Moreover, Stauffer et al. (77) argue that surface spots can significantly alter the colors of cool dwarfs in young clusters; the presence of spots may also alter the alkali line strengths (79). Could such color alterations themselves lead to correlated alterations in the alkali and chromospheric emission residuals?

For clusters such as M34 and the Pleiades where the cool dwarf Li-$T_{\rm eff}$ trend is comparable or just slightly steeper than the $T_{\rm eff}$ sensitivity of the Li abundance, and the general trend of emission is increasing with declining $T_{\rm eff}$, the observed alkali-emission correlations are in the opposite sense expected for simple color alterations. The same also holds for the Stuik et al. (79) results, where the associated spot-induced Li equivalent width variations are along a locus of near-constant abundance. As an empirical check, we repeated our Pleiades and M 34 analyses using residuals measured against $(B-V)$ and $(V-I)$ independently. No significant change in the significance or strength of any of the correlations (or lack thereof) was found. We did find, however, that the 1σ dispersion in K residuals in cool M34 stars was altered from the 21.2% level measured in the EW(K)-$(B-V)$ plane to the 12.3% level when measured about the fit in the EW(K)-$(V-I)$ plane; this reduction is significant at the 95% confidence level. No significant change is seen in the Li dispersion or the alkali dispersions in the Pleiades, however

In Figure 17, we show a combined version of Figures 12 and 13 with the M34 K residuals replaced by the residuals of the λ6455 Ca I feature, selected because of its modest excitation (2.5 eV) and ionization (6.1 eV) potentials but its modest linestrength compared to the alkali features. Presumably the latter is reflected in the feature's formation depth: e.g., the λ7699 K I formation depth on the MOOG reference optical depth scale ranges from -3.5 to -4.0 for cool M34 dwarfs having 4250-5000 K compared to depths of -1.5 to -2.0 for the Ca I feature. The 1σ dispersion for the Ca I feature is a modest $\sim$9% in the warm M34 stars. However, the value is a large $\geq$30% in the cool M34 dwarfs. Most notably, Figure 17 indicates that marked significant Li- and emission-Ca I correlations exist for the cool M34 stars whether the analysis is done using $(B-V)$ or $(V-I)$. Higher quality data are needed to gauge better the degree to which blending–exaggerated by moderate rotational velocities–might be affecting the Ca I line strengths; at present, we surmise from comparisons with more slowly rotating cool dwarfs that simple measurement error is not enough to explain the enhanced Ca I line strengths in the most active cool M34 dwarfs. Fig. 17

These M34 results may suggest a root photospheric origin for (at least some portion of) the alkali and Ca I correlations, and that chromospheric emission serves only as a proxy for this phenomenon. The Ca I results are consistent with the picture of Stuik et al. (79) where surface inhomogeneities alter conditions in the photosphere. It is interesting to note, however, that King et al. (37) did not note any such correlations in the Pleiades with the stronger 2.7 eV λ6717 Ca I line. This notable difference might be understood if the formation is sufficiently high and the radiative transfer details are such that the alteration in photospheric conditions are not communicated to this stronger feature in contrast to the weaker Ca I and strong alkali resonance features. Detailed NLTE computations are needed to investigate this possibility.

Recent observational investigations of a number of spectral lines of several elements suggests the significant effect of over-excitation/ionization in young cool stars (King et al. 2000; Schuler et al. 2003; Yong et al. 2004; Schuler et al. 2004; Morel & Micela 2004; Morel et al. 2004). The preliminary view emerging from these results is that the anomalous effects seem to be more significant in cooler, younger, and more chromospherically active stars (e.g., Morel & Micela 2004). Are the correlations we see here simply manifestations of this phenomenon? We believe not, and note that the above emerging picture based on inter-cluster comparisons or intra-cluster comparisons over a significant $T_{\rm eff}$ baseline is qualitatively opposite to our results from star-to-star scatter in a given cluster. For example, the recent body of cool star abundance work suggests that low excitation neutral features are *under*enhanced in cooler,younger, and more chromospherically active stars. This effect may contribute to a partly illusory Li- or K-Teff relation in a given cluster (see Schuler et al. 2003), but the correlations seen here in the *scatter* about the alkali-Teff relation indicate *over*enhancements in more relatively active stars. We conclude that the behavior we see here, then, is different in nature and/or origin from that being reported concerning other abundance anomalies in cool stars.

3.7. *Intra*-Cluster Age Spreads

An important note in the study of IC 2602 by Randich (59) is the difference in the degree of scatter in K I and Li I in this cluster's cool stars. Similar behavior is seen here for M34 even after correcting for the activity dependence so clear in Figure 12. The left panel of Figure 18 shows the K I line strength residuals from Figure 12 after being corrected for the dependence on Hα flux. The scatter in these residuals of residuals is about 10%, whereas the scatter in activity-corrected Li abundance (right panel) in cool

M34 dwarfs is nearly a factor of two. This suggests an additional mechanism which is afflicting Li (or its measurement) over and above the activity-dependent effects on K I. One possible mechanism is the presence of an *intra*-cluster age spread which leads to differing (time-dependent) star-to-star Li depletion. While controversial and perhaps unpalatable, the idea of significant age spreads (up to 50%) in young and old disk clusters and stellar kinematic groups is not new (e.g., Chereul, Créze & Bienaymé 1999; Eggen 1998,1992; Eggen & Iben 1988)[6]. Fig. 18

To explore the possibility of intra-cluster age spreads, raw Li residuals and those corrected for any relation with activity were plotted against luminosity deviation in the color-magnitude diagram by fitting the density of points, presumably reflecting a median main-sequence, with a low order polynomial. The activity-adjusted residuals of K I line strength and Li abundance in cool M34 stars are plotted versus ΔV in Figure 18. While the activity-corrected K I residuals show no correlation with deviation from the M34 main-sequence, the activity-corrected Li residuals show a correlation significant at the 99.5% confidence level. Some 79% of the variance in activity-corrected residual Li abundance is related to that in ΔV; correcting for this leaves remaining scatter of 0.12 dex that, finally, seems in line with the observational uncertainties of Jones et al. (34).

The trend in activity-corrected Li in Figure 18 could be interpreted as an age spread if the superluminous stars with high Li are younger, and have therefore suffered less Li depletion (by whatever mechanism). It has frequently been conjectured that rotation and/or activity can alter position a star's position in the H-R diagram. If this were the case here, it is then curious that a) activity-based corrections to the Li residuals plotted in

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[6]The mass-dependent age spreads suggested by (26) would presumably affect the large scale structure of the Li-$T_{\rm eff}$ trend in a cluster; this dependence (however influenced) is removed here, and its study would require comparison with theoretical evolutionary models.

Figure 18 still exhibit a trend with ΔV b) the activity-corrected Li residuals do not show a trend with rotational velocity in Figure 16, and c) K I and Li I exhibit strikingly different behavior in Figure 18.

Models of standard PMS Li depletions in cool stars are extremely sensitive to adopted opacities (e.g., Swenson et al. 1994, Chaboyer et al. 1995, Piau & Turck-Chieze 2002). Thus, another possible cause of star-to-star Li scatter is intra-cluster abundance scatter– either primordial or due to accretion of circumstellar material; indeed, the latter mechanism has been suggested to *directly* cause photospheric Li differences via pollution (23). Inasmuch as (within the framework of standard stellar physics anyway) stellar structure– and hence position in the H-R diagram– at a given age is set by a star's mass and chemical composition, intra-cluster heavy element abundance variations should lead to scatter within the H-R diagram. Putative variations in heavy element abundances are in the wrong sense to explain the righthand panel of Figure 18. An increased heavy element abundance should not only lead to an apparently superluminous position in the H-R diagram, but also result in enhanced PMS Li depletion; the observations in Figure 18 indicate the superluminous stars have relatively enhanced Li abundances, however[7]. Moreover, while understanding the source of systematic trends of their heavy element abundances with $T_{\rm eff}$ in M 34 dwarfs remains important, Schuler et al. (65) note the M34 heavy element scatter (real or not) in the M 34 dwarfs they study is not correlated with Li scatter.

