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ALKALI-ACTIVITY CORRELATIONS IN OPEN CLUSTERS

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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 $\sim 4 \times 10^7$ yr. Alkali-alkali and/or alkali-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 that at least some part of intracluster Li variance is not due to real differential Li depletion. Although up to ~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, for example, that *at least* three independent mechanisms (including a possible intracluster age spread) influence the distribution in the M34 Li-$T_{\rm eff}$ plane. We argue that Li-activity correlations are not illusory manifestations of a physical Li-rotation connection. Although an unexpected correlation between Li, chromospheric emission, and the λ6455 Ca I feature in cool M34 dwarfs indicates that 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.

Key words: line: formation — open clusters and associations: general — stars: abundances — stars: activity — stars: 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; 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 (Pasquini 2000), with the exception of G dwarfs in M67.

The observed steepening decline in the Li-$T_{\rm eff}$ relation for progressively older clusters, the relative overabundance of Li in short-period tidally locked binaries in clusters of intermediate to old age, and the 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 clusters in the zero-age main sequence (ZAMS) or pre–main-sequence (PMS) age ranges. Other refinements that might account for Li scatter in young clusters include star-to-star composition differences (Piau & Turck-Chieze 2002), the effects of magnetic fields (Ventura et al. 1998), 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. (1995) 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. (2000) 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. On the basis of preliminary work with Li in the dual young clusters NGC 2451A and B, Margheim et al. (2002) 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; suspected by Soderblom et al. 1993a for Pleiades stars with $B - V \leq 0.9$). Randich (2001; hereafter R01) reports that active stars with $0.75 \leq (B - V)_0 \leq 1$ 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 the values of inactive field stars (Tripicchio et al. 1999). 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 as well. 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 that the λ7699 K I feature can be used as an excellent "proxy" to investigate the details of λ6707 Li I line formation (Stuik et al. 1997). Such work (e.g., Houdebine & Doyle 1995) and the above observations suggest that significant Li scatter in young clusters might arise from differential non-LTE (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, although intricately interrelated, processes that make modeling the Li I and K I features difficult; besides Stuik et al. (1997) and Houdebine & Doyle (1995), two other notable explorations of alkali resonance line formation are Bruls et al. (1992) and Carlsson et al. (1994), who review previous work and lay out considerable groundwork 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. 1994 and Stuik et al. 1997), 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 data sets with which to do so. The objects we consider provide a potentially important age baseline. Although 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 (Schuler et al. 2003) 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 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 de-trend the various measurements (Li, activity, potassium) as a function of color or temperature using polynomial fitting as in King et al. (2000). 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, or $T_{\rm eff}$ can be isolated. For each stellar aggregate, all available Li or K or activity[1] data were used in the fitting regardless of whether it was 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 aggregate's 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, whereas 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 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 (1) 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 (2) 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 data sets. 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 nine very young (a few megayears) aggregates were available. Model-dependent ages, which generally ignore the possibility of age spreads of a few megayears, 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. (1997); $B-V$ photometry is taken from Alcalá et al. (1995). 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. (2002). 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). The $R-I$ colors, Li equivalent widths, and Hα–to–bolometric luminosity ratios in the σ Ori PMS cluster ($\sim$3 Myr; 27 objects) come from Zapatero Osorio et al. (2002). Mamajek et al. (2002) provide photometric temperatures and Li and Hα equivalent widths of PMS stars in the Upper Cen–Lupus ($\sim$17 Myr; 63 objects) and Lower Cen–Crux ($\sim$16 Myr; 47 objects) subgroups of the Sco-Cen OB association. The $B-V$ colors and Li abundances provided by Soderblom et al. (1999) and King (1998) and X-ray–to–bolometric luminosity ratios from Flaccomio et al. (2000) 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 ($\leq$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)

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

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

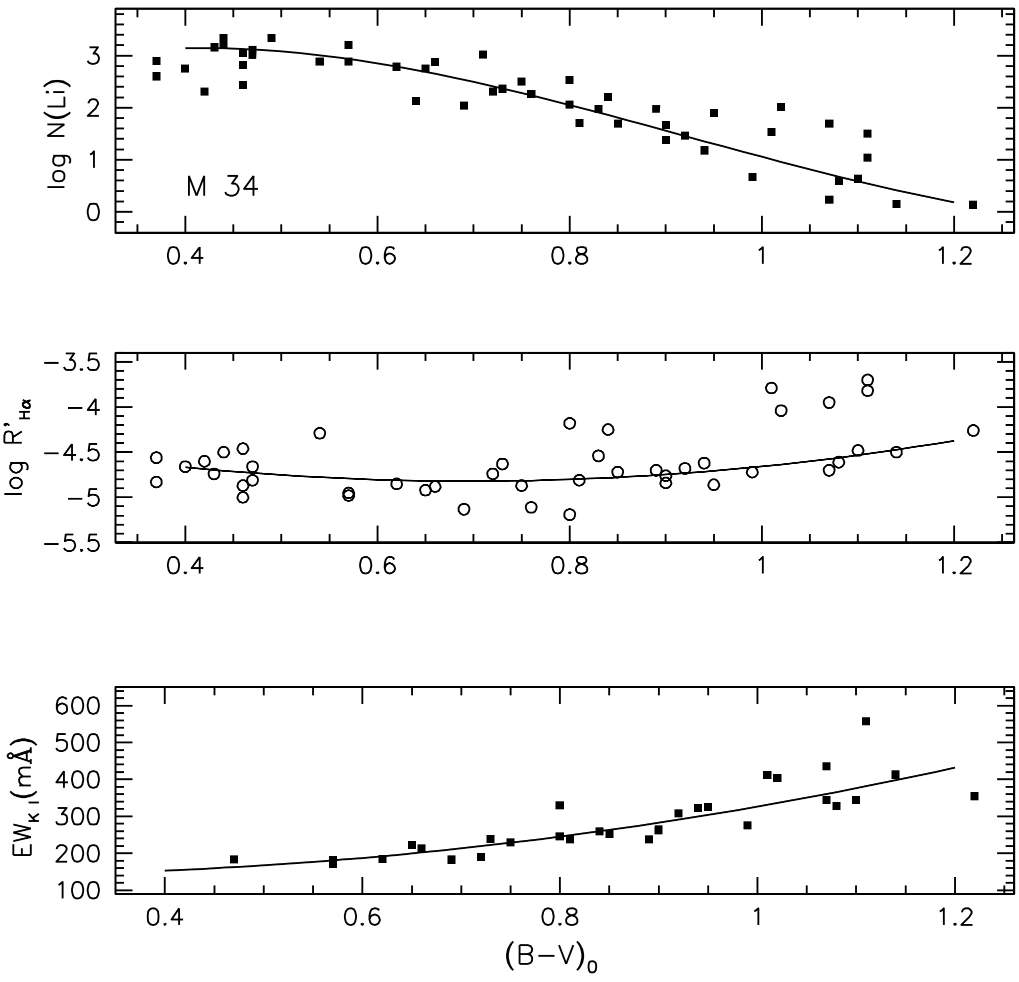

Fig. 1.—Plots of Li abundances (*top*), Hα emission fluxes (*middle*), and λ7699 K I equivalent widths (*bottom*) vs. dereddened $(B-V)_0$ color for M34. The solid lines are polynomial fits around which residual values (observed minus fitted) are later calculated at a given color.

compose the first sample. The second sample consists of Li equivalent widths, *ROSAT*-based X-ray fluxes, and spectral types from Wichmann et al. (1997b); we calculated $T_{\rm eff}$ values from the spectral types in the same manner as Wichmann et al. (1997a).

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 are 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, although 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–Lupus 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.

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

The clusters IC 2391, IC 2602, and α Per may all be coeval at ~50 Myr, although the estimated ages range from 35 to 50 Myr for the former two clusters (e.g., Barrado y Navascués et al. 1999) and from 50 to 70 Myr for α Per (e.g., Prosser 1992); consistent comparison clearly indicates that 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 IC 2602 members were taken from Randich et al. (2001), Stauffer et al. (1997), and R01, respectively. Values of the $L_{\rm X}/L_{\rm Bol}$ ratios were taken from Stauffer et al. (1997) and supplemented by X-ray data from Simon & Patten (1998) and Randich et al. (1995); when needed, bolometric luminosities were calculated using the distance moduli inferred from Figure 4 of Stauffer et al. (1997) and the bolometric corrections of Johnson (1966). 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 (1992), Stauffer et al. (1993), Balachandran et al. (1988; updated as needed in Balachandran et al. 1996), Randich et al. (1998), Prosser et al. (1996), and Randich et al. (1996). Figures 4 and 5 show the residual Li abundances versus residual chromospheric/coronal emission measurements. Randich et al. (2001) 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 $(B-V)_0 \sim 1.0$.

