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A Spectroscopic Analysis of V505 Persei and the Origin of the Lithium Dip

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Abstract

We study the observed Li Dip in stellar clusters and field stars, testing Rotationally Induced Mixing (RIM) by measuring Li abundances in a middle-aged (1.1±0.15 Gyr), metal poor ([Fe/H]=-0.15±0.03), short period binary, V505 Per, finding Li abundances of Log N(Li)=2.67±0.1 and 2.42±0.2 from the primary and secondary components, respectively. These abundances are significantly higher than observed abundances from single stars of similar metallicity and ZAMS $T_{\rm eff}$ as shown by comparison with NGC 752, and suggest that RIM may be a primary cause of the Li Dip.

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Chapter 1

Introduction

1.1 Early Studies and Discovery

For years, Lithium has been studied in astronomy as a possible tracer element, that is, an element that by its presence or absence provides information on something else. This is generally possible due to the fragility of Li; it is destroyed at temperatures of 2.5×10^6 K or higher, allowing it to, by its presence or absence, be a good probe of stellar structure, evolution, and transport of materials. For example, the depletion of Li in so-called “blue-stragglers”, was used to test structure, material transport, and evolution. The depletion of Li in “blue-stragglers” has been given as evidence that such stars undergo strong mixing (Pritchet & Glaspey, 1991), as such mixing would bring surface Li to Li burning regions and deplete it.

As a further example of Li being used to study stellar evolution, in the mid-1960s, Herbig was studying stellar Li in the hopes of connecting Li abundances to stellar ages (Herbig, 1965). In 1965, Wallerstein et al. were examining [Li/Ca], compared to the stellar color index ($B-V$), in the hopes of finding a solid relationship between [Li/Ca] and $B-V$, so that Li abundances could be tied to Ca abundances.

They found in passing an odd and then unexplained anomaly in the Li abundances. At around 6500K, they found that the value of [Li/Ca] abruptly changed from relatively constant measurable abundances to upper limits about 30% lower than the measurements. At the time, this drop merely meant to them that they could not create an equation of [Li/Ca] as a function of $B-V$ for the higher temperatures, but they announced that they could create such a function at lower temperatures. Years later Cayrel et al. (1984) studied Li in order to better understand the steady decrease of Li in late stellar spectral types, and found a strong correlation between Li abundance and effective stellar temperature ($T_{\rm eff}$) in these late spectral types, though they also found that the rate Li depletion was higher than could be explained by standard models (see Figure 1.1), which rely on a deepening surface convection zone (SCZ).

Such difficult-to-explain trends or gaps are disturbing, since Li is usually used in making predictions about some other quantity, such as the age of a star (Herbig, 1965; Deliyannis, 2009), or the $T_{\rm eff}$ of a star (Wallerstein et al., 1965; Cayrel et al., 1984), and testing models such as explanations for "blue-stragglers" (Pritchet & Glaspey, 1991; Shetrone & Sandquist, 2000). Such usefulness only exists if accurate models and predictions exist, however, so oddities in Li abundances merit further study, and can cause modifications to current theory.

In 1986, Boesgaard & Tripicco took measurements of Li in the Hyades, graphed Li as a function of $T_{\rm eff}$, and found an odd shape, as seen in the top panel of Figure 1.1. As predicted by standard convection based models (Deliyannis, 1998), Li abundances are predicted to show little or no main sequence depletion in F and G class stars, and to show steadily increasing main sequence depletion for later spectral types. Boesgaard & Tripicco (1986) found that around 6500K, for a width of about 300K, there was an abrupt and startling break from this prediction: a so-

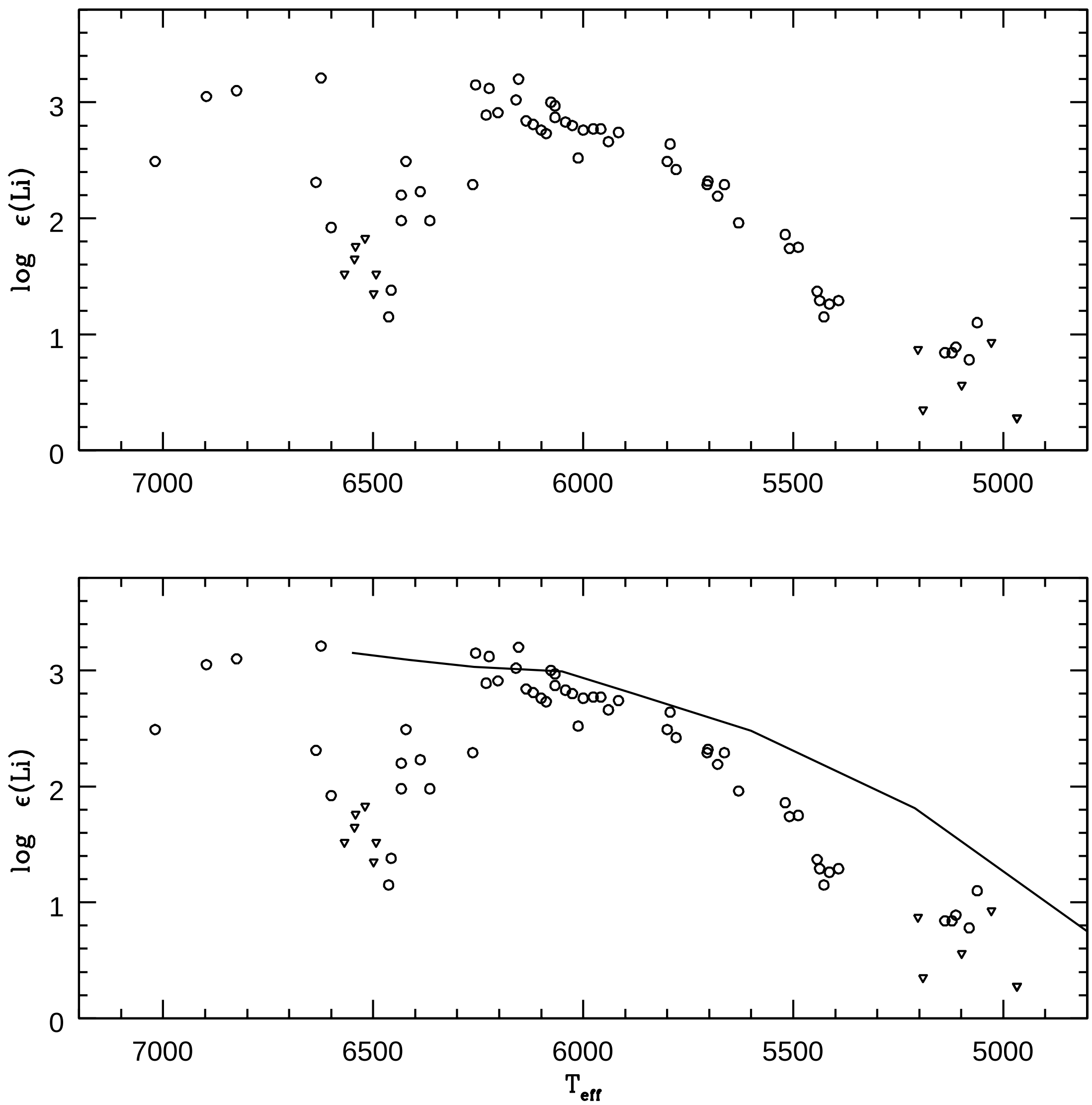

Figure 1.1: This graph, shows both the Li abundances of the Hyades alone (Balachandran, 1995), as well as with the standard model predictions for the approximate age and metallicity of the Hyades ([Fe/H]=0.15, 600 Myrs) for comparison (Pinsonneault, 1997). Triangles are upper limits, circles are measured abundances.

called “chasm” in the Li abundances, where the Li abruptly dropped from nearly the same abundance as predicted by the convection-based models to mere upper limits, then climbed back up to near-predicted levels, after which the decrease in Li at cooler temperatures was faster than expected (see Figure 1.1). This feature was found to persist in any main sequence cluster with an age greater than 100 Myrs (see Charbonnel & Vauclair (1992) for a full list of clusters and references), in selections of field stars (Stephens et al., 1997), and even in selections of sub-giants from considerably older clusters (Balachandran, 1995). We will refer to it as the Li Dip for the remainder of this work.