A more plausible alternative is that the superluminous stars might be unrecognized tidally-locked binaries, which may exhibit enhanced Li at an age of 250 Myr (e.g., Ryan

[7]For completeness, it should be noted that a potentially complicating factor is He variations, which also affect both position in the H-R diagram and theoretical PMS Li depletion. Rigorously, it is ΔY and ΔZ conspiring together to influence ΔM_V and Δlog N(Li). How $\Delta Y/\Delta Z$ behaves in any real star-to-star variation is completely uncertain.

& Deliyannis 1995); the radial velocities in (34), while essentially single epoch, provide no evidence for binary status for the superluminous stars in Figure 18 however. No such trends between residual Li abundances or activity-corrected residual Li abundances and ΔV were found in the Hyades[8], IC 2602, or the Pleiades (warm dwarfs in the latter exhibited a mild trend significant at the 80% confidence level). Thus, evidence for age spreads based on the scatter in Li is currently limited to M34.

4. Epilogue and Future Work

While our study has noted the existence of correlations between λ6707 Li I or λ7699 K I and stellar activity in a couple additional clusters, the most significant result is the richness of the behavior of such correlations. The variety of *intra*-cluster (e.g., warm stars versus cool stars), *inter*-cluster (e.g., trends with different signs in the M 34 or the Pleiades and the Hyades), line-based (Li I versus K I), and activity-based (e.g., x-rays versus Hα) differences indicate that it is difficult to speak of “a” particular alkali-activity connection or identify a single unique source for such a connection. Indeed, the cool stars in M34 suggest that, here, no less than 3 mechanisms are operating to create the distribution in the Li-$T_{\rm eff}$ plane– standard PMS depletion, some mechanism (real or illusory) related to activity or rotation, and a third mechanism related to position in the color-magnitude diagram that is distinct from the second. While a variety of behavior has been elucidated by this census, the alkali-activity problem is one that will have to be addressed on a star-by-star and cluster-by-cluster basis. Only then will it be clear how much of the star-to-star Li dispersion

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[8]Hyades ΔV estimates were made using absolute magnitudes calculated using both the Hipparcos and refined secular parallaxes from (12) in order to account for depth effects in this nearby system.

in disk clusters is, in fact, "real".

Several needs identified here might guide such future study. First, use of Li-K relations alone may not be robust indicators of alkali-activity relations (whatever their source); activity data itself is of irreplaceable value in this regard. Second, and relatedly, many clusters (including some studied here) lack published traditional spectroscopically-based activity data (line emission from Hα, Ca II, etc); x-ray data themselves may not be sufficient to betray the presence of a relation (whatever its source) between alkali line strength and chromospheric activity.

An important open question is if the alkali-activity relations studied here are, themselves, illusory? E.g., might they simply represent measurement errors which are v sin i dependent, and thus manifest themselves as activity-dependent given a rotation-activity relation? A third avenue of needed study, then, is the measurement and remeasurement of Li abundances using spectrum synthesis to account for the effects of line blending related to large projected rotational velocity. Fourth, and relatedly, study is needed of the λ7699 K I line to determine if rotational broadening is responsible for contamination of this line's strength– most likely from neighboring telluric features in the atmospheric A-band.

Cool stars in IC 2391 and M 34 are examples of cases where an astounding ~90% of the variance in Li abundance or K I line strength is correlated with that in chromospheric activity. Assessing the role of "activity" per se in such relations is of particular importance. If indeed there is a direct relation with chromospheric properties influencing alkali line strengths via radiative transfer effects– as opposed to activity measures being a proxy for surface inhomogeneities or rotation which (themselves) lead to systematic measurement errors in alkali line strengths– then a resulting corollary suggests a fifth line of attack. Namely, if a snapshot of different stars in an open cluster indicates a direct relation between activity level and alkali line strength, this same effect should be seen in a given star as its activity waxes and wanes. Simultaneous long-term monitoring of activity levels, Li I, and K I line strengths could establish the role of activity in alkali-activity relations. Insight from the few such studies already undertaken is still lacking. While Boesgaard (6) noted no λ6707 Li I variations in the very active and spotted stars she monitored, Patterer et al. (50) noted significant line strength variations in 5 of 7 weak-lined T Tauri stars they monitored over four nights. What is now needed is monitoring of stars in our specific cluster samples that demonstrate alkali-activity relations. This qualification seems important since Favata et al. (19) note differences in the presence of Li-activity correlations between their Pleiades cluster and field star samples; while such a difference is curious, it nevertheless suggests that monitoring of active field stars assumed to be analogs of the cluster stars studied here may be misleading.

We gratefully acknowledge support for this work from NSF awards AST-0086576 and AST-0239518 to JRK, and a generous grant from the Curry Foundation to Clemson University. We also thank the anonymous referee for numerous helpful suggestions that greatly improved the original manuscript.

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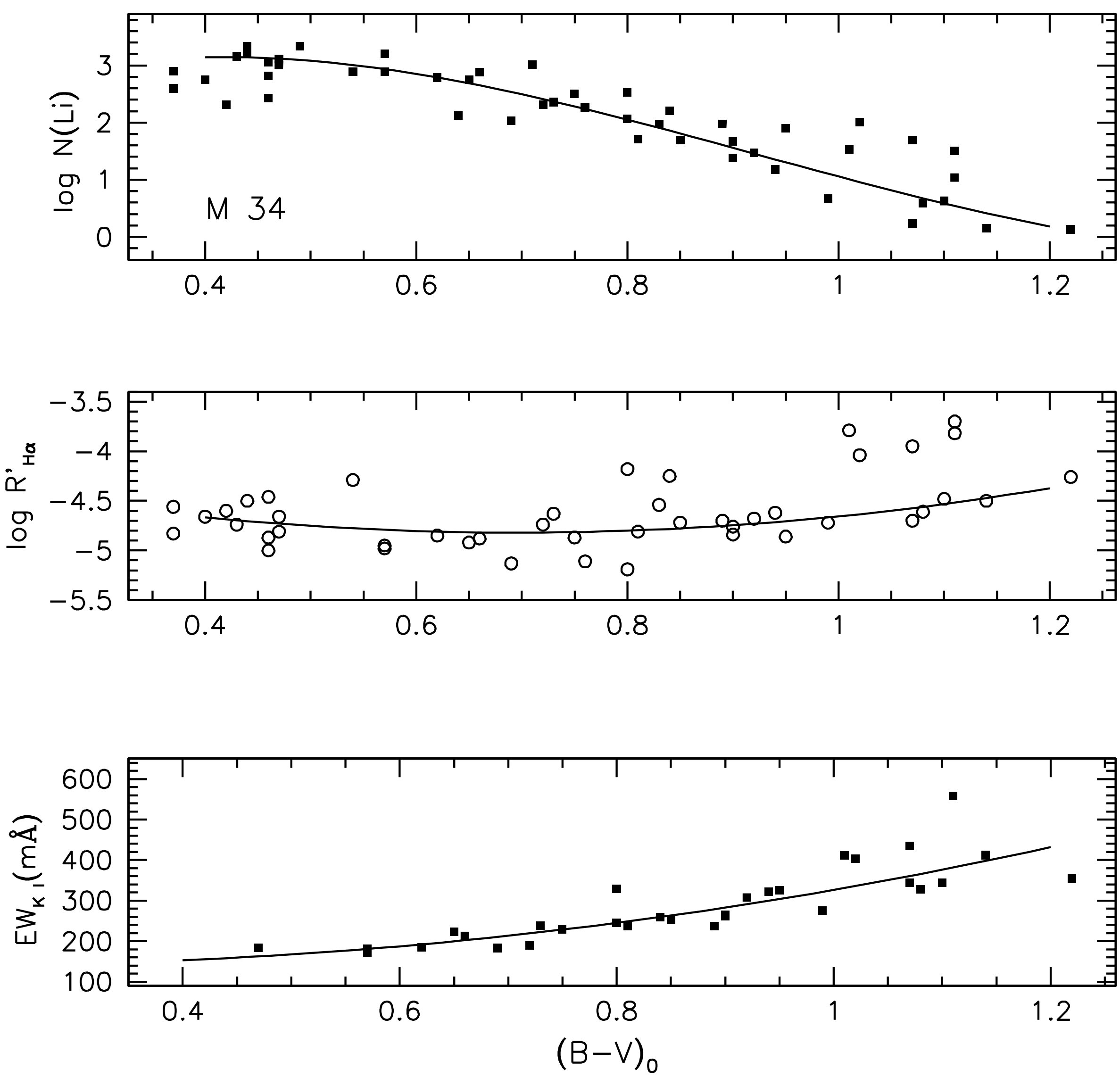