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.

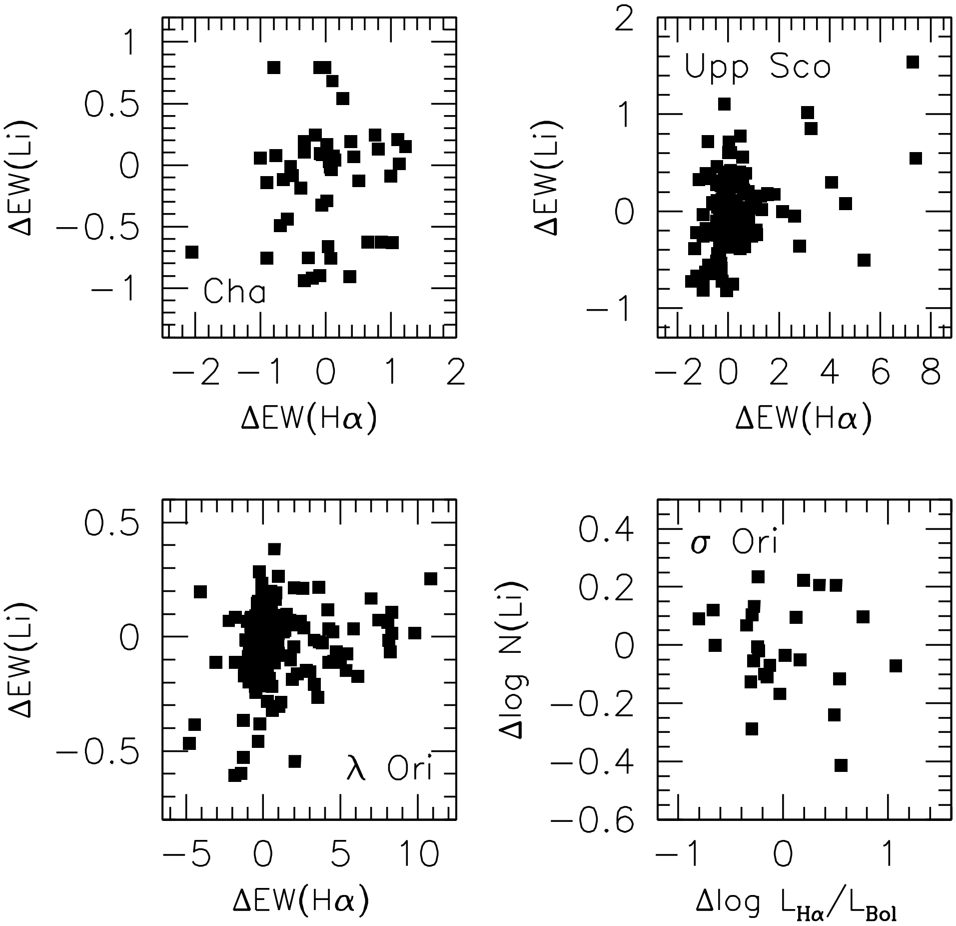

Fig. 2.—Residual Li equivalent widths (or abundances) vs. residual Hα emission indicators for PMS stars in the very young associations/star-forming regions of Chameleon, Upper Scorpius, λ Orionis, and σ Orionis.

The correlation coefficient suggests that 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 that a correlation between residual Li and Hα is significant at a marginal 93.9% confidence level; the correlation coefficient here suggests that 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 54% of the variance in Li abundance being associated with that in the X-ray luminosity rankings. Since 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 as 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, however, in concluding that 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-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)-Δ log L_X/L_{Bol} planes, respectively. 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 with that of Li abundance, particularly in the cool stars.

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

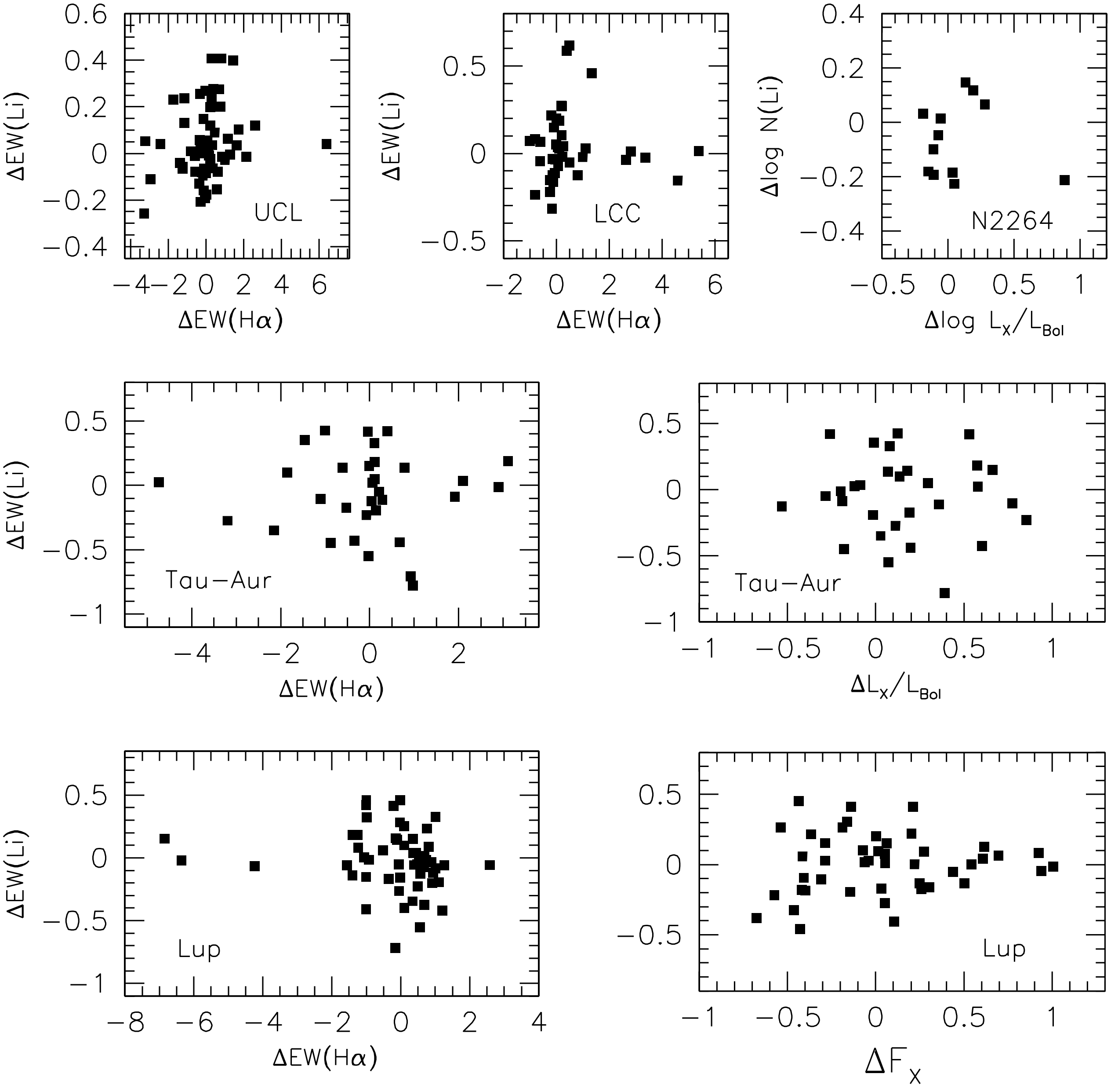

FIG. 3.—Residual Li equivalent widths or abundances vs. residual traditional chromospheric/coronal activity indicators for PMS stars in the very young associations/star-forming regions Upper Cen–Lupus, Lower Cen–Crux, NGC 2264, Taurus-Auriga, and Lupus.

et al. 1993; Pinsonneault et al. 1998) suggest that NGC 2516 is slightly older. Estimates for Blanco 1 suggest ages both slightly below (van Leeuwen 1999) and above (Panagi & O'Dell 1997) the Pleiades value; one can probably reasonably conclude that the cluster is Pleiades age ±20%. Li abundances and photometry of Blanco 1 members are taken from Table 1 of Jeffries & James (1999). Hα equivalent widths were taken from Panagi & O'Dell (1997) and Panagi et al. (1994), who also present Li measurements. We have not used the latter data, since Li equivalent widths for stars in common with Jeffries & James (1999) are discordant; we suspect that resolution differences may play a role in this, but the possibility of intrinsic variability (Patterer et al. 1993) remains an intriguing open question worthy of future study. Blanco 1 X-ray luminosities are taken from Micela et al. (1999a). Li abundances, $T_{\rm eff}$ values, and X-ray luminosities for NGC 2516 are taken from Jeffries et al. (1998). Li abundances, K I equivalent widths, photometry, and optical activity measures for the Pleiades are identical to those described in King et al. (2000).[3] These were supplemented by X-ray luminosity ratios (with respect to bolometric) from Stauffer et al. (1994) and Micela et al. (1999b, 1996); when needed, bolometric luminosities were calculated using the distance modulus of 5.63 from Pinsonneault et al. (1998) and the bolometric corrections of Johnson (1966).