Despite the widespread existence of the Li Dip, its exact parameters vary somewhat from cluster to cluster. In the Hyades, it is about 300K wide, centered at 6500K, with the blue side being extremely steep and showing merely upper limits, while the red side is shallower and shows actual measurements (Boesgaard & Tripicco, 1986). Balachandran (1995) noted that for older clusters the slope of the red side becomes progressively more shallow, and the center of the dip shifts based on the metallicity of the cluster. Furthermore, older clusters show a progressive erosion of the Li abundances surrounding the dip, and young, high metallicity clusters, while sometimes showing a slight drop in the Li abundances at the dip, do not have a distinct chasm, showing actual abundances instead of upper limits in the dip. Also, while theory had predicted a Li reduction at temperatures lower than 6000K, the actual reduction is considerably steeper than predicted. What seems to be most constant about the Li Dip are two things: first, that the blue side is steeper than the red side for any given cluster; second, that the position of the Li Dip does not shift with regards to ZAMS T_{eff} (Balachandran, 1995). Further complicating any comparison of the the Li Dip in different clusters is that, as shown by Deliyannis (2009), both metallicity ([Fe/H]) and age influence Li abundances, both in the level of Li found on either side of the Li Dip and in the depth of the Dip itself. Even relatively small changes in metallicity can create large changes in Li abundace, since initial Li abundance depends on [Fe/H] and Li depletion depends on both [Fe/H] and stellar age (Deliyannis, 2009). So, for a comparison of Li Dip stars from different clusters or of field stars to be meaningful, not only should Li be graphed against ZAMS $T_{\rm eff}$, but stars of similar metallicity and age should be compared.

1.2 Explanations and Tests

As soon as the Li Dip was discovered, even before the original Boesgaard & Tripicco paper was published (Michaud, 1986), attempts to modify existing theory began. One of the earliest explanations for the Li Dip was a combination of diffusion and mass loss, presented by Michaud in 1986, but this explanation failed to adequately explain the Li Dip. The predicted abundance profile from diffusion does not adequately match the observed profile in the Hyades, being narrower than than the observed Li Dip (Richer & Michaud, 1993). Furthermore, since a diffusion model predicts that the missing Li from the Li Dip will largely sit just below the SCZ, one would expect to see the Li Dip disappear in subgiants as the SCZ deepens and recovers the Li deposited beneath the old SCZ, but the Li Dip persists in M67 (Balachandran, 1995), whose stars should have recovered the lost Li if diffusion were the sole or principal cause of the Li Dip (Deliyannis, 1998).

Similarly, mass loss fails as a primary explanation. If mass loss were to be the primary cause of the Li Dip, then Li depletion would be nearly completely depleted before Beryllium (Be) showed any signs of depletion, but Deliyannis et al. (1998) found that there is a depletion in Be corresponding to, but shallower than, the Li Dip, which mass loss cannot explain while any detectable Li remains.

Another interesting proposal to explain the Li Dip was mixing due to gravity waves (García López & Spruit, 1991). This model does indeed create a steep drop-off on the blue side of the Li Dip, but it required gravity waves about 15 times stronger than the authors felt was reasonable based on mixing length estimates to obtain the required depth. Thus, gravity waves are not a primary cause of the Li Dip either.

All of these explanations may have an effect on the Li Dip, but since the dip does not conform to the predictions of these proposals, an explanation that can serve as a primary explanation must still be found. An idea that has shown promise in explaining the Li Dip is Rotationally Induced Mixing (RIM) (Charbonnel & Vauclair, 1992), which seeks to tie the loss of Li in the dip to the loss of angular momentum experienced by low mass, main-sequence stars.

Physically, rotationally induced mixing is caused by angular momentum and angular velocity gradients. When such a gradient exists, currents arise that generally act to reduce any differential rotation caused by the gradient. These currents create turbulence, which can cause significant mixing (Pinsonneault et al., 1992). RIM suggests that as stars spin down, they transport angular momentum internally, and the angular momentum gradient shifts, creating turbulence that in turn causes mixing between the surface preservation region for Li and regions of the star hot enough to destroy Li, thus lowering the surface Li abundance when the star loses angular momentum. Initial tests have been conducted comparing simulations, based on mathematical models with various parameters, to real world observations, and such comparisons have at least shown that RIM can be made to match such real-world observations (Charbonnel & Vauclair, 1992).

To better test RIM, however, a prediction needs to be made and verified. To do this, a group of stars that do not spin down on the main-sequence needed to be identified, and tested for Li abundances. In the various tests of Li abundance,

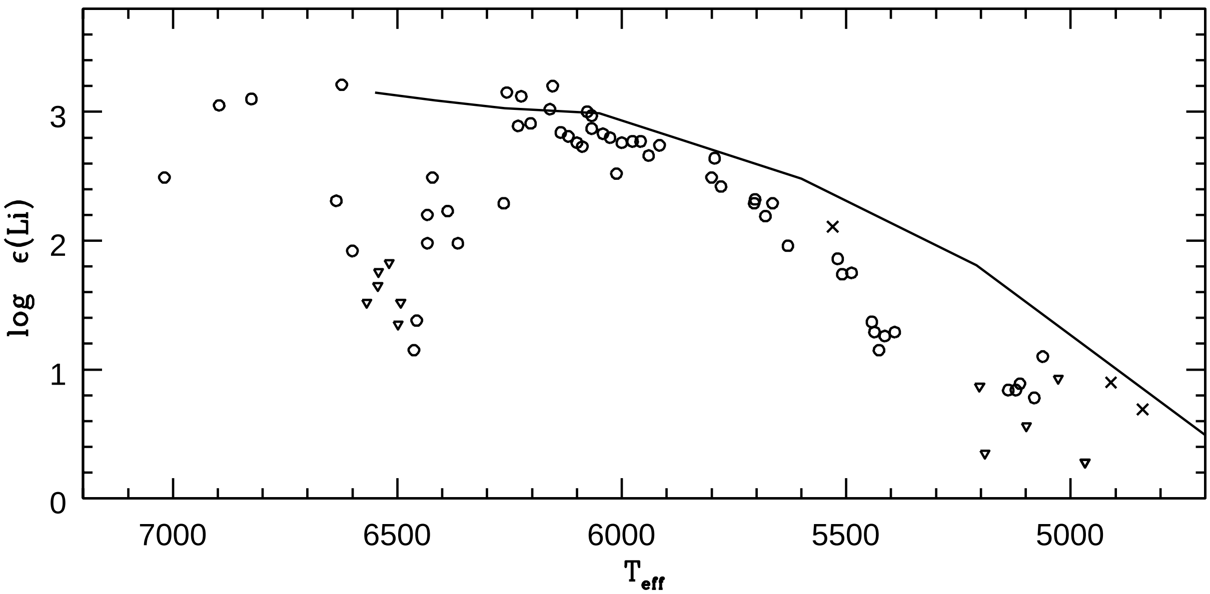

Figure 1.2: This adds 3 SPTLBs (Ryan & Deliyannis, 1995), marked as X's, to the Figure 1.1. Note how their Li abundances are above the mean trend of the Hyades.

one group of stars stood out: short-period binaries. When looking at the too-steep drop-off in the stars cooler than the Li Dip, a small number of stars float above the observed trend of Li depletion, much closer to the theoretical prediction (see Figure 1.2). These were stars identified as short-period tidally locked binaries (SPTLBs) (Ryan & Deliyannis, 1995). According to circularization theory (Zahn & Bouchet, 1989), any binary system with a period of less than eight days should circularize due to tidal effects well before entering the main sequence, thus shedding angular momentum, and suffering the internal momentum transport and mixing associated with losing angular momentum before the star is hot enough to burn Li. Thus, if RIM is the primary cause of the Li Dip, SPTLBs with the correct ZAMS T_{eff} should show measurable Li abundances, and specifically should show Li abundances comparable to that predicted by standard models, and to the plateaus on either side of the dip. The abundance is not expected to be exactly equal to that predicted by standard models, however (Ryan & Deliyannis, 1995). SPTLBs are expected to circularize in the early pre-main sequence (PMS) but are also expected to experience a desynchronization and resynchronization episode in the late PMS, causing some Li depletion (Zahn & Bouchet, 1989). Thus, the SPTLBs should show a Li abundance that is in most cases higher than the mean trend for their cluster, or higher than the trend for any cluster of the same age and metallicity, but lower or equal to the predicted value from standard models.