Fig. 1.— The top, middle, and bottom panels show Li abundances, Hα emission fluxes, and λ7699 K I equivalent widths plotted versus dereddened $(B-V)_0$ color for M34. The solid lines are polynomial fits around which residual values (observed minus fitted) are later calculated at a given color.

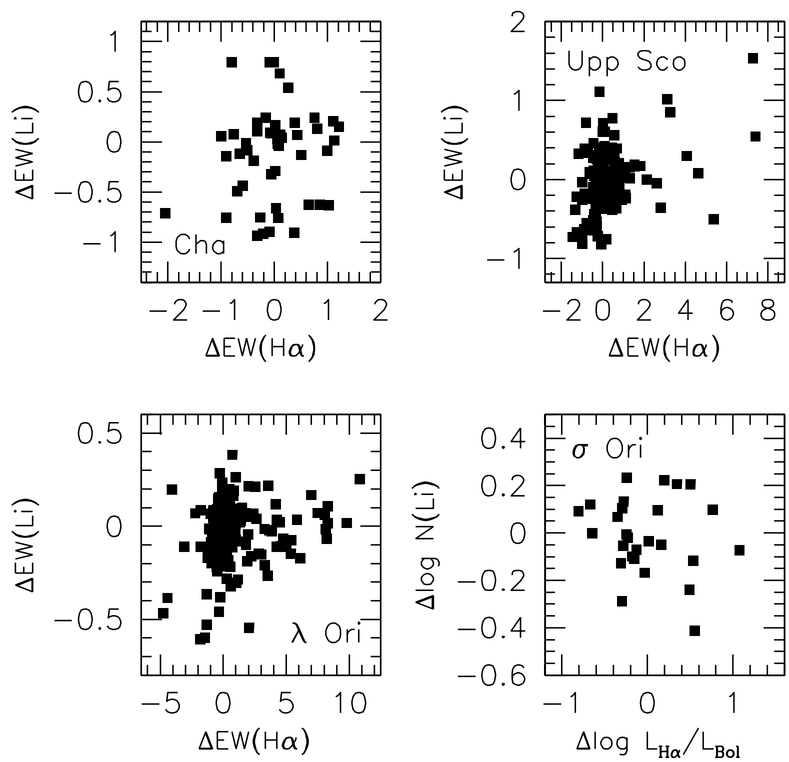

Fig. 2.— Residual Li equivalent widths (or abundances) are shown versus residual Hα emission indicators for PMS stars in the very young associations/star forming regions of Chameleon, Upper Sco, λ Orionis, and σ Orionis.

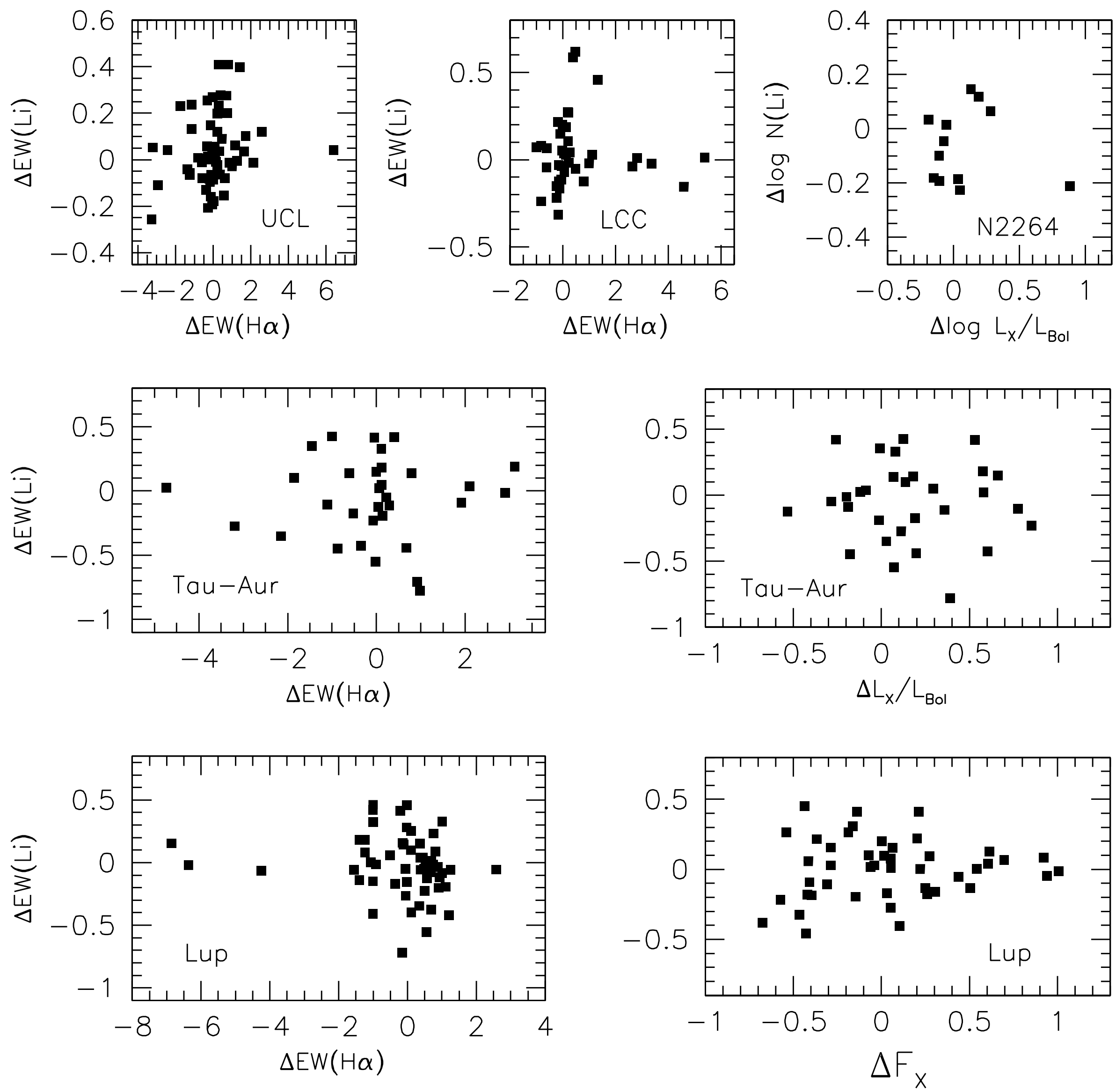

Fig. 3.— Residual Li equivalent widths or abundances are shown versus residual traditional chromospheric/coronal activity indicators for PMS stars in the very young associations/star forming regions Upper Cen Lup, Lower Cen Crux, NGC 2264, Taurus-Auriga, and Lupus.