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 that 69% of the observed variance in Blanco 1 Li abundances is associated with that in Hα equivalent widths).

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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) de-trended Li abundances are employed here.

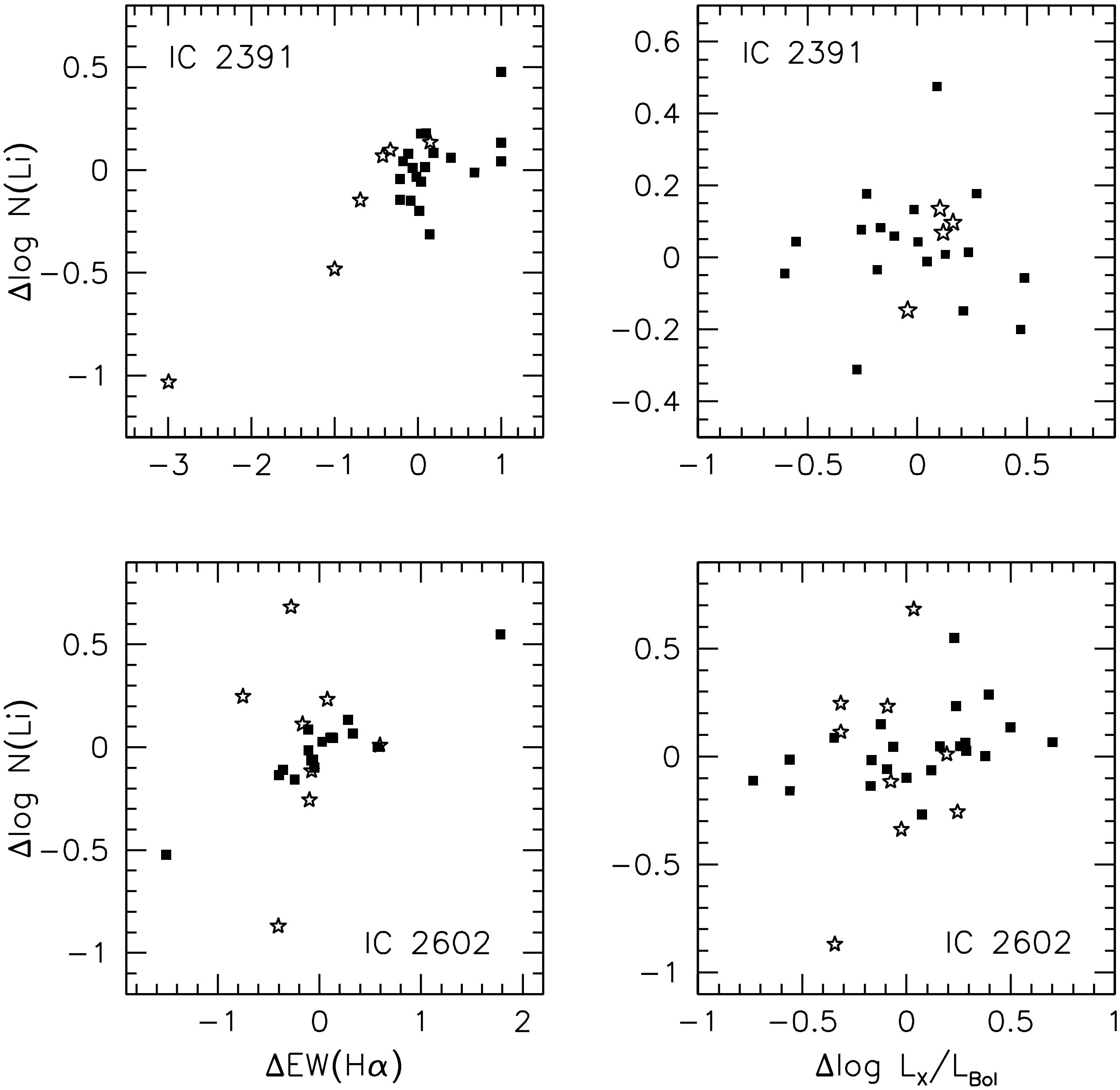

FIG. 4.—*Top*: Residual Li abundance vs. residual Hα line strength (*left*) and X-ray luminosity (*right*) in IC 2391. Squares are warm objects ($B - V \leq 1.0$); stars are cool objects ($B - V \geq 1.0$). *Bottom*: Equivalent data for IC 2602.

Although the Li-Hα results are ambiguous, the difference between them and the Li–X-ray results is analogous to that seen for IC 2391 and IC 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, IC 2602, and (now) Blanco 1 suggest, concluding that 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.

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" vs. "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 Pleiades stars (a marginal 82.8% confidence level); residual Li abundance versus residual X-ray luminosity for cool Pleiades stars (41.5% confidence level); and residual K I equivalent width versus residual Ca II infrared triplet flux for cool Pleiades stars (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 Pleiades

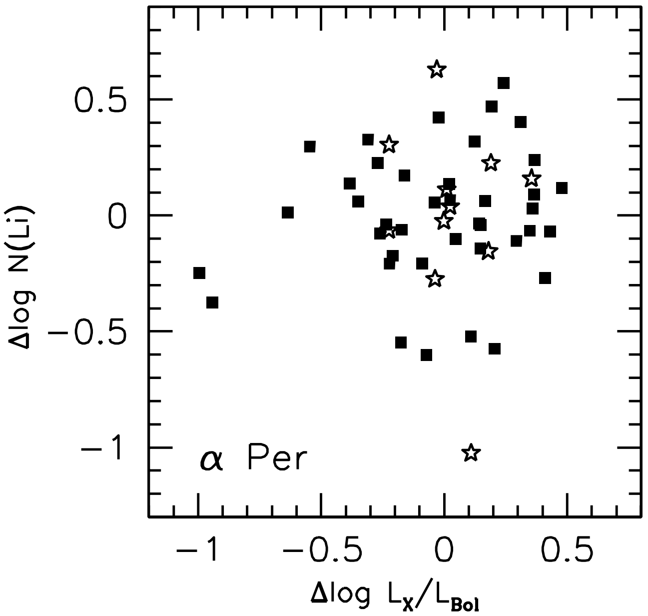

FIG. 5.—Residual Li abundances vs. residual X-ray luminosities for the α Per cluster. Warm and cool stars (defined as in Fig. 4) are again designated by squares and stars, respectively.

stars, respectively; 68% and 75% of the variance in residual K I equivalent width is related to that in Ca II flux in warm Pleiades stars and to that in Hα flux in cool Pleiades stars, respectively.

Although 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 Pleiades stars; some 42% of the variance in Li abundance is associated with that in K I line strength for these objects.

2.4. *Intermediate-Age, Post-ZAMS Clusters: NGC 6475, M34, and the Hyades*

The clusters NGC 6475 (220 Myr; Meynet et al. 1993) and M34 (180–250 Myr; Meynet et al. 1993; Jones et al. 1997) are perched in age between the ~100 Myr old Pleiades and the ~650 Myr old Hyades (e.g., Perryman et al. 1998). James & Jeffries (1997) 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 (Sneden 1973), R. Kurucz (1992, private communication) model atmospheres, and $T_{\rm eff}$ values calculated from equation (3) of Soderblom et al. (1993b); results are given in Table 1. M34 photometry, Li abundances, and Hα and Ca II infrared triplet chromospheric flux ratios are taken from Jones et al. (1997) and Soderblom et al. (2001); 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 (Schuler et al. 2003) 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. (2002). Hyades Li abundances are taken from Balachandran (1995) and culled of SB2 and short-period tidally locked binaries.

The NGC 6475 results are given 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 shows no correlation with residual Ca II, Hα, or X-ray flux ratios. On the other hand, although 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 and perhaps residual Hα emission, but not residual X-ray emission.

The residual Li abundances and K I equivalent widths are shown versus residual chromospheric fluxes for M34 in Figure 12.