One such SPTLB is V505 Persei. It is an eclipsing binary, so it has good physical determinations of mass and radius. It has a period of 4.2 days (Marschall et al., 1997), putting it well inside the limit of what should be tidally circularized long before the main sequence. Since V505 Per is a middle age star of slightly sub-solar metallicity (Tomasella et al., 2008), it should compare easily to NGC 752, a similarly middle-aged and slightly sub-solar metallicity cluster (Daniel et al., 1994). Thus, the goal of the article that this thesis is largely based on (See the Appendix for an in-preparation version of the article) was to measure the Li abundance of V505 Per and plot Li against ZAMS T_{eff}, and see if the Li abundance of V505 Per is significantly higher than the Li Dip stars of equivalent ZAMS T_{eff} in NGC 752.

Chapter 2

Data and Analysis

2.1 Observations

The data were taken on the Keck I 10-m telescope during two nights in 1997, August 30 and 31 UT. The images were high-resolution spectroscopic data, R=45,000, and three images were taken each night, with a total exposure time of 8 and 5.5 minutes for the first and second nights, respectively. Standard data reduction was carried out in IRAF[1]

To increase the S/N ratio, we coadded the 3 images from each night. This should not cause problems since the exposure time was a few minutes and the orbital period of V505 Per is a few days. We calculated the S/N ratio, near the λ6707 Li I features, as 846 and 583 on the first and second nights, respectively. The coadded spectra were fit with a low-order polynomial to normalize the continuum. In both nights, the two binary components are easily distinguished, and we identified them using slight differences in the line strengths of the λ6717 Ca I feature as well as

[1]IRAF is distributed by the National Optical Astronomy Observatory, which is operated by the Association of Universities for Research in Astronomy (AURA) under cooperative agreement with the National Science Foundation.

the relative Doppler shifts expected from Tomasella et al. (2008). We measured the relative Doppler shifts using that same λ6717 Ca I feature.

2.2 Syntheses

In order to get Li and Fe abundances, we synthesized spectra and compared the synthetic and observed spectra, as opposed to measuring the observed equivalent width and line depth directly. This was done to avoid the inherent problems in measuring line strength in a spectroscopic binary. The continua of both stars inevitably contaminate the lines of the other, so simply measuring line strength would have yielded artificially low abundances. Therefore, we synthesized a spectrum for each component of the binary system, weighted the spectra according to their respective luminosities, shifted them to match the observed Doppler shift, combined them, and then compared the combined spectrum to the observed spectrum, with a χ^2 analysis giving a numerical evaluation of how well the combined synthetic spectrum fit the observed spectrum.

In order to create synthetic spectra, combine them, and make meaningful comparisons, we needed to perform several steps in sequence. First we created a model atmosphere, using the grids of Kurucz (1992) and the MSPAWN72 program. This required having values for $T_{\rm eff}$, log g, microturbulent velocity (ξ), and [Fe/H], all of which were entered into MSPAWN72 which used them to generate a model atmosphere based on the Kurucz grids. $T_{\rm eff}$ and log g were obtained from Tomasella et al. (2008), while ξ was calculated based the following equation: $\xi = 1.645+3.854\times10^{-4}\times(T_{\rm eff}-6387)-0.6400(log\,{\rm g}-4.373)-3.427\times10^{-4}\times(T_{\rm eff}-6387)(log\,{\rm g}-4.373) km\times s^{-1}$ (Allende Prieto et al., 2004). [Fe/H] was more difficult to define, since our first comparisons were supposed to verify a value for [Fe/H]. We used an initial estimate of [Fe/H]=-0.35 (Nordström et al., 2004), and refined that value based on iterative comparisons between our synthetic spectra and the observed spectra.

Once the model atmosphere was created, we used the model atmosphere to generate a synthetic spectrum in the program MOOG (Sneden, 1973), which is a program intended to synthesize and analyze spectra, assuming local thermodynamic equilibrium. We input the model atmosphere from MSPAWN72, as well as a line list of the λ6707 Li I region, which we obtained from King et al. (1997). MOOG used this information to create a synthetic spectra, and the synthetic spectrum was smoothed by convolving it with a Gaussian, which had a full width half max (FWHM) derived from analysis of a number of clean, weak lines in the observed spectra. Note that each component of the binary had a different FWHM, and so it was important to keep the data files for each star separate from the beginning of the analysis. There was no time at which the primary and secondary stars used the same data files.

Star	$T_{\rm eff}$ (K)	*log* g	M ($M_\odot$)	R ($R_\odot$)	ξ (km/s)
V505 Per A	6512±21	4.32±0.01	1.2693±0.0011	1.287±0.014	1.73
V505 Per B	6462±12	4.33±0.01	1.2514±0.0012	1.266±0.014	1.70

Table 2.1: V505 Per Parameters
$T_{\rm eff}$, *log* g, M, and R are taken from Tomasella et al. (2008), while ξ is calculated based on Nordström et al. (2004).

Once a synthetic spectrum for each star was created in MOOG, the spectra were taken to IRAF, where they were weighted, Doppler shifted, and combined. Weighting was calculated based on relative luminosity, calculated from the radius (R) squared of each star times the monochromatic Planck function, calculated at λ6707 Å. Since the primary component had the larger luminosity, its weighting factor was set equal to unity, so that the spectra from the secondary component was weighted relative to the primary. The amount of expected Doppler shift was calculated form the position of the λ6717 Ca I feature in the observed spectra, and that observed Doppler shift was applied to the synthetic spectra before using the SARITH package in IRAF to resample and combine the synthetic spectra. The result from SARITH was a single synthetic spectrum representing both stars of the binary, which was then re-weighted and compared to the observed spectrum.

2.3 Comparisons

The procedure outlined above would create a single, synthetic binary spectrum. In order to obtain a numerical abundance, whether for [Fe/H] or Li, this procedure was followed dozens, possibly hundreds of times.

To determine [Fe/H], a χ^2 was calculated by comparing the λ6705 Fe I of the observed and synthetic spectra, and over several iterations the best fit was determined. Once [Fe/H] was confirmed, the same procedure was repeated for Li, using the λ6707 Li I line for comparison, and using our result for [Fe/H] in MSPAWN72.

One primary difference between our methods for determining [Fe/H] and Li was that we forced [Fe/H] to have the same value for both stars, while we allowed Li to be different for each. This simplified calculating [Fe/H], and since the two components of V505 Per would have formed at approximately the same time from the same dust cloud, and since neither star is able to produce Fe, they should also have the same [Fe/H] value. Li, on the other hand, can be destroyed during hydrogen burning, and since Li abundances were the main question of interest, we did not assume that both stars had the same Li abundance, instead allowing Li abundances to vary. Furthermore, in the observed spectrum from the second night, the λ6705 Fe I line of V505 Per B was contaminated by a known detector artifact, making it impractical to evaluate [Fe/H] separately for the observations from each night, while

Li was determined separately for each night (see Figure 2.1). Ultimately, the Li abundances derived to match the observations from each night were averaged, thus providing a final Li abundance for each star.

2.4 Results

To follow Balachandran's lead (1995) and plot Li against ZAMS T_{eff}, we needed to find the ZAMS T_{eff} of each star. This required us to first find the age of the stars, which using the Yonsei-Yale isochrones (Demarque et al., 2004), we did, placing the stars in the radius vs. mass plane to determine which isochrone they intersected. In order to create the isochrones for the R vs. M plane, we used [M/H]=-0.14, and [α/Fe]=0. Following our determination of the stars' ages, we used the Revised Yale Isochrones (Green, Demarque, & King, 1987) to find the theoretical change in temperature between the stars' current T_{eff} and the ZAMS T_{eff}, which we applied to the T_{eff} from Tomasella et al. (2008) to determine ZAMS T_{eff}.