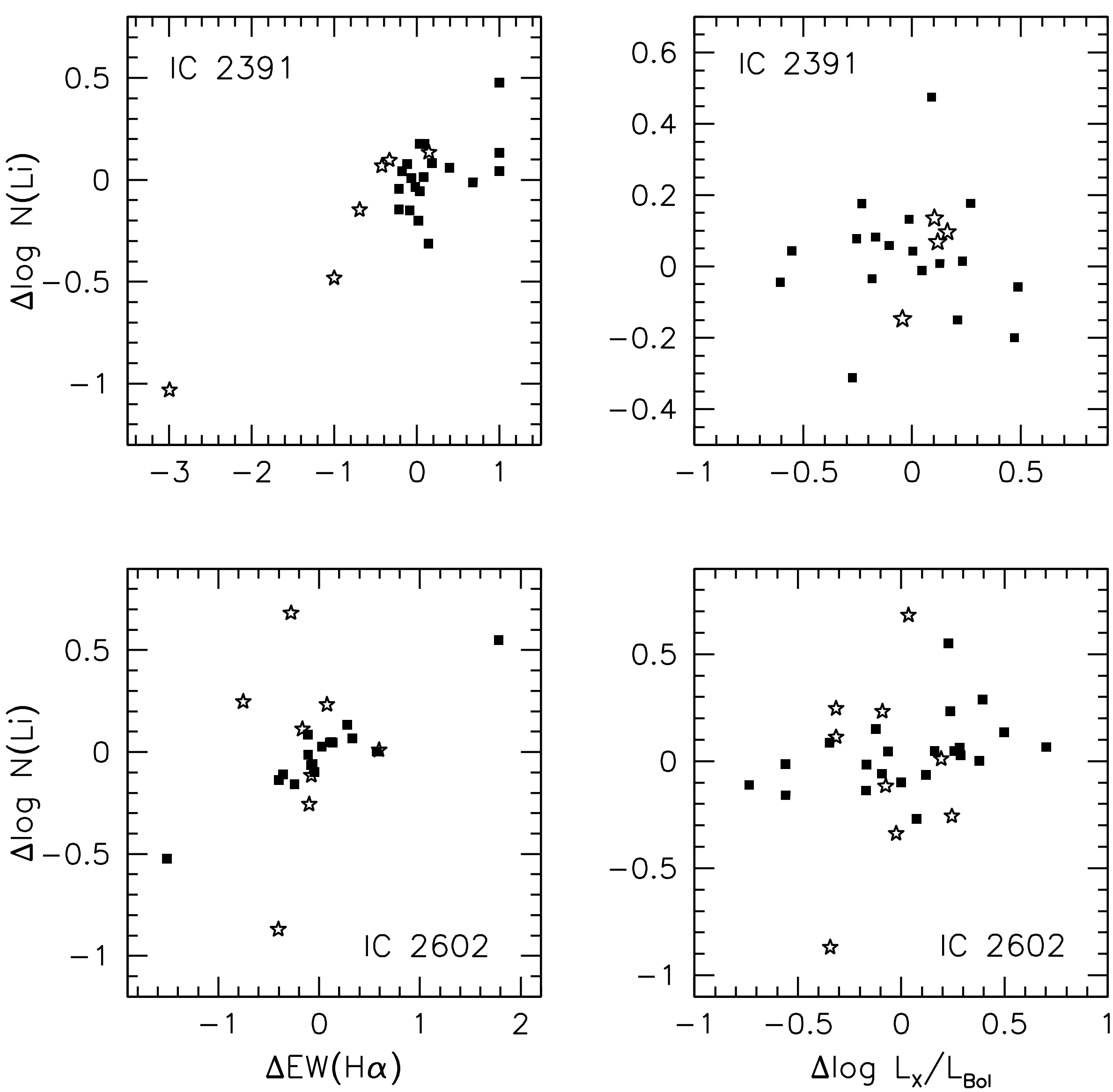

Fig. 4.— The top panels show residual Li abundance versus residual Hα line strength (left) and x-ray luminosity (right) in IC 2391. Solid squares are warm object ($B-V\leq1.0$); open five-point stars are cool objects ($B-V\geq1.0$). The bottom panel shows the equivalent data in IC 2602.

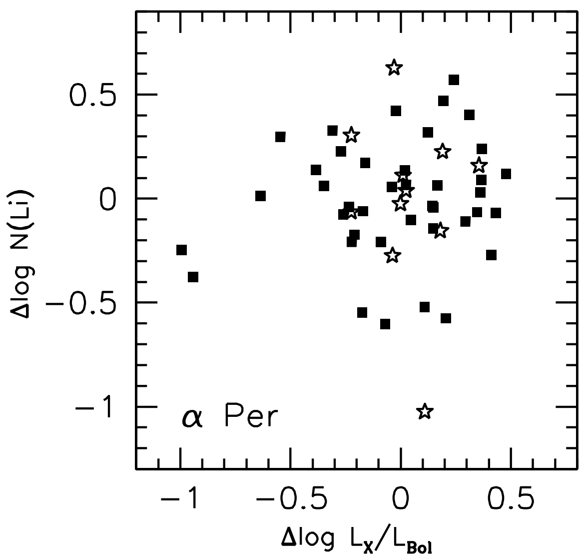

Fig. 5.— Residual Li abundances are shown versus residual x-ray luminosities for the α Per cluster. Warm and cool stars (defined similarly for Figure 4) are again designated by filled squares and open five-point stars.

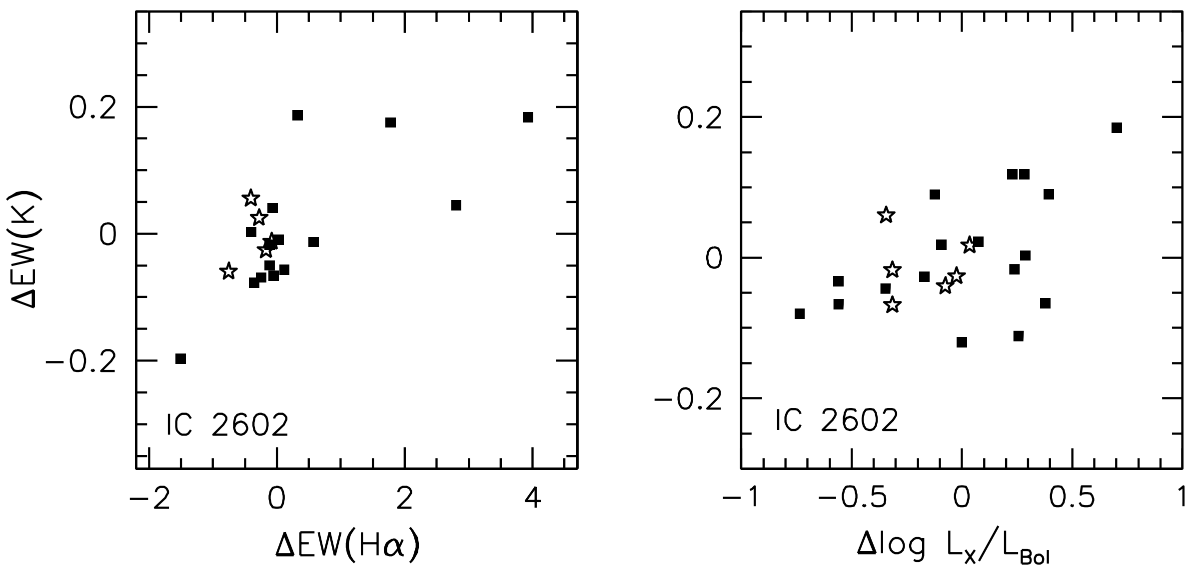

Fig. 6.— Residual λ7699 K I equivalent widths are shown versus residual Hα equivalent width and residual x-ray luminosity in IC 2602. The symbols have the same meaning as in Figures 4 and 5.