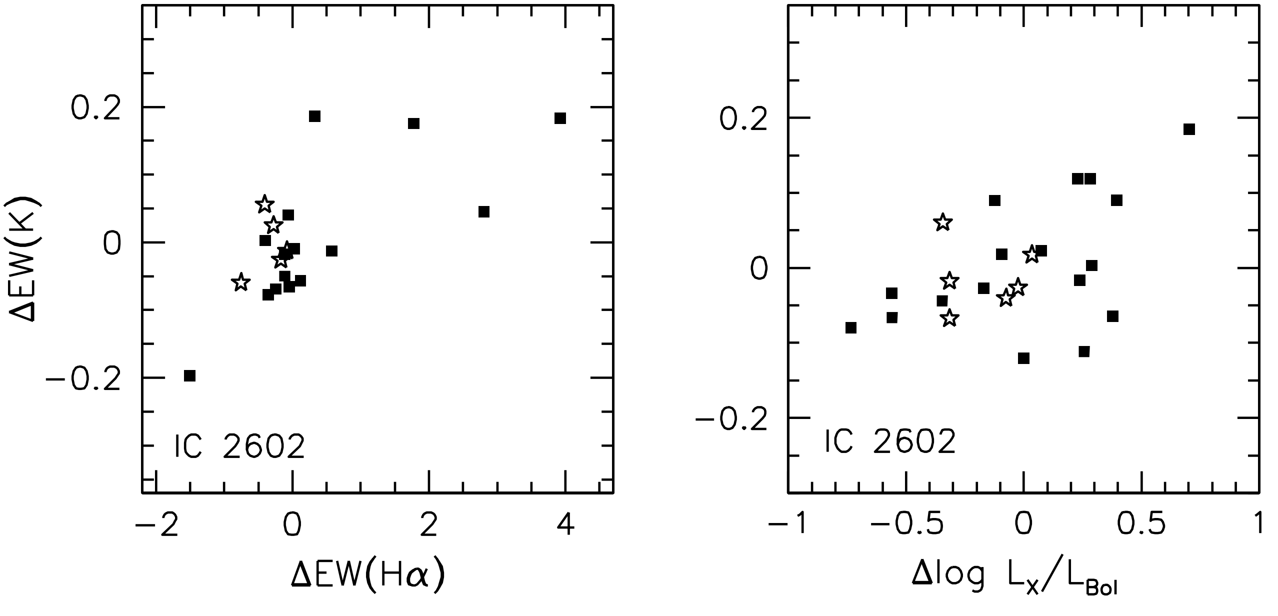

FIG. 6.—Residual λ7699 K I equivalent widths vs. residual Hα equivalent width (*left*) and residual X-ray luminosity (*right*) in IC 2602. The symbols have the same meaning as in Figs. 4 and 5.

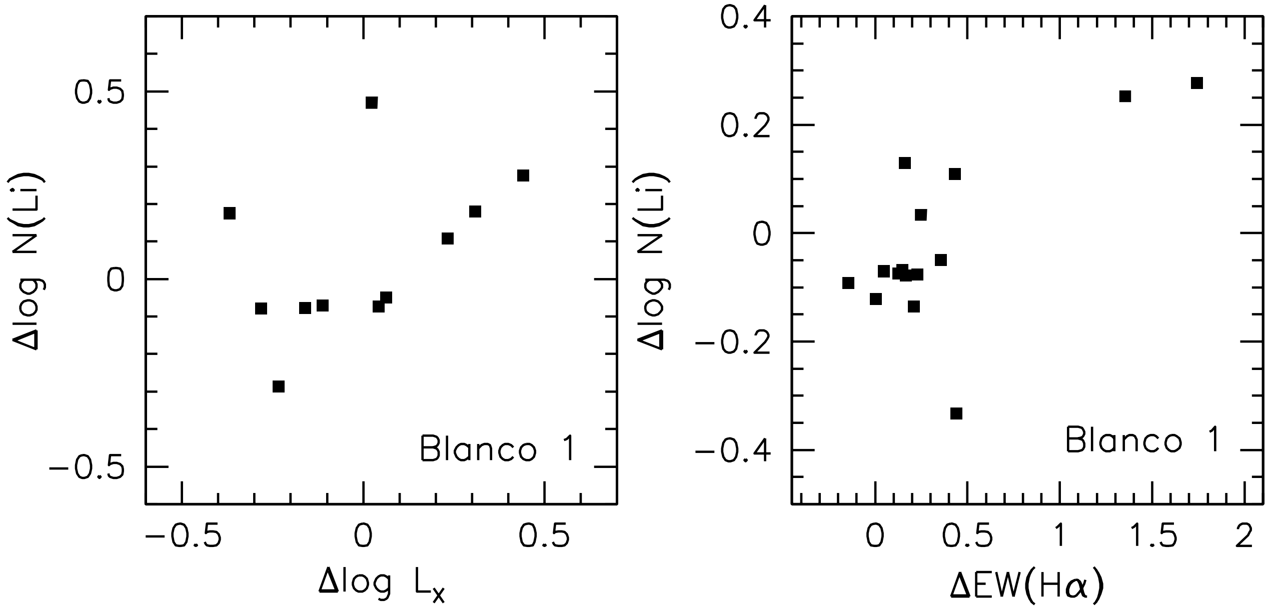

FIG. 7.—Plots of residual Li abundances vs. residual X-ray luminosity (*left*) and Hα equivalent width (*right*) for Blanco 1 members. All stars (except one in the right panel) fall into our "warm" category definition.

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.

Like the Pleiades, there is clear evidence of Li-activity and K-activity correlations in M34, although 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 those of the Pleiades. In M34, the warm dwarfs do not exhibit a significant Li-K correlation (76% confidence level), although the variance in Li abundance associated with that in K I line strength (40%) is similar to the warm Pleiades stars. Rather, it is the cool M34 objects that 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.

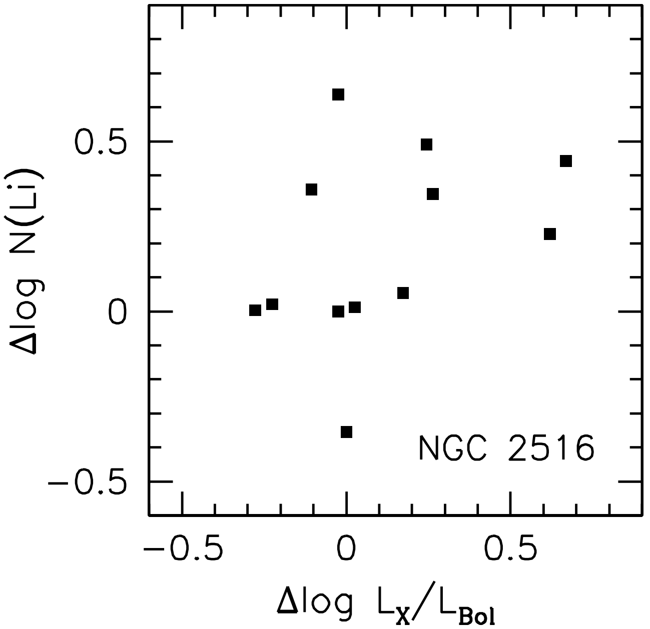

FIG. 8.—Plot of residual Li abundances vs. residual X-ray–to–bolometric luminosity ratios for NGC 2516 members. All stars fall into our "warm" category definition.

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.

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 in which 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 in which the correlation is statistically significant but not markedly strong (generally ≤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. (1993), 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 toward future observational clarification. A question mark indicates cases in which an interestingly high but not significant correlation is found or in