Star	[Fe/H]	Li	Age (Gyrs)
V505 Per A	-0.15+0.03-0.02	2.67±0.10	1.15±0.15
V505 Per B	-0.15+0.03-0.02	2.42±0.20	1.15±0.15

Table 2.2: V505 Per Results

The analysis of the first night's data yielded [Fe/H]=-0.15+0.03-0.02. The uncertainty is from the χ^2 fitting, with continuum placement not taken into account, but it is still in good agreement with Tomasella's [M/H]=-0.12±0.03 (2008). For Li, we found average abundances of 2.67±0.10 and 2.42±0.20 for the primary and secondary components respectively. About 0.03-0.06 of this error bar is accounted for by our χ^2 fitting, 0.01-0.02 from uncertainties in the T_{eff}, and the rest from uncertainties in the continuum. The uncertainty from T_{eff} is largely irrelevant when compared to the

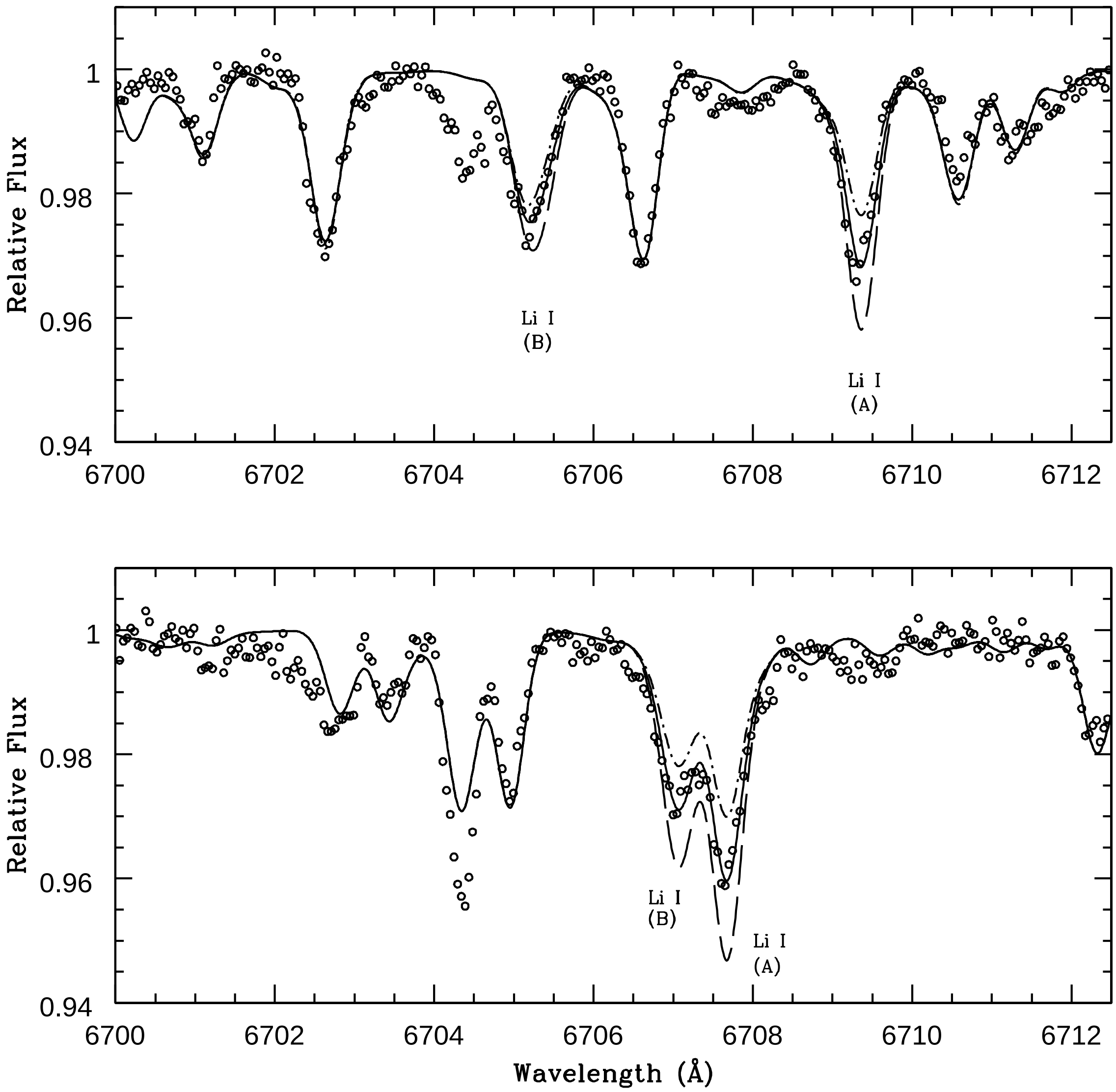

Figure 2.1: This shows an overlay of the final synthetic spectrum (solid line) overlaid on the observed spectrum (dots), with two other synthetic spectra for comparison (dashed and dotted lines), offset by ±0.15 dex. The top panel uses observations from the first night, and the bottom panel uses observations from the second night. Note the odd line that appears at 6704.5 Å in both nights of observation. Since it appears in both nights in the exact same location, which no line from either star could do, it is not from either star and does not need to be matched by the synthetic spectra.

uncertainty from the χ^2 fitting, and both combined are smaller than the uncertainty introduced by the continuum.

We determined an age of 1.15±0.15 Gyrs for the system (see Figure 2.2). The vast majority of this uncertainty comes from uncertainty in the radius of the stars. This in turn yielded a ZAMS $T_{\rm eff}$ of 6483K for the primary, and 6432K for the secondary.

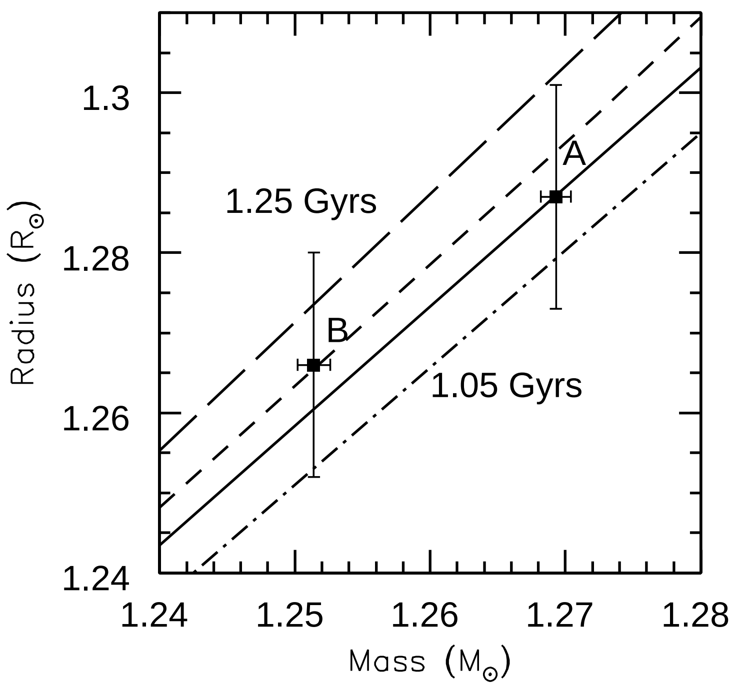

Figure 2.2: This plot shows several isochrones, created using the Yonsei-Yale (Green, Demarque, & King, 1987) isochrones with [M/H]=-0.14, ranging from 1.05 Gyr to 1.25 Gyr, plotted on a grid of radius vs. mass.

For discussion of the results and their meaning beyond what is presented here and in Chapter 3, please see the attached paper in the Appendix.