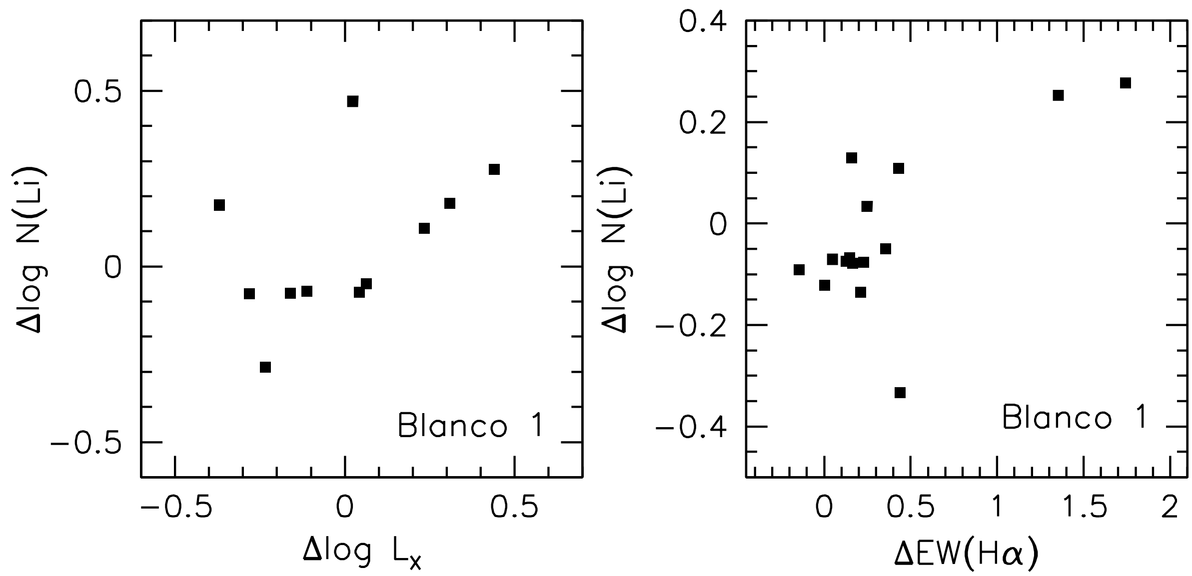

Fig. 7.— Residual Li abundances are plotted versus residual x-ray luminosity (left panel) and Hα equivalent width (right panel) for Blanco 1 members. All stars (except 1 in the right panel) fall into our "warm" category definition.

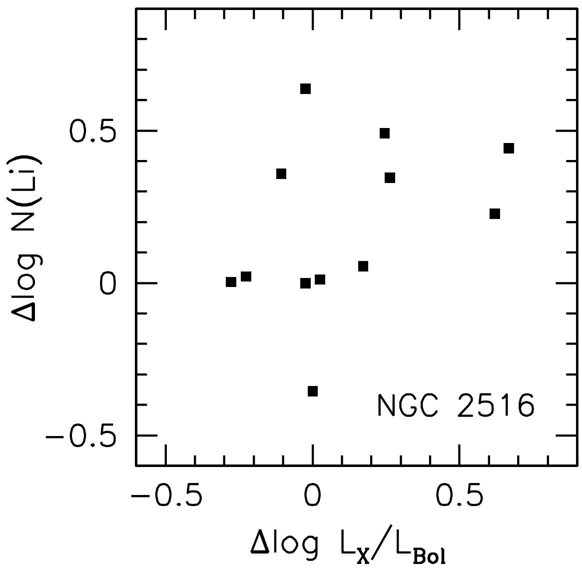

Fig. 8.— Residual Li abundances are plotted versus residual x-ray-to-bolometric luminosity ratios for NGC 2516 members. All stars fall into our "warm" category definition.

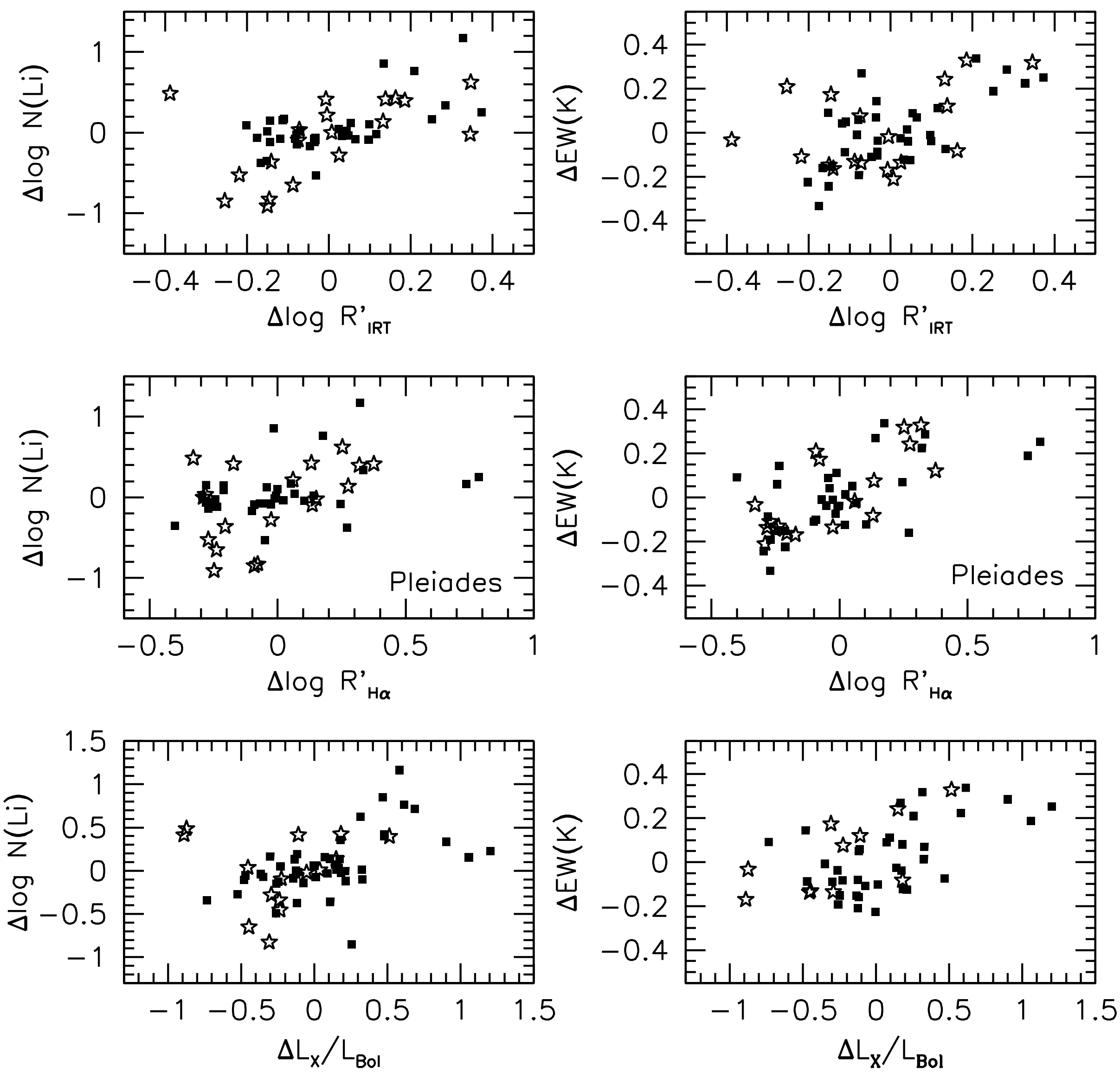

Fig. 9.— Residual Li abundances (left hand panels) and residual fractional λ7699 K I equivalent widths (right hand panels) are plotted versus residual Ca II infrared triplet flux ratios (top panels), residual Hα flux ratios (middle panels), and residual x-ray-to-bolometric luminosity ratios (bottom panels) for the Pleiades. "Warm" objects are shown as filled squares, while "cool" objects are denoted by open stars.