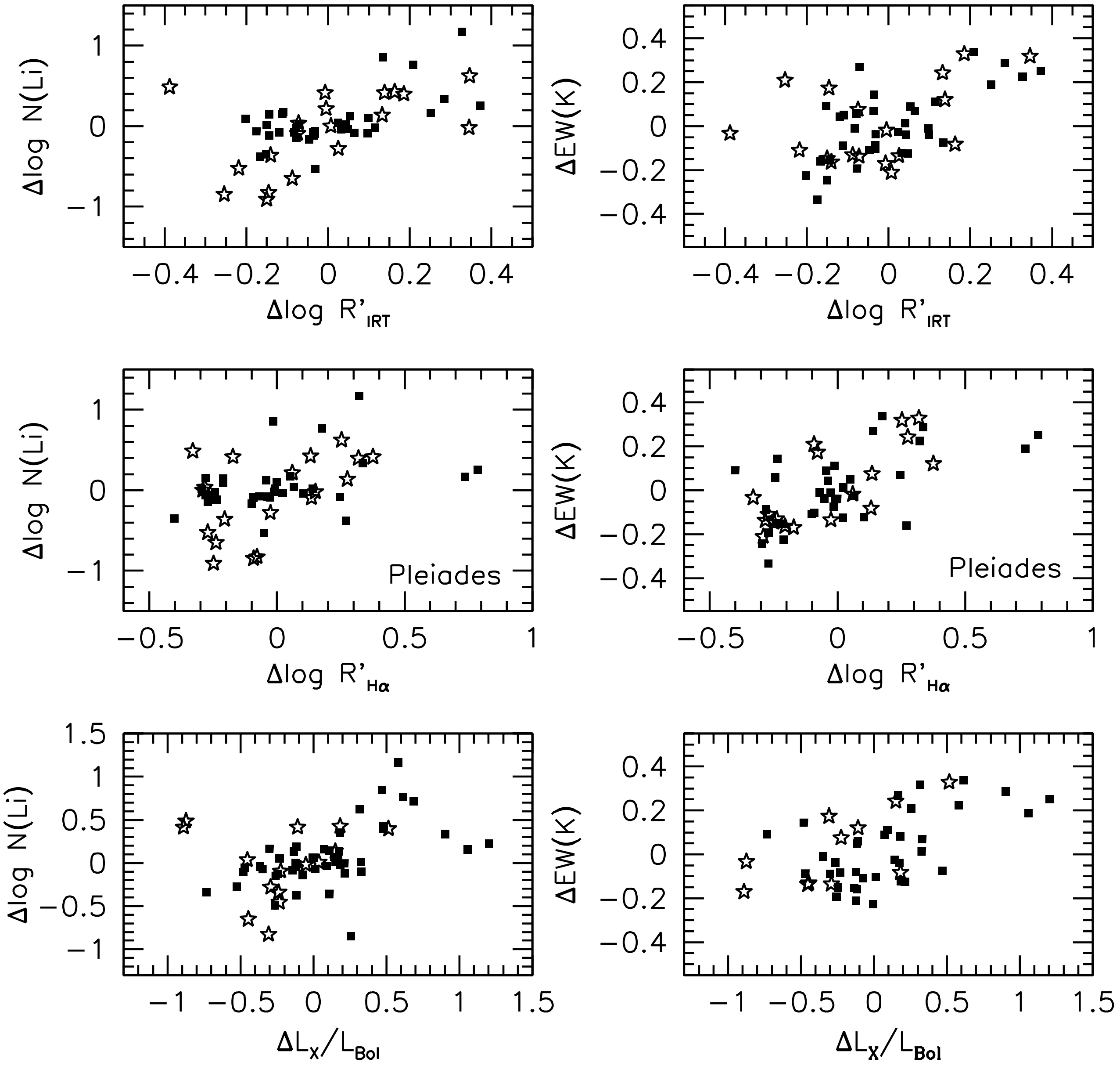

FIG. 9.—Plots of residual Li abundances (*left*) and residual fractional λ7699 K I equivalent widths (*right*) vs. residual Ca II infrared triplet flux ratios (*top*), residual Hα flux ratios (*middle*), and residual X-ray–to–bolometric luminosity ratios (*bottom*) for the Pleiades. "Warm" objects are shown as squares, whereas "cool" objects are denoted by stars.

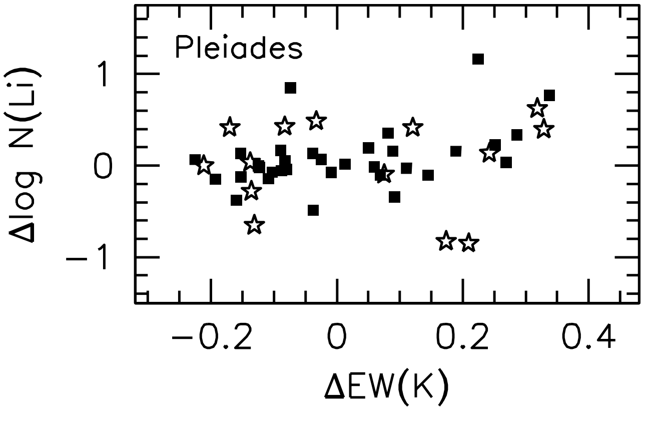

FIG. 10.—Plot of residual Li abundances vs. residual fractional λ7699 K I equivalent widths for warm (*squares*) and cool (*stars*) Pleiades stars.

which additional data are needed to definitively address the existence or not of correlations.

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. Although 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 (≥a few angstroms) needed to significantly afflict the Li equivalent widths (Strom et al. 1989).

Instead, we conjecture that the absence of a correlation between the Li and Hα residuals in most of our very young

TABLE 1
NGC 6475 Li Abundances

Star JJO Number[a]	$T_{\rm eff}$ (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
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

[a] JJO indicates the numbering of stars in the optical data of James & Jeffries (1997).

TABLE 2
M34 λ7699 K I and λ6455 Ca I Equivalent Widths

Star JP Number[a]	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	. . .
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

[a] JP indicates the numbering of stars in the system of Jones & Prosser (1996).

systems is due to the Hα emission not having a chromospheric origin (as in our older clusters) but rather an origin in circumstellar accretion processes (Hartmann et al. 1994). Whether the same is true of X-ray emission is the subject of considerable debate (e.g., Flaccomio et al. 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 the 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 IC 2391 at which 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 et al. (2001).

3.2. *X-Rays versus Other Activity Proxies*

The cool stars in NGC 6475 (Fig. 11) and the Pleiades (Fig. 9) and the warm stars in Blanco 1 (Fig. 7) and IC 2391 (Fig. 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 one unambiguously positive result ("Y") in the Li–X-ray column of Table 3. The warm IC 2602 and Pleiades stars exhibit significant residual Li-Hα (and Li–Ca II) correlations *and* residual Li-$L_{\rm X}$ correlations. However, the *magnitude* of the residual Li-$L_{\rm X}$ correlations (measured by the amount of variance in Li attributable to that in $L_{\rm X}$) 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 the case that coronal conditions do not influence the details of neutral alkali line formation in our stars in which 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 et al. 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

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[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.

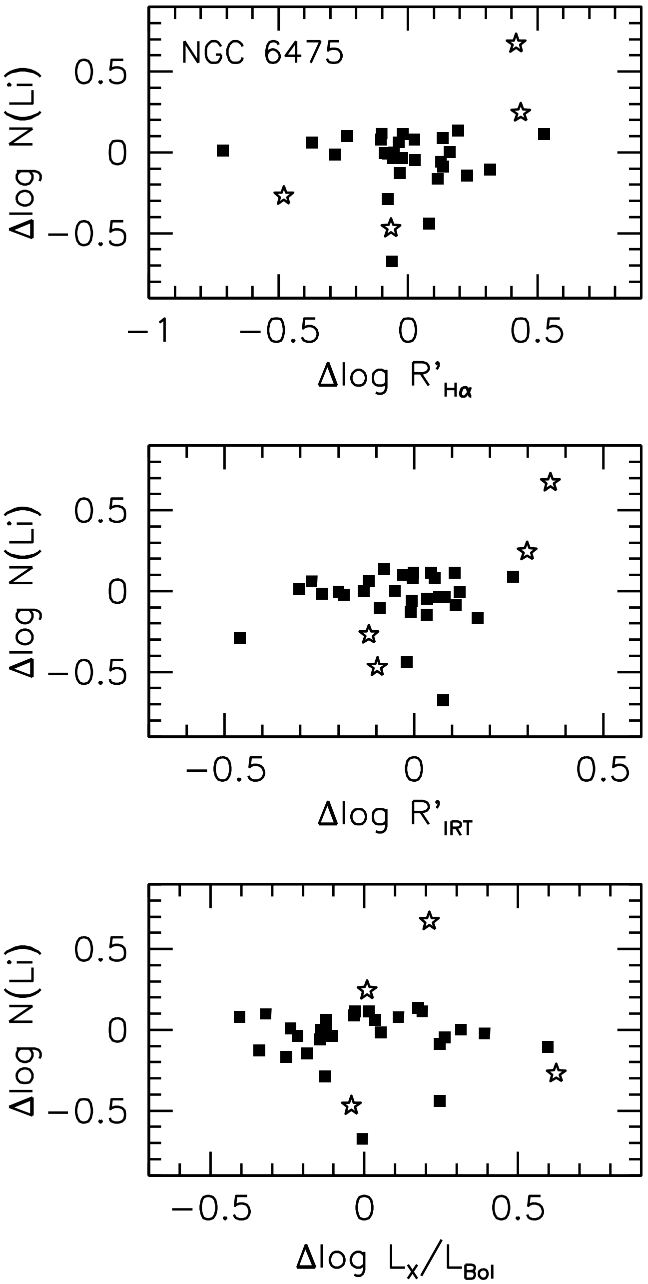

FIG. 11.—Plots of residual Li abundances vs. residual Hα flux (*top*), residual λ8542 Ca II flux (*middle*), and residual X-ray luminosity (*bottom*) ratios for NGC 6475. The symbols have the same meaning as in previous figures.