Chapter 3

Conclusions

Li is an important element for probing stellar interiors and evolution. It has been studied extensively so that it can be effectively used to accurately indicate other parameters, including studies by Herbig (1965) trying to link Li to stellar ages, studies by Wallerstein et al. (1965) studying a possible link between [Li/Ca] and stellar color ($B-V$), and work by Cayrel et al. (1984) focusing on the relation between Li and spectral type, especially later spectral types. Both Wallerstein et al. (1965) and Cayrel et al. (1984) essentially attmepted to trace Li evolution in terms of stellar mass. Later, Boesgaard & Tripicco (1986) found a strong deviation from the predicted Li vs $T_{\rm eff}$ behavior in the Hyades, in the form of a sharp drop in Li abundance of mid-F class stars with a $T_{\rm eff}$ of about 6500±150K. Various astronomers found that this deviation persisted in every cluster aged more than 100 Myrs (Charbonnel & Vauclair, 1992) as well as in field stars (Stephens et al., 1997).

A number of theories were proposed to deal with this gap, primarily as modifications to existing theory, including a combination of microscopic diffusion and mass loss by Michaud (1986), a gravity waves proposal by García López & Spruit (1991), and rotationally induced mixing (RIM) (Charbonnel & Vauclair, 1992; Pinsonneault et al., 1992).

Of these, only RIM has not suffered apparently insurmountable challenges as an explanation for the Li Dip. As a way to test RIM, Ryan & Deliyannis (1995) suggest that SPTLBs would not suffer the extreme Li depletion of the Li gap, if RIM is the primary mechanism for producing the gap. Balachandran (1995) pointed out that even the Li Dip in field stars or different clusters could be compared by plotting the Li abundance against ZAMS $T_{\rm eff}$, not merely $T_{\rm eff}$. Of course, this does not overcome challenges presented by age and metallicity related Li depletion (Deliyannis, 2009), but it does guarantee uniform placement of the Li gap. What does overcome the systematic variation of Li associated with age and metallicity is comparing Li abundances between stars of the same age and metallicity.

Thus, RIM predicts that a Li vs ZAMS $T_{\rm eff}$ plot of a SPTLB when compared to a cluster of similar age and metallicity, such as NGC 752 (Daniel et al., 1994), should show that the SPTLB has a higher Li abundance than the stars of the comparison cluster, helping to confirm or reject RIM as a valid explanation of the Li dip. When V505 Per, a SPTLB, was plotted on the Li and ZAMS $T_{\rm eff}$ plane, it was found to lie squarely in the Li gap, as outlined by the stars of NGC 752 plotted in the same plane (see Figure 3.1). It showed some minor depletion compared to the Li abundances outside of the gap in NGC 752, but as pointed out by Ryan & Deliyannis (1995), some minor depletion is expected according to circularization theory, and the depletion is truly minor when compared to the Li abundances of the non-binary stars of the same ZAMS $T_{\rm eff}$ in NGC 752.

These results are strongly suggestive. V505 Per shows a superabundance of Li compared to the gap stars of NGC 752, but it is only one SPTLB, and in order to prove a theory beyond a reasonable doubt a consistent trend is required. In order to establish such a consistent trend, we believe that the Li abundance of a series of

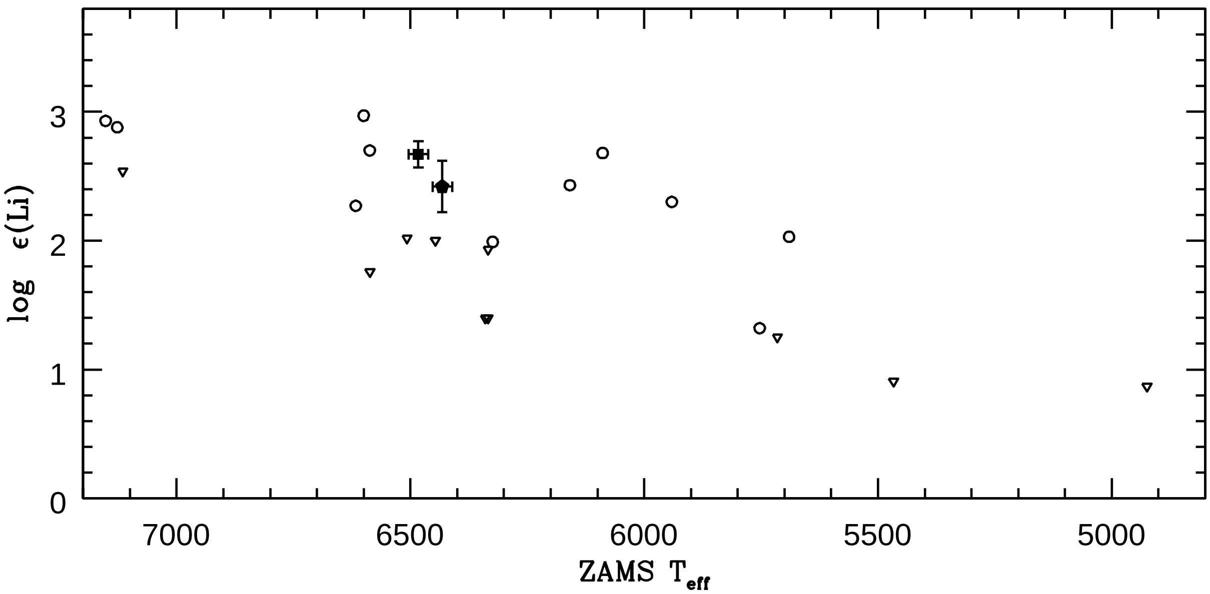

Figure 3.1: This shows a Li vs. ZAMS T_{eff} chart. The solid squares are the two stars of V505 Per, the hollow shapes are measurements and upper limits for NGC 752 (Balachandran, 1995).

Li Dip SPTLBs should be measured and compared to stars of equivalent metallicity and ZAMS T_{eff}. If possible, the Li abundance of entire clusters containing SPTLB should be studied, so that the Li abundances of the SPTLB and single stars are easily comparable. Such a study may be able to advance the support of RIM enough to make it acceptable beyond a reasonable doubt.

Appendix

Much of the work for this thesis was originally done for a paper. This paper is therefore attached here for convenience. It contains further discussion on the analaysis of the data and relevance of the results.

This paper is in preparation for submission as *A Spectroscopic Analysis of the Eclipsing Short Period Binary V505 Persei and the Origin of the Lithium Dip* (Baugh et al., in-preparation).

A SPECTROSCOPIC ANALYSIS OF THE ECLIPSING SHORT PERIOD BINARY V505 PERSEI AND THE ORIGIN OF THE LITHIUM DIP

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Figure 3.2:

ABSTRACT

As an independent test of rotationally induced mixing as the source of the well-known Li dip in sufficiently old Pop I mid-F dwarfs, we utilize high-resolution and -S/N Keck/HIRES spectroscopy to measure the Li abundance in the components of the ∼1 Gyr modestly metal-poor ([Fe/H]= −0.15) eclipsing short-period binary V505 Per. We find Li abundances of log N(Li)∼2.7±0.1 and 2.4±0.2 in the $T_{\rm eff}$∼6500K and 6450K primary and secondary components, respectively. The V505 Per components are located in the midst of the Li dip, and their Li abundances are at least a factor of 2-5 larger than the Li abundance detections and upper limits in the similarly metallicity open cluster NGC 752 and younger Hyades and Praesepe open clusters. If recent estimates of the scaling of initial Li abundances with metallicity are correct, then the differences would be even larger with respect to the more metal-rich Hyades and Praesepe clusters, and perhaps NGC 752 if the most recent solar-metallicity estimates for this cluster are correct. The results suggest, independently of complementary evidence based on Li/Be ratios, that main-sequence angular momentum evolution is the origin of the Li dip. Specifically, our stars' Li abundances indicate that tidal circularization can be sufficiently efficient and occur early enough in the lifetime of short period binary mid-F stars to reduce the effects of rotationally induced mixing and destruction of Li occuring during the main-sequence in otherwise similar non-SPTLB stars.