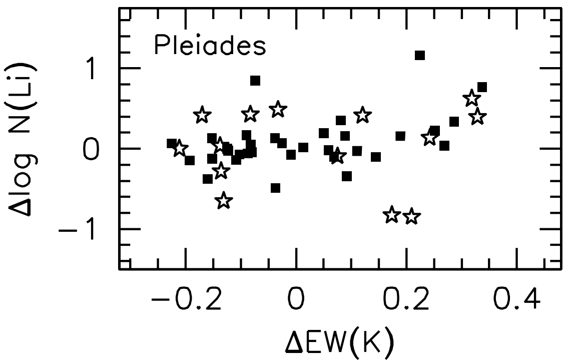

Fig. 10.— Residual Li abundances versus residual fractional λ7699 K I equivalent widths for warm (filled squares) and cool (open stars) Pleiads.

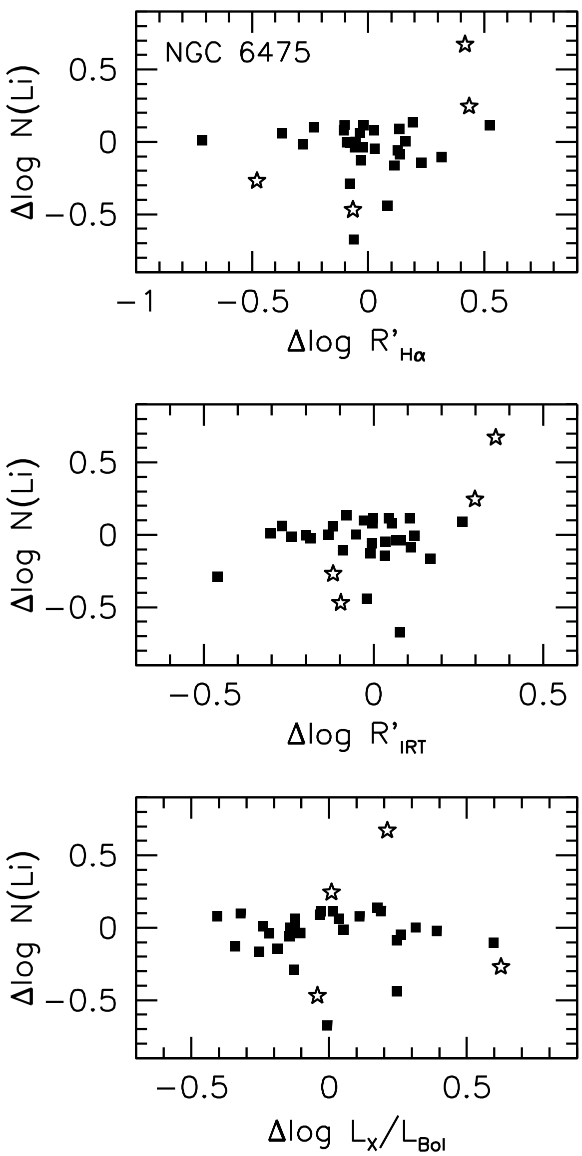

Fig. 11.— Residual Li abundances are plotted versus residual Hα flux (top), residual λ8542 Ca II flux (middle), and residual x-ray luminosity (bottom) ratios for NGC 6475. The symbols have the same meaning as in previous figures.

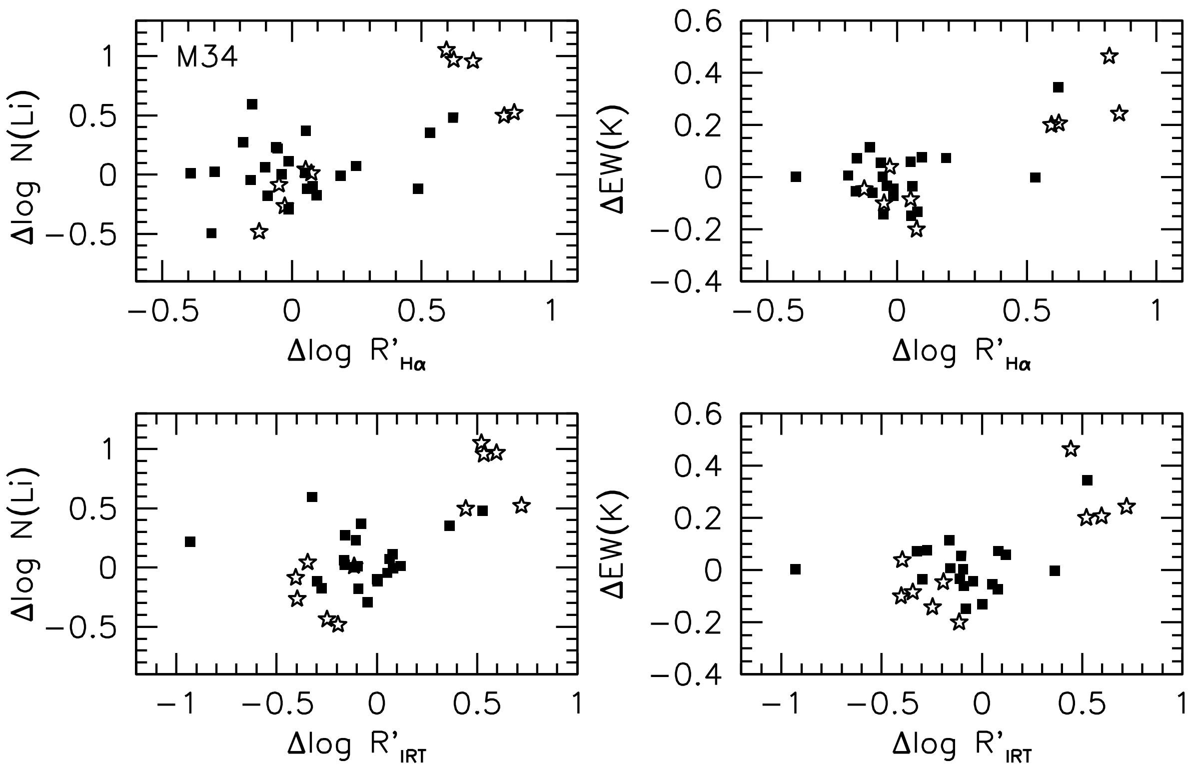

Fig. 12.— Residual Li abundances (left column) and residual fractional K I line strengths (right column) are plotted versus residual Hα (top row) and Ca II infrared triplet fluxes (bottom row) for M34 dwarfs. The symbols have the same meaning as in previous figures.

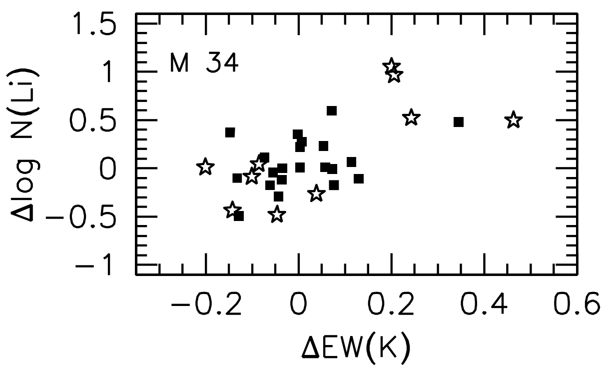

Fig. 13.— Residual Li abundances are shown versus residual fraction K I line strengths for M34 dwarfs. The symbols have the same meaning as in previous figures.

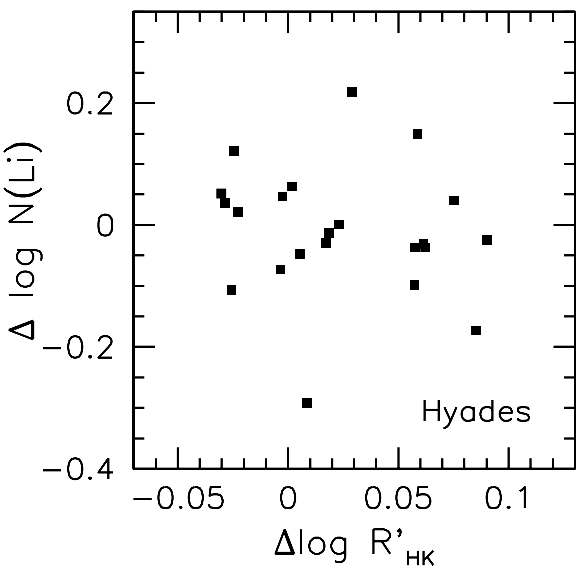

Fig. 14.— Residual Li abundance is plotted versus residual Ca II H&K flux for Hyades dwarfs.