of this scenario from M34 data is presented in § 3.6. Our results suggest that the activity-based effects on photospheric stratification that 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. (1993a), "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 threefold. 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 that there is no relation between Li-activity residuals in α Per (Fig. 5) and NGC 2516 (Fig. 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 intriguing issue of intercluster 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 that 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 is discussed below. Here, however, we note that there is a rich behavior in these correlations, including interesting intracluster and intercluster 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 cannot be claimed with high confidence on the basis of extant data. However, warm stars in all of 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 seven 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 Pleiades stars (Fig. 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 (Fig. 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. (1995), who compared the cumulative distributions of X-ray flux for Pleiades G dwarfs and K dwarfs in "high-" and "low"-Li samples to conclude that there was an Li–X-ray connection for cool Pleiades stars but not for warm ones. Our results, which search specifically for Li–X-ray correlations in similarly defined cool and warm Pleiades samples, run counter to these

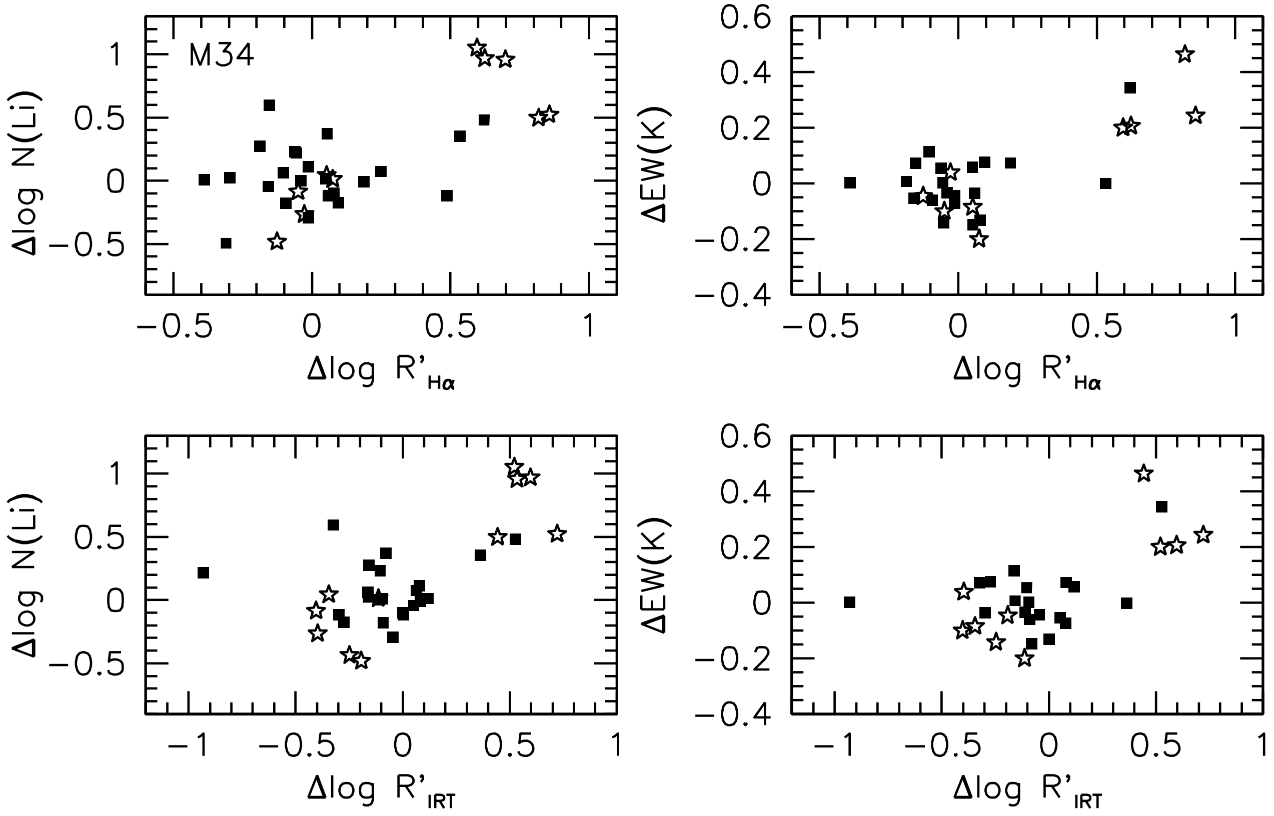

FIG. 12.—Plots of residual Li abundances (*left*) and residual fractional K I line strengths (*right*) vs. residual Hα (*top*) and Ca II infrared triplet fluxes (*bottom*) for M34 dwarfs. The symbols have the same meaning as in previous figures.

results; we find that it is the warm Pleiades stars that evince a Li–X-ray correlation, whereas cool Pleiades stars 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 (although see below concerning the cool Pleiades stars). As we conclude elsewhere, 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

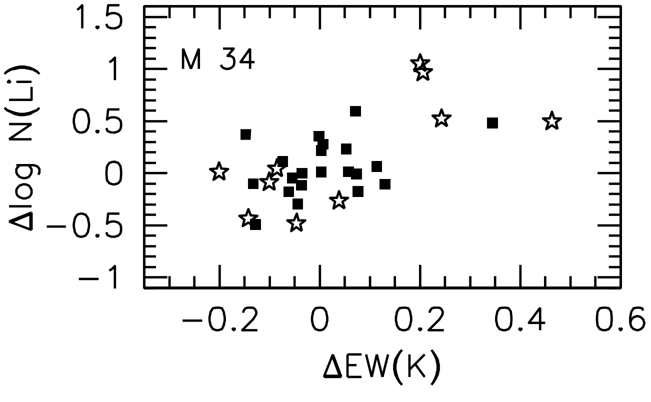

FIG. 13.—Plot of residual Li abundances vs. residual fraction K I line strengths for M34 dwarfs. The symbols have the same meaning as in previous figures.

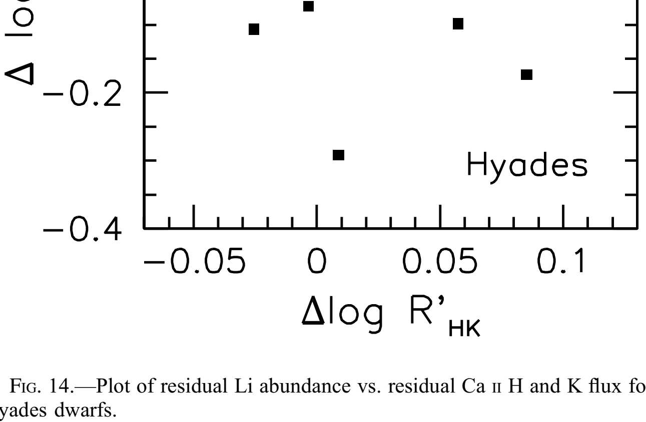

FIG. 14.—Plot of residual Li abundance vs. residual Ca II H and K flux for Hyades dwarfs.

TABLE 3

Qualitative Summary of Correlations

Cluster/SFR Sample	Li-K	Li–X-ray	Li-Hα	Li–Ca II	K–X-ray	K-Hα	K–Ca II
Chamaeleon	...	...	N	...	...	...	...
Upper Scorpius	...	...	Y?	...	...	...	...
λ Ori	...	...	?	...	...	...	...
σ Ori	...	...	N	...	...	...	...
Upper Cen–Lupus	...	...	N	...	...	...	...
Lower Cen–Crux	...	...	N	...	...	...	...
NGC 2264	...	N	...	...	...	...	...
Taurus-Auriga	...	N	N	...	...	...	...
Lupus	...	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
NGC 6475 (warm)	...	N	N	N	...	...	...
NGC 6475 (cool)	...	N?	?	?/Y?	...	...	...
M34 (warm)	N	...	N	N	...	N	N
M34 (cool)	Y/Y?	...	Y	Y	...	Y/Y?	Y/Y?
Hyades (warm)	...	...	...	N	...	...	...

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 with the scatter in Li in cool IC 2602 stars, and 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, whereas no trend exists between residual Li and K I for the cool dwarfs.

Figure 9 confirms that residual K I line strength, like Li abundance, is correlated with residual activity measures for warm Pleiades stars. Interesting behavior is seen for the cool Pleiades stars, 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 the opposite of 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 Pleiades stars have undergone Li but not K depletion, we expect that 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 Pleiades stars 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 Pleiades stars, 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 analogue remains a dominant source of the K residuals.

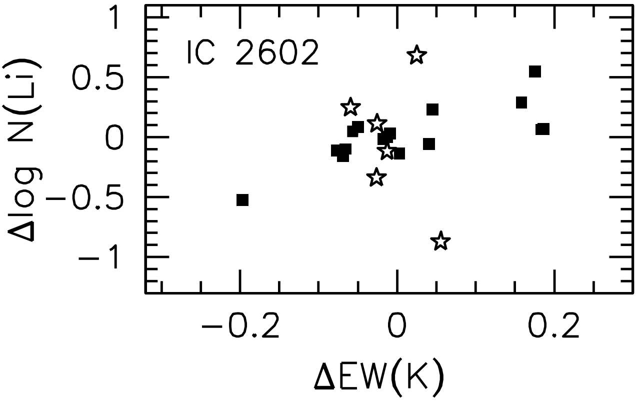

Fig. 15.—Plot of residual Li abundance vs. residual fractional K I line strength for IC 2602 stars. The symbols have the same meaning as in previous figures.