Subject headings: stars: binaries: spectroscopic – stars: binaries: eclipsing – stars: individual: V505 Per – stars: abundances – stars: evolution – stars: rotation

1. INTRODUCTION

Lithium is an element of fundamental and broad astrophysical importance. Due to its fragility, this light element is quickly destroyed in solar-type stars when brought into regions where $T \geq 2.5 \times 10^6 K$; thus, it is useful in studying the transport of matter in stars, which provides observational data on stellar structure and evolution (see Pinsonneault 1997 for a review). In addition, stellar Li abundances have cosmological applications. Combining the abundance of Li in old stars with accurate stellar evolution models, accounting for stellar destruction and Galactic production, should lead to the primordial Li abundance, which provides constraints on the details of Big Bang nucleosynthesis (Boesgaard & Steigman 1985) and an independent check on some cosmological parameters determined by WMAP (Coc et al. 2004). The vulnerability of Li to destruction that makes Li a good probe of stellar structures and evolution can also hampers understanding of initial stellar abundances from primordial nucleosynthesis.

The astrophysical usefulness of Li, therefore, can strongly depend on having correct stellar models that can accurately trace the *in situ* history of Li. Standard stellar models suggest that, for stars of about 1.2 $M_{\odot}$, Li is depleted late in the pre-main sequence (PMS), diluted after the main sequence (MS), but not significantly destroyed during the MS. Since Li burns at relatively low temperatures, anytime the the surface convection zone (SCZ) reaches deep enough into the star's interior, visible Li depletion will occur at the surface. This occurs in the late PMS but, for stars of around 1.2 $M_{\odot}$, the SCZ during the MS is not deep enough to carry Li into the region of the star where it can be appreciably burned. Even during late PMS convective burning, such depletion is minimal at this mass. For a 1.2 $M_{\odot}$ star with $[\mathrm{Fe/H}] \leq -0.1$, the maximum expected depletion on both the MS and the PMS is less than 0.1 dex (Pinsonneault 1997). Therefore, little Li depletion in stars of this mass (or higher) is expected on the PMS, and virtually none on the MS, based on the predictions from standard stellar models (Deliyannis 1998).

Despite this prediction, when Li abundance is plotted against $T_{\rm eff}$ for Population I MS stars, a noticeable Li depletion occurs around 6300 to 6900 K. In the Hyades, for example, Boesgaard & Tripicco (1986) found that stars with 6500 K$\leq T_{\rm eff} \leq$6850 K were depleted by factors of $\geq$0.5-2 dex when compared with stars merely 200-300 K hotter or cooler. This abrupt F-star Li depletion (the "Li dip") presents a significant challenge to standard stellar models, which predict negligible Li depletion on the main sequence, and casts doubt on the ability of such models to either predict or backtrack Li abundances to initial values. To make proper use of Li abundances, stellar models that can accurately explain the Li Dip by modeling Li abundances over a star's lifetime, are necessary. A number of refinements to standard stellar models have been proposed to explain the Li Dip (Balachandran 1995), but we focus on rotationally-induced mixing (RIM) (Charbonnel & Vauclair 1992; Pinsonneault et al. 1992). RIM models propose that a loss of angular momentum, as stars spin down on the main-sequence, could cause slow mixing between the photosphere and the hotter denser region beneath the SCZ, and thus cause the surface Li to be depleted.

In order to test this theory, Ryan & Deliyannis (1995) suggest that the Li abundances of short-period tidally-locked binaries (SPTLBs) be measured. The combination of RIM and stellar tidal theory (Zahn & Bouchet 1989) predict that because a SPTLB loses most of its angular momentum during the very early PMS, when interior densities and temperatures are too low to burn Li, it would not suffer main-sequence Li depletion responsible for the Li dip since it would no longer have significant angular momentum to lose and drive the requisite mixing. Thus, one method to test if angular momentum transfer is indeed the causal force behind the Li Dip is to find SPTLBs whose ages and temperatures should place them in the Li Dip, and measure their Li. A Li abundance higher than otherwise similar Li Dip stars would support RIM models. V505 Persei, a Pop I short-period binary system, is made up of two F stars of nearly equal mass, radii, and $T_{\rm eff}$ (Marschall et al. 1997; Tomasella et al. 2008). Its mas, $/T_{\rm eff}$, and ∼4 day period makes it a good candidate to test if an early PMS loss of angular momentum can later preserve Li compared to otherwise similar non-SPTLB stars. We measure the Li abundance of V505 Per and compare V505 Per in the log ϵ(Li) vs. ZAMS $T_{\rm eff}$ plane with stars in the intermediate-age open cluster NGC 752, showing in the process that the components of V505 Per have a Li abundance higher than single stars of their ZAMS $T_{\rm eff}$.

2. DATA AND ANALYSIS

2.1. Observations

High-resolution (R=45,000) spectroscopy of HD 14384 was obtained on the nights of UT 30 and 31 August 1997 using the HIRES spectrograph on the W.M. Keck I 10-m telescope. Three individual exposures were obtained on each night, totaling 8 and 5.5 minutes on the first and second nights respectively. Standard echelle reductions including debiasing, flat-fielding, scattered light removal, order tracing/extraction, and wavelength calibration were carried out with standard routines in IRAF[1]

Given the short spans of integration relative to the 4.2 d period, we coadded the 3 individual spectra from a given night to increase the S/N. The S/N ratio measured from Poisson statistics in the pseudo-continuum near the λ6707 Li I features is 846 and 583 on the first and second nights. Combined spectra were then fit with a low order polynomial to perform a continuum normalization. Our co-added normalized spectra can be seen in Figure

[1]IRAF is distributed by the National Optical Astronomy Observatory, which is operated by the Association of Universities for Research in Astronomy (AURA) under cooperative agreement with the National Science Foundation.

Star	$T_{\rm eff}$	*log* g	M	R
V505 Per A	6512±21	4.32±0.01	1.2693±0.0011	1.287±0.014
V505 Per B	6462±12	4.33±0.01	1.2514±0.0012	1.266±0.014

Table 1: V505 Per Parameters

Note. — $T_{\rm eff}$, *log* g, M, and R are given in Tomasella et al. (2008).

1. The physically similar components of the SB2 are clearly and consistently distinguished and identified in our spectra both by slight differences in the strengths of the λ6717 Ca I feature and the relative Doppler shifts expected from the orbital ephemeris of Tomasella et al. (2008). The relative Doppler shifts of the components in each night's coadded spectrum, needed for the spectrum synthesis we describe next, were measured from the centroids of the Ca I features.

2.2. Syntheses and Comparison

In order to get Li and Fe abundances, we conducted spectrum synthesis of the λ6707 Li I region to account for the line blending between the stellar components. In order to do so, we needed to know several parameters: the $T_{\rm eff}$, log g, radius (R), and microturbulent velocity (ξ) of each star. The modeling of Tomasella et al. (2008) provides values for $T_{\rm eff}$ and log g (as well as masses and radii), and we determined ξ using the $T_{\rm eff}$- and log g-dependent calibration of Allende Prieto et al. (2004). The λ6707 linelist used was that of King et al. (1997). While [Fe/H] was eventually determined from a comparison of the observed and synthetic spectra, we adopted an initial metallicity of [Fe/H]$= -0.35$ from the photometric determination of (Nordström et al. 2004).

We used the $T_{\rm eff}$, log g, and [Fe/H] values to interpolate model atmospheres from the grids of Kurucz (1992). The LTE synthesis program MOOG (Sneden 1973) was used to create a synthetic spectrum for each star. The spectra were smoothed by convolving them with a gaussian that had a full width half max (FWHM) derived from analysis of a number of clean, weak lines in the observed spectra. The synthetic spectra of the two components were Doppler shifted and then combined, using the product of the square of their radii and the Planck function value at 6707 Å (a pseudo-monochromatic luminosity) as a weighting factor. Finally, we compared the synthetic spectra to the observed spectra using χ^2 minimization methods.

To determine [Fe/H], we used the λ6705 Fe I line for comparison, forcing both stars to have an assumed identical Fe abundance. Once a best-fit value of [Fe/H] had been determined, we moved on to the λ6707 Li I features, for which we did not force identical abundances in the two components in order to allow for possible differing Li depletion in the two stars. These synthetic spectra can be seen compared to the observed data in Figure 1.