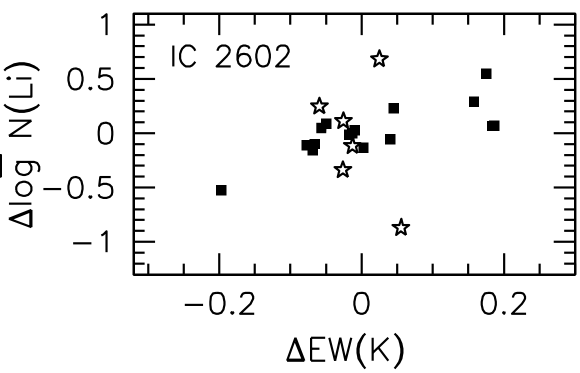

Fig. 15.— Residual Li abundance versus residual fractional K I line strength for IC 2602 stars. The symbols have the same meaning as in previous figures.

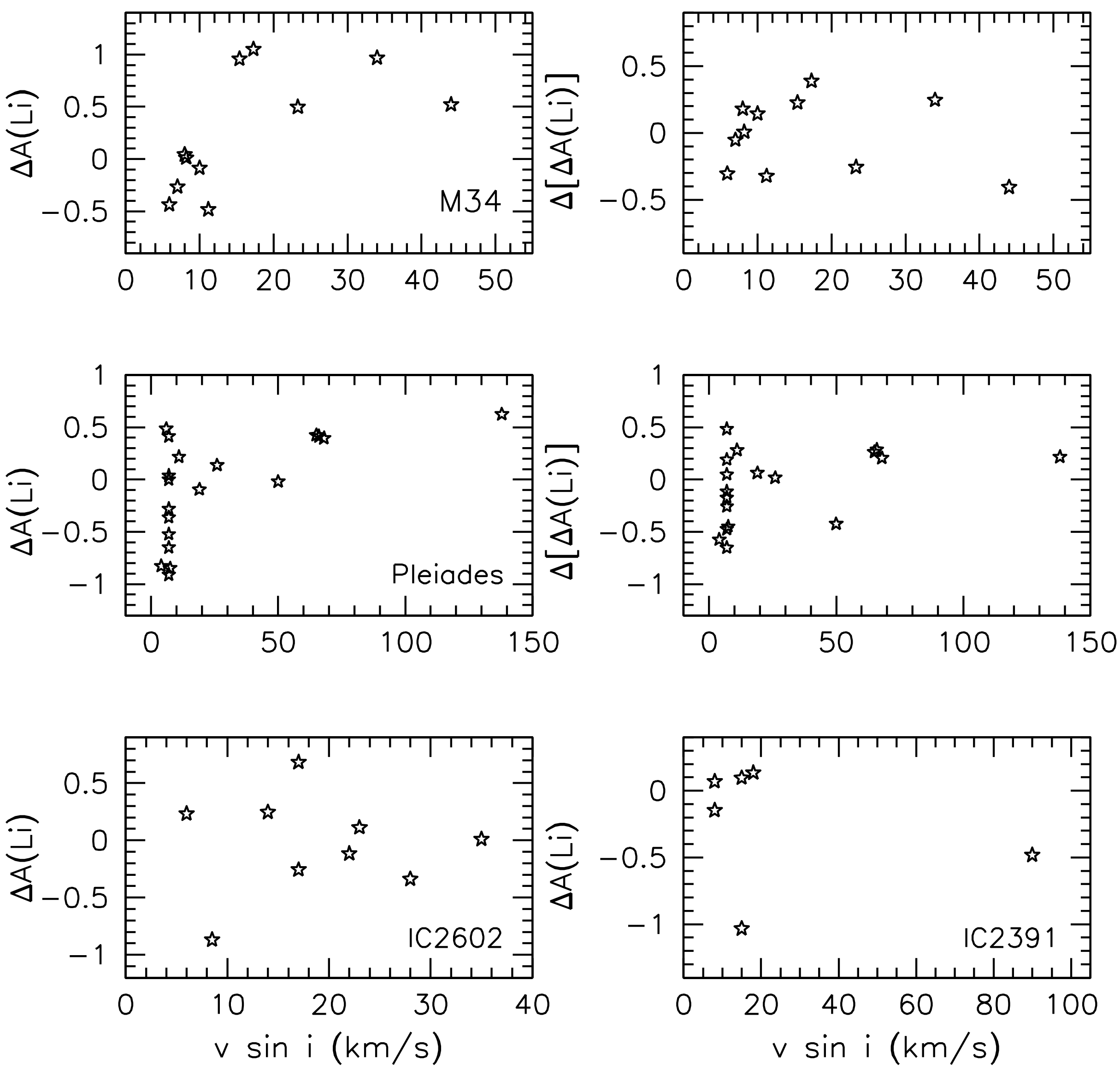

Fig. 16.— (Top) Residual Li abundances (left) and activity-corrected residual Li abundances (right) in cool M34 dwarfs are plotted versus projected rotational velocity. (Middle) Same for cool Pleiades dwarfs. (Bottom) Residual Li abundances versus projected rotational velocity for IC 2602 (left) and IC 2391 (right) stars.