The $\Delta \log N(\mathrm{Li})$ versus $\Delta\mathrm{EW(K)}$ relations for the Pleiades (Fig. 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 Pleiades stars 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) intercluster 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 (Fig. 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 that 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 that 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, for example, 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 stars 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, respectively) is reduced to $\sim$0.10 dex. Similarly, scatter in the warm IC 2602 objects drops from 0.21 dex to 0.12 dex.

Although 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 an intrinsic scatter of $\geq$0.15–0.20 dex over and above that due to observational uncertainty; R01 argues strongly for significant intrinsic Li scatter in cool IC 2602 stars. Thus, whereas 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. (1997).

Although we reach different findings, Favata et al. (1995) suggest that Li-activity relations in cool Pleiades dwarfs (and presumably elsewhere) might simply reflect a Li-rotation relation. That is, 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, for example, influence the physical depletion of Li in the star; any connection to activity is indirect. This view contrasts with the picture assumed above, in which 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. (1997), 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 (Martín & Claret 1996) and another component arising from the influence of angular momentum loss on Li depletion on the main sequence (Chaboyer et al. 1995).

We believe, however, that there is good reason to believe that the Li-activity relation is *not* an indirect reflection of the causal influence of rotation on Li depletion. Although the ability of rotation to significantly alter stellar structure sufficiently to induce a direct Li-rotation correlation in young stars has been questioned (King et al. 2000), stronger evidence is the existence of K-activity relations in the Pleiades (Fig. 9), IC 2602 (Fig. 6), and M34 (Fig. 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 R01) 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 Pleiades stars and M34 dwarfs. Moreover, data like those in Figure 6*d* of King et al. (2000), which shows an anticorrelation between residual Li abundance and rotational period in cool Pleiades stars 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. (2002).

The Li-rotation picture is captured in Figure 16 for M34, the Pleiades, and IC 2391 and IC 2602. The top panels display residual Li abundances for cool M34 dwarfs versus projected rotational velocity.[5] The residuals in the top right panel are residuals of residuals: the remaining scatter after $\Delta \log N(\mathrm{Li})$ variations are removed using an average of linear least-square fits to the $\Delta \log N(\mathrm{Li})$–H$\alpha$ and $\Delta \log N(\mathrm{Li})$–Ca II trends in Figure 12. The middle row of Figure 16 is an analogous plot for cool Pleiades stars 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.

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–de-trended Li residuals in M34 show no correlation with rotational velocity, providing no evidence that independent effects due to activity and rotation are operating. Although 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 velocities in the Pleiades. Furthermore, no residual Li-rotation patterns whatsoever are clear for IC 2602 and IC 2391. Rather, dispersion in 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

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

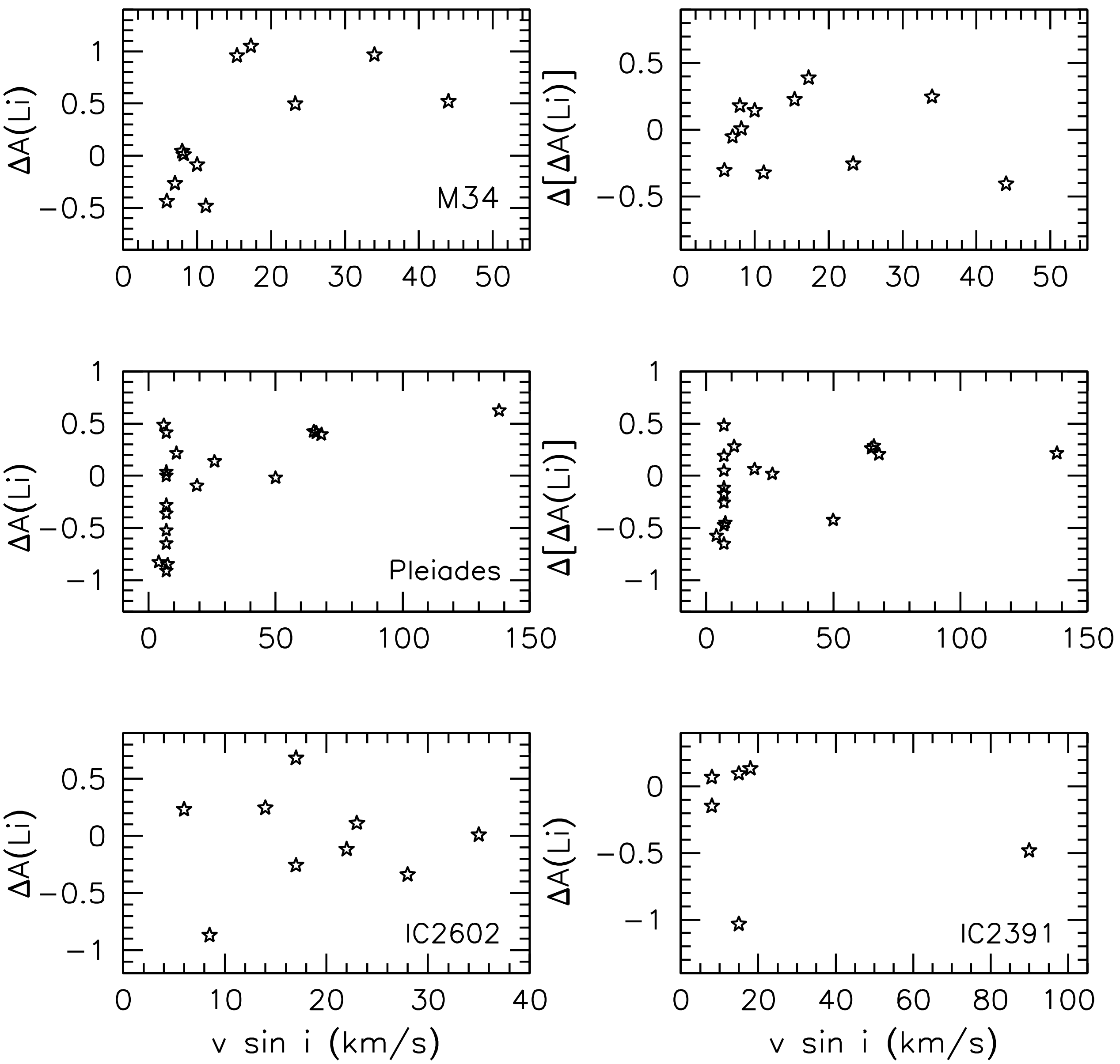

FIG. 16.—*Top*: Plots of residual Li abundances (*left*) and activity-corrected residual Li abundances (*right*) in cool M34 dwarfs vs. projected rotational velocity. *Middle*: Same as above for cool Pleiades dwarfs. *Bottom*: Residual Li abundances vs. projected rotational velocity for IC 2602 (*left*) and IC 2391 (*right*) stars.

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 (1) illusory themselves, (2) an indirect result of other relations, or (3) 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. (2003) 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 (Stuik et al. 1997). Could such color alterations themselves lead to correlated alterations in the alkali and chromospheric emission residuals?

For clusters such as M34 and the Pleiades in which 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. (1997) results, in which 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 M34 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 1 σ 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