2.3. Results

The analysis of the first night's data yielded [Fe/H]= -0.15 ± 0.03. The quoted error is due to the 1σ level fitting uncertainties alone; even so, our metallicity estimate is in good agreement with the [M/H]=-0.12±0.03 estimate of Tomasella et al. (2008). The metallicity of the second night was not calculated due to the unfortunate placement of the λ6705 Fe I feature in the secondary star with a detector/reduction artifact that can be seen in Figure 1; in carrying out the Li syntheses, we assumed the [Fe/H] value from the first night's data. Based upon the Li syntheses (Figure 1), we find average abundances of 2.67±0.1 and 2.42±0.2 for the primary and secondary components respectively. The quoted uncertainties in the absolute Li abundance are dominated by uncertainties in the continuum location;

contributions from uncertainties in the χ^2 minimization and $T_{\rm eff}$ uncertainties amount to only ±0.03-0.06 dex and ±0.01-0.02 dex, respectively.

3. DISCUSSION

The interpretation of the Li abundances in our SPTLB components requires that they be placed in the context of the Li dip morphology defined by other single (or non-SPTLB) stars. Balachandran (1995), in her comparisons of the Li dip in various open clusters, found that the $T_{\rm eff}$ at which the Li Dip occurs varies based on metallicity, but that the zero age main sequence (ZAMS) $T_{\rm eff}$ at which the Li Dip is located does not vary; this provides a means by which the Li Dip morphology of different populations of disk stars can be compared. Additionally, Balachandran (1995) found that the morphology of the cool side of the Li dip is age dependent. Thus, comparing our stars with bona fide Li dip stars requires knowledge of our SPTLB components' ZAMS $T_{\rm eff}$ and age.

For consistency, we followed the approach of Balachandran (1995) to find the ZAMS $T_{\rm eff}$ of each star by looking at $T_{\rm eff}$ differences implied by isochrones (and their assumed color transformations) between our stars in their current evolutionary state and on the ZAMS. This required that we first determine the age of our SPTLB stars, which we did by placing the components in the radius versus mass plane and comparing these locations with sequences from [m/H]= −0.14 Yonsei-Yale isochrones (Demarque et al. 2004). As seen in Figure 2, an age of 1.15±0.15 Gyr is implied for the system; the majority of this quoted age uncertainty comes from uncertainty in the stellar radii estimates. Then, following Balachandran (1995), we used the Revised Yale Isochrones (Green, Demarque, & King 1987) to determine the temperature difference between the $T_{\rm eff}$ at 1.15 Gyr and on the ZAMS. This theoretical $T_{\rm eff}$ difference was then applied to our current $T_{\rm eff}$ from Tomasella et al. (2008) to determine ZAMS $T_{\rm eff}$ values of 6483 and 6432 K for the primary and secondary components.

In Figure 3, we present the Li-ZAMS $T_{\rm eff}$ diagram containing the V505 Per components (solid symbols) and the literature data (open symbols) reanalyzed by Balachandran (1995) for the open cluster NGC 752, which has a 1.5-2 Gyr age and metallicity of [Fe/H]$= -0.15$ according to Daniel et al. (1994). Both our SPTLB components are positioned well inside the Li dip defined by the NGC 752 Li data (or those of the younger and more metal-rich Hyades or Praesepe clusters; see Figure 12 of Balachandran 1995). It can also be seen that the Li abundances of our SPTLB components are a factor of 3-5 larger than the upper limits for the NGC 752 Li dip stars. This difference persists when the comparison is made to Hyades and Praesepe stars of the same or similar ZAMS $T_{\rm eff}$ that have a mixture of Li detections and upper limits.

Deliyannis (2009), in estimating initial stellar Li abundances in open clusters of differing metallicity, provides an emprical measurement of Li production in the Galactic disk parameterized in terms of Fe production. He finds a initial Li-to-Fe (logarithmic by number) relation in the disk with slope $\sim$1 dex/dex. For comparison, the Galactic chemical evolution model in Figure 9 of Travaglio et al. (2001) results in a slope of $\sim$0.7 dex/dex over the range $-1\leq$[Fe/H]$\leq$0, though this slope may be errantly small since it is unable to reproduce the initial solar Li abundance. Regardless, such a relation means that for our Li comparison to be meaningful, account of initial Li abundances must be made. The most direct way to do this is to compare V505 Per with stars of similar metallicity, which explains our choice of NGC 752. Sestito, Randich & Pallavicini (1994) argue that their high-resolution spectroscopy of solar-type dwarfs in NGC 752 suggests [Fe/H]$= +0.01$ for this cluster, 0.15 dex larger than the canonical value quoted by Daniel et al. (1994). If so, the initial Li versus [Fe/H] relation of Deliyannis (2009) suggests an even larger difference in the depletion factors of our SPTLB components and the NGC 752 Li dip stars. The same conclusion is reached in comparisons with the Li dip stars in younger clusters such as Praesepe and the Hyades. These have canonically accepted ages around 600 Myr and super-solar metallicities ([Fe/H]$\sim+0.10$ to +0.15). The (Deliyannis 2009) Li-Fe relation implies the initial Hyades and Praesepe Li abundances were a factor of 2 larger than for our SPTLB components. Nevertheless, despite their older age, our SPTLB components exhibit Li abundances a factor of 2 larger than nearly all Li detections or upper limits at similar ZAMS $T_{\rm eff}$ in the Hyades and Praesepe.

4. CONCLUSIONS AND SUMMARY

Li is an important element for probing stellar interiors and evolution. It can be used to study transport of matter in the stars, related aspects of stellar and Galactic chemical evolution, and the process of BBN. Such uses depend heavily on accurate predictions of Li abundance evolution within stars. It is known that standard stellar models are unable to explain the Li dip in Pop I mid-F dwarfs. Modified stellar models that include the action of rotationally-induced slow mixing are, qualitatively anyway, able to explain the Li dip as the result of slow Li mixing in stars that are currently undergoing angular momentum loss and are sufficiently massive that interior temperatures are able to burn Li as a result of such mixing. Observational evidence that seems to uniquely finger the action of RIM processes in creating the Li dip comes in the form of identification of Li dip stars having significantly depleted ^{9}Be but still detectable (though highly depleted) Li (Stephens et al. 1997; Boesgaard et al. 2004).

Here, we present an independent observational test of the RIM explanation of the Li dip. We find that the components of the mildly metal-poor ([Fe/H]~-0.15) intermediate age ($\sim$1.1 Gyr) short-period tidally locked binary V505 Per both reside in the Pop I Li dip defined by open cluster observations. If angular momentum loss in such a system occured very early during the pre-main sequence phase, then it would suffer no or reduced RIM during the main-sequence compared to non-SPTLB stars occupying the Li dip region; as a result, the V505 Per components would exhibit larger Li abundances than otherwise similar stars in the Li gap. Indeed, we find that the V505 Per components' Li abundances are at least a factor of 2-5 times larger than both: a) the Li upper limits in the ∼1.5-2 Gyr and similarly mildly metal-poor (Fe/H~ -0.15) cluster NGC 752, and b) the upper limits and Li detections in the younger metal-rich Hyades and Praesepe clusters. If the contention of Deliyannis (2009) is correct and initial Li abundances scale with [Fe/H] in the recent Galactic disk, then the Li overabundance of V505 Per is even more dramatic in the case of the younger clusters (which presumably started with a higher initial Li abundance) and perhaps NGC 752 if the recent higher [Fe/H] value of Sestito, Randich & Pallavicini (1994) is correct.

Our results independently suggest that angular momentum evolution on the main-sequence is responsible for the Li dip, confirming the conclusions drawn from Li/Be ratios in a variety of field and cluster dwarfs (Boesgaard et al. 2004). While the Li abundances in our V505 Per components likely reflect some Li depletion from a plausible initial abundance in the range log N(Li)=3.0-3.3, they nevertheless suggest that early tidal circularization is efficient in mid-F stars in the Li dip, and can mitigate the effects of RIM of Li depletion. Identification of additional Li dip SPTLBs, analysis of their Li abundances, and comparison with those of single stars of similar Li dip position, metallicity, and age would be a profitable means to confirm and extend these conclusions.