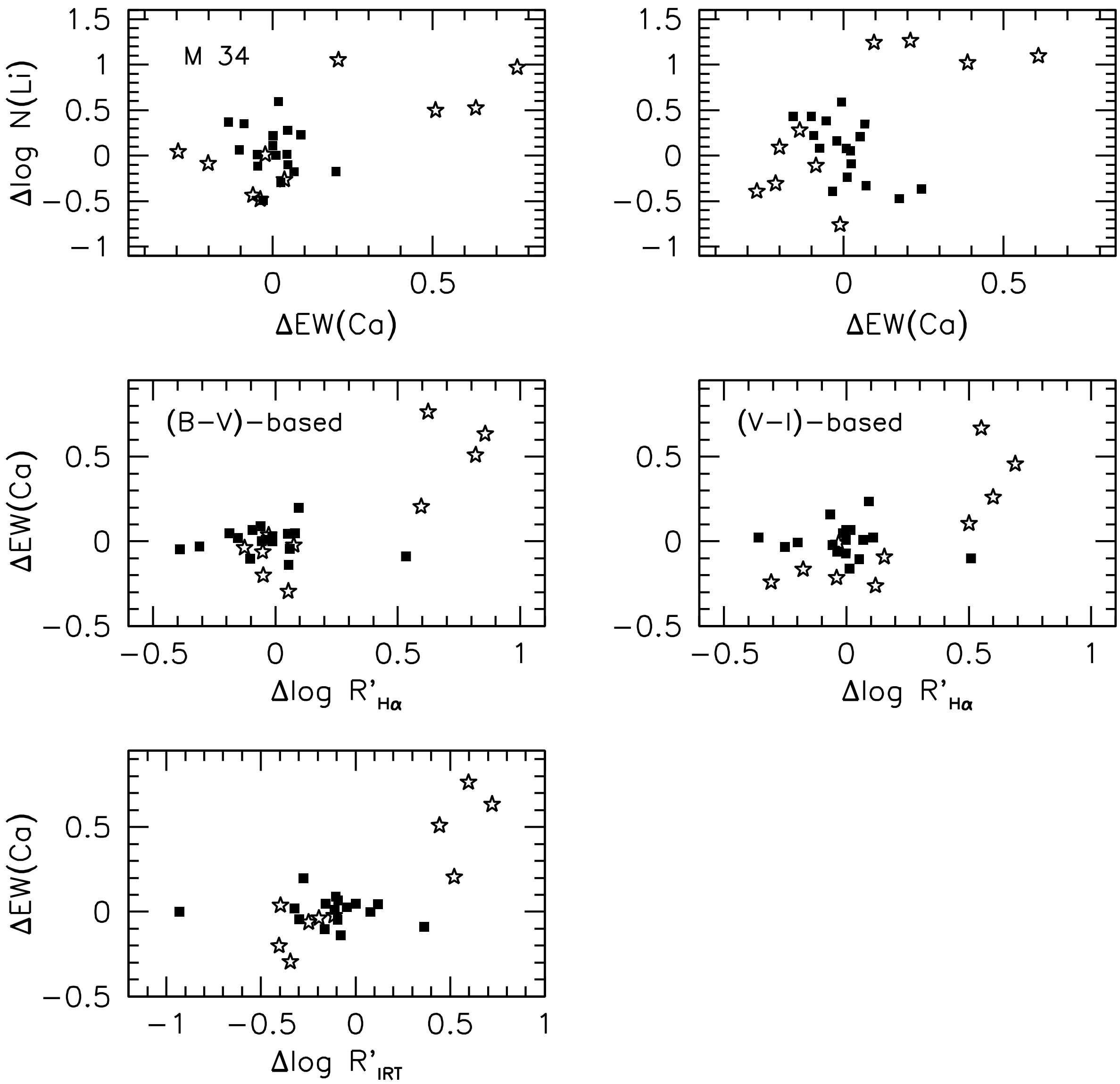

Fig. 17.— A combined version of Figures 12 and 13 for M 34 stars, but replacing the λ7699 K I residuals with those measured for the λ6455 Ca I feature. The left hand column contains relations between residuals measured from $(B-V)$ colors; the right hand column contains relations between residuals measured from the $(V-I)$ colors. Notable differences in residual Li and chromospheric emission with Ca residual are seen for the cool stars (open star symbols).

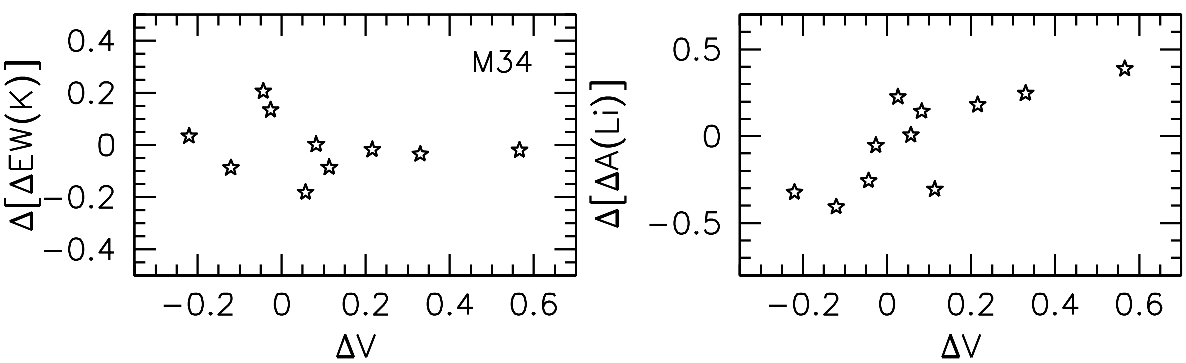

Fig. 18.— Activity-corrected residual fractional K I line strengths (left) and Li abundances (right) for cool M 34 dwarfs are plotted versus V magnitude deviation from a fit to a mean main-sequence. Positive values of ΔV represent objects superluminous compared to the mean main-sequence.

Table 1. NGC 6475 Li Abundances

Star JJ #	$T_{\rm eff}$ K	EW(Li) mÅ	log N(Li)
1	5810	124.0	2.867
2	6008	105.0	2.930
3	6386	58.0	2.884
4	5888	30.0	2.110
6	6008	90.0	2.829
7	5849	101.0	2.759
8	5142	126.0	2.127
9	5622	127.0	2.693
10	5585	109.0	2.540
11	5048	68.0	1.605
12	5810	101.0	2.722
13	5659	102.0	2.576
14	4555	123.0	1.281
15	4604	203.0	1.804
16	5696	125.0	2.759
17	5549	91.0	2.384
18	5477	124.0	2.517
19	4899	104.0	1.671

Table 1—Continued

Star JJ #	$T_{\rm eff}$ K	EW(Li) mÅ	log N(Li)
20	4654	59.0	0.958
22	6564	60.0	3.037
23	5696	99.0	2.595
24	5079	127.0	2.053
25	5079	108.0	1.939
26	5888	97.0	2.768
28	6343	59.0	2.860
29	5810	97.0	2.695
31	5772	118.0	2.792
33	5339	103.0	2.224
34	5373	90.0	2.177
35	5442	87.0	2.235
36	5810	49.0	2.291
40	4439	17.0	0.329
41	6214	89.0	2.997

Table 2. M 34 λ7699 K I and λ6455 Ca I Equivalent Widths

Star JP #	EW(K I) mÅ	EW(Ca I) mÅ
42	265.6	125.7
133	185.5	70.0
158	329.7	···
172	328.9	112.5
194	343.9	100.8
199	245.8	97.4
208	213.1	84.0
224	229.1	93.8
229	354.4	150.8
257	183.9	···
265	434.9	···
268	412.8	152.6
288	322.5	147.9
289	262.1	117.8
296	183.5	80.4
298	307.8	126.0
320	238.5	···
331	171.0	···

Table 2—Continued

Star JP #	EW(K I) mÅ	EW(Ca I) mÅ
366	222.4	67.4
377	259.2	99.0
392	325.8	127.1
397	237.9	106.6
415	190.3	92.6
424	558.1	···
425	403.2	···
482	276.0	122.0
489	237.7	100.2
515	182.1	61.8
516	343.9	134.4
536	411.6	···
570	253.8	105.2

Table 3. Qualitative Summary of Correlations

Cluster/SFR Sample	Li-K	Li-xray	Li-Hα	Li-Ca II	K-xray	K-Hα	K-Ca II
Cha	...	...	N	...	...	...	...
Upp Sco	...	...	Y?	...	...	...	...
λ Ori	...	...	?	...	...	...	...
σ Ori	...	...	N	...	...	...	...
Upp Cen-Lup	...	...	N	...	...	...	...
Low Cen-Crux	...	...	N	...	...	...	...
NGC 2264	...	N	...	...	...	...	...
Tau-Aur	...	N	N	...	...	...	...
Lup	...	N	N	...	...	...	...
IC 2391 (warm)	...	N	?	...	...	...	...
IC 2391 (cool)	...	?	Y	...	...	...	...
IC 2602 (warm)	...	Y?	Y	...	Y?	Y	...
IC 2602 (cool)	...	N	N	...	N	N	...
α Per (warm)	...	N	...	...	...	...	...
α Per (cool)	...	N	...	...	...	...	...
NGC 2516 (warm)	...	N	...	...	...	...	...
Blanco 1 (warm)	...	N	?/Y?	...	...	...	...
Pleiades (warm)	Y?	Y	Y	Y	Y	Y	Y
Pleiades (cool)	N	N	N?	Y	Y	Y	N

Table 3—Continued

Cluster/SFR Sample	Li-K	Li-xray	Li-Hα	Li-Ca II	K-xray	K-Hα	K-Ca II
NGC 6475 (warm)	...	N	N	N	...	...	...
NGC 6475 (cool)	...	N?	?	?/Y?	...	...	...
M 34 (warm)	N	...	N	N	...	N	N
M 34 (cool)	Y/Y?	...	Y	Y	...	Y/Y?	Y/Y?
Hyades (warm)	...	...	...	N	...	...	...