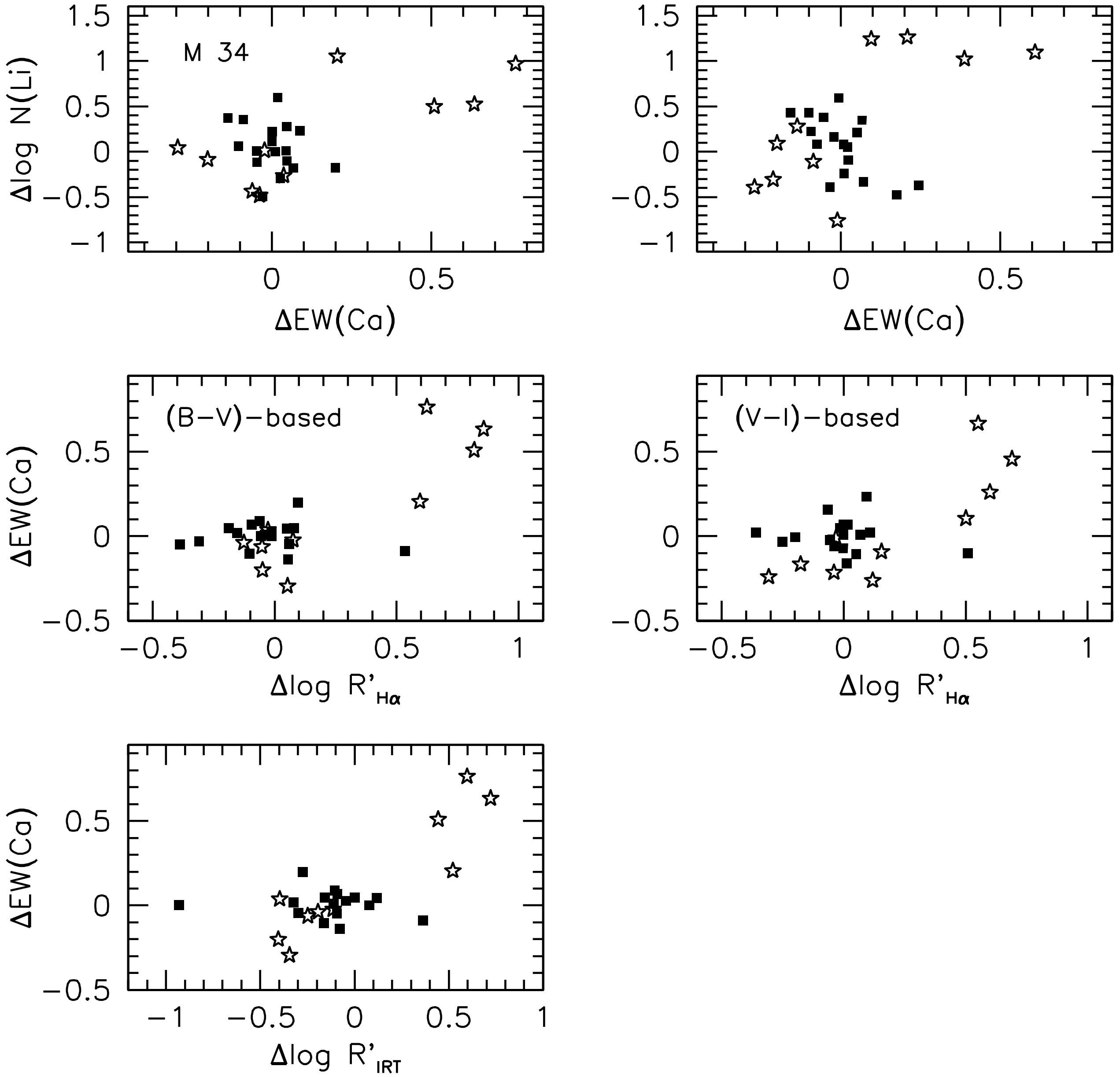

FIG. 17.—A combined version of Figs. 12 and 13 for M34 stars, but replacing the $\lambda7699$ K I residuals with those measured for the $\lambda6455$ Ca I feature. *Left*: Relations between residuals measured from $B - V$ colors; *right*: relations between residuals measured from the $V - I$ colors. Notable differences in residual Li and chromospheric emission with Ca residuals are seen for the cool stars (*stars*).

ionization (6.1 eV) potentials but its modest line strength compared with the alkali features. Presumably the latter is reflected in the feature's formation depth: for example, the $\lambda7699$ 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 with depths of −1.5 to −2.0 for the Ca I feature. The 1 σ dispersion for the Ca I feature is a modest ~9% in the warm M34 stars. However, the value is a large ≥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.

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. (1997), in which surface inhomogeneities alter conditions in the photosphere. It is interesting to note, however, that King et al. (2000) did not note any such correlations in the Pleiades with the stronger 2.7 eV $\lambda6717$ 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 overexcitation/ionization in young cool stars (King et al. 2000;

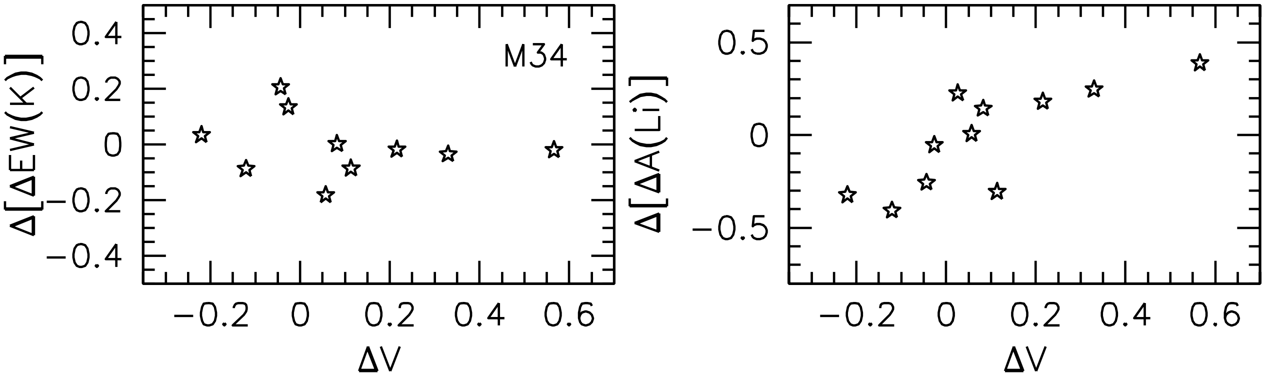

FIG. 18.—Plots of activity-corrected residual fractional K I line strengths (*left*) and Li abundances (*right*) for cool M34 dwarfs vs. *V*-magnitude deviation from a fit to a mean main sequence. Positive values of ΔV represent objects superluminous compared with the mean main sequence.

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 we note that the above emerging picture based on intercluster comparisons or intracluster 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 underenhanced in cooler, younger, and more chromospherically active stars. This effect may contribute to a partly illusory Li- or K-$T_{\rm eff}$ relation in a given cluster (see Schuler et al. 2003), but the correlations seen here in the *scatter* about the alkali-$T_{\rm eff}$ relation indicate overenhancements 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. *Intracluster Age Spreads*

An important note in the study of IC 2602 by R01 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 that is 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 (Fig. 18, *right*) in cool M34 dwarfs is nearly a factor of 2. This suggests an additional mechanism that is afflicting Li (or its measurement) over and above the activity-dependent effects on K I. One possible mechanism is the presence of an intracluster age spread that leads to differing (time-dependent) star-to-star Li depletion. Although 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 et al. 1999; Eggen 1998, 1992; Eggen & Iben 1988).[6]

To explore the possibility of intracluster 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. Whereas 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 a remaining scatter of 0.12 dex that, finally, seems in line with the observational uncertainties of Jones et al. (1997).

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 (1) activity-based corrections to the Li residuals plotted in Figure 18 still exhibit a trend with ΔV, (2) the activity-corrected Li residuals do not show a trend with rotational velocity in Figure 16, and (3) 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 intracluster 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 (Gonzalez 1998). 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, intracluster 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 right-hand 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; however, the observations in Figure 18 indicate that the superluminous stars have relatively enhanced Li abundances.[7] Moreover, although

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[6] The mass-dependent age spreads suggested by Herbig (1962) 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.

[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 $\Delta \log N(\mathrm{Li})$. How $\Delta Y/\Delta Z$ behaves in any real star-to-star variation is completely uncertain.

understanding the source of systematic trends of their heavy-element abundances with $T_{\rm eff}$ in M34 dwarfs remains important, Schuler et al. (2003) note that the M34 heavy-element scatter (real or not) in the M34 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 & Deliyannis 1995); however, the radial velocities in Jones et al. (1997), although essentially single epoch, provide no evidence for binary status for the superluminous stars in Figure 18. 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 on the basis of the scatter in Li is currently limited to M34.

4. EPILOGUE AND FUTURE WORK

Although our study has noted the existence of correlations between λ6707 Li I or λ7699 K I and stellar activity in a couple of additional clusters, the most significant result is the richness of the behavior of such correlations. The variety of intracluster (e.g., warm stars vs. cool stars), intercluster (e.g., trends with different signs in M34 or the Pleiades and the Hyades), line-based (Li I vs. K I), and activity-based (e.g., X-rays vs. 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 three 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. Although 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 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 themselves are 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. For example, might they simply represent measurement errors that 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 M34 are examples of cases in which an astounding $\sim$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 inquiry. 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. Although Boesgaard (1991) noted no λ6707 Li I variations in the very active and spotted stars she monitored, Patterer et al. (1993) noted significant line-strength variations in five of seven 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. (1995) note differences in the presence of Li-activity correlations between their Pleiades cluster and field-star samples; although such a difference is curious, it nevertheless suggests that monitoring of active field stars assumed to be analogues of the cluster stars studied here may be misleading.

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[8] Hyades ΔV estimates were made using absolute magnitudes calculated using both the *Hipparcos* and refined secular parallaxes from de Bruijne et al. (2001) in order to account for depth effects in this nearby system.

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