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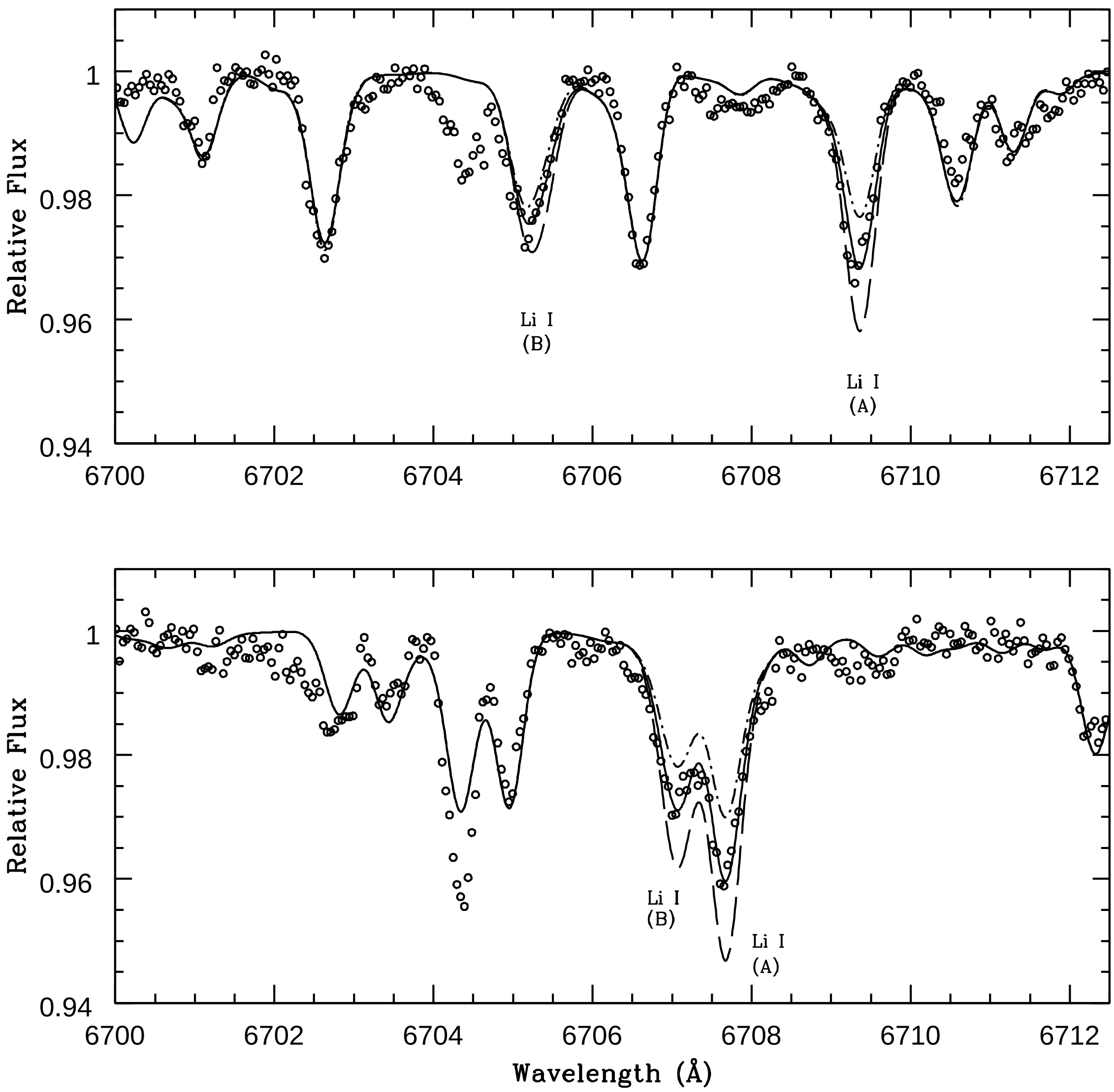

Fig. 1.— The final synthetic spectrum (solid line) overlaid on the observed spectrum (dots), with two other synthetic spectra for comparison (dashed and dotted lines), offset in Li abundance by ±0.15 dex. The "feature" at 6704.5 Å is a detector/reduction artifact and is convolved with the Fe I line of the B component in the second night's spectrum.

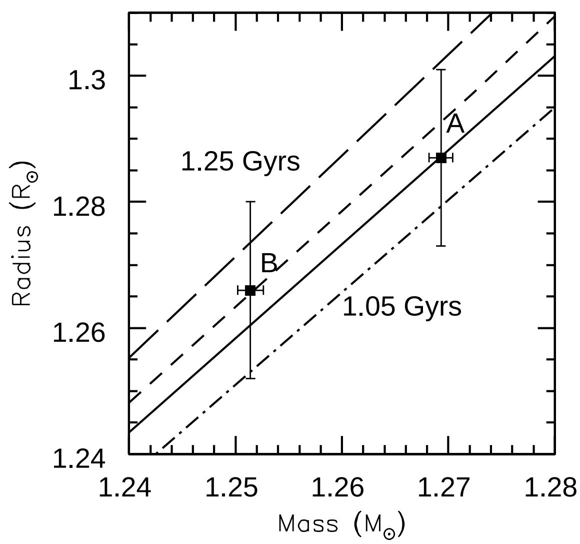

Fig. 2.— Yale-Yonsei isochrones (lines) for [Fe/H]= −0.14 and [α/Fe]= 0 from 1.05-1.25 Gyr are plotted in the radius versus mass plane with the physical determinations of the V505 Per A and B components.

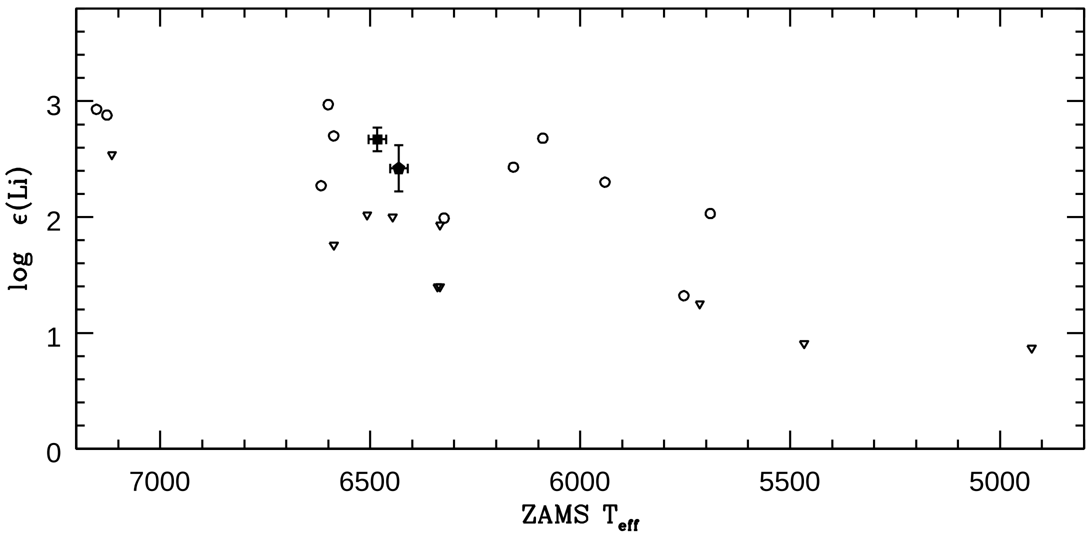

Fig. 3.— The Li abundance versus ZAMS $T_{\rm eff}$ plane containing the two components of V505 Per (solid squares) and objects in the 1.5-2 Gyr old cluster NGC 752 chart (open symbols; inverted triangles are upper limits); the NGC 752 abundance data is taken from the reanalysis of Balachandran (1995).

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