8-1-1994

Lithium in a Short-Period Tidally Locked Binary of M67: Implications for Stellar Evolution, Galactic Lithium Evolution, and Cosmology

Constantine P. Deliyannis
University of Hawaii

Jeremy R. King
Clemson University, jking2@clemson.edu

Ann M. Boesgaard
University of Hawaii

Sean G. Ryan
Anglo-Australian Observatory

THE ASTROPHYSICAL JOURNAL, 434:L71–L74, 1994 October 20

LITHIUM IN A SHORT-PERIOD TIDALLY LOCKED BINARY OF M67: IMPLICATIONS FOR STELLAR EVOLUTION, GALACTIC LITHIUM EVOLUTION, AND COSMOLOGY

CONSTANTINE P. DELIYANNIS[1,2]
Institute for Astronomy, University of Hawaii, 2680 Woodlawn Drive, Honolulu, HI 96822.
E-mail: con@galileo.ifa.hawaii.edu

JEREMY R. KING[1,2]
Department of Astronomy, University of Texas, Austin, TX 78712.
E-mail: king@astro.as.utexas.edu

ANN M. BOESGAARD
Institute for Astronomy, University of Hawaii, 2680 Woodlawn Drive, Honolulu, HI 96822.
E-mail: boes@galileo.ifa.hawaii.edu

AND

SEAN G. RYAN
Anglo-Australian Observatory, PO Box 296, Epping, NSW 2121, Australia.
E-mail: sgr@aaoepp2.ano.gov.au

Received 1994 May 18; accepted 1994 August 1

ABSTRACT

In open clusters, late-F stars exhibit a Li maximum (the Li "peak" region) at lower abundance with age, which could be due either to stellar depletion or Galactic Li enrichment (or some other cause). We have observed a short-period tidally locked binary (SPTLB) on the Li peak region in the old cluster M67 to distinguish between alternatives. SPTLBs which synchronized in the early pre–main sequence would avoid the rotational mixing which, according to Yale models, may be responsible for depleting Li with age in open cluster dwarfs. We find that both components of the M67 SPTLB have a Li abundance lying about a factor of 2 or more above any other M67 single star and about a factor of 3 or more above the mean Li peak region abundance in M67. Our results suggest that the initial Li abundance in M67 is at least as high as $\sim 3.0 = 12 + \log(N_{\rm Li}/N_{\rm H})$. Our high M67 SPTLB Li abundance and those in other clusters support the combination of Zahn's tidal circularization and the Yale rotational mixing theories and may indicate that the halo Li plateau (analogous to the cluster Li peak region) abundance has been depleted from a higher primordial value. Implications are discussed.

Subject headings: binaries: spectroscopic — early universe — stars: abundances — stars: evolution — stars: individual (Sanders 1045) — stars: interiors — stars: rotation

1. INTRODUCTION

Lithium (Li) is important for improving our understanding of stellar structure and evolution, and subsequently for cosmology through the use of realistic stellar models to determine the primordial Li abundance (Li_p) from the Li abundances observed in halo dwarfs. Li_p is still not known with confidence. Standard[3] stellar evolutionary models suggest that the Spite Li plateau [$A(\mathrm{Li}) = 12 + \log(N_{\rm Li}/N_{\rm H}) \sim 2.1$] is little depleted (Deliyannis et al. 1989; Deliyannis, Demarque, & Kawaler 1990), consistent with standard big bang nucleosynthesis (BBN) but possibly indicating a need for nonbaryonic dark matter (Deliyannis 1990; Walker et al. 1991), whereas models with rotationally induced mixing from angular momentum loss and redistribution imply that the plateau is significantly depleted (Deliyannis 1990; Pinsonneault, Deliyannis, & Demarque 1992) from an initial $A(\mathrm{Li}) \sim 2.7$–3.3, suggesting that standard BBN might be incomplete with implications for dark matter. Clearly, observations to distinguish between alternatives would be of great importance.

Standard stellar models cannot reproduce the main features of the Li-$T_{\rm eff}$ profile observed in open clusters, nor their changes with age. Models with rotationally induced mixing ("Yale" models; Pinsonneault, Kawaler, & Demarque 1990) are much more successful in explaining these features.

Given the significance to cosmology, it is desirable to subject the rotational mixing models to a variety of tests. A class of stars that are predicted *not* to undergo (Yale) spin-down and mixing has been postulated (Deliyannis 1990): short-period tidally locked binaries (SPTLBs). According to the tidal circularization theory of Zahn & Bouchet (1989), circularized binaries observed today with critical periods below ~8 days would have undergone (initial) *synchronization* in the early pre–main sequence, *before* their interiors were hot enough to destroy Li. They would thus avoid the spin-down, mixing, and associated Li depletion predicted by the Yale models during the late pre–main-sequence and main-sequence stages, where Li depletion is observed in single stars. Indeed, a variety of SPTLB's and binaries approaching this condition with Li lying above the mean trend have been observed, lending support to the Yale + tidal scenario. We note, however, that this higher Li could, in general, itself be depleted (§ 3; see Ryan & Deliyannis

[1] Visiting Astronomer at the Cerro Tololo Inter-American Observatory, National Optical Astronomy Observatories, operated by the Association of Universities for Research in Astronomy, Inc. (AURA) under a cooperative agreement with the National Science Foundation.
[2] Hubble Postdoctoral Fellow.
[3] We define standard models as those ignoring diffusion, mass loss, rotation, magnetic fields, and other physics not usually included in stellar evolution calculations.

1994 for more detailed discussions of the observations, these ideas, and their background, and for important complications).

We focus in this paper on the Li peak region, i.e., the T_{eff} range over which stars in the Hyades, M67, and other open clusters exhibit a Li abundance maximum, roughly between 5950 and 6350 K. This region may be of key importance to cosmology. According to the Yale models, the Li peak diminishes in abundance with age due to rotational mixing, ending up at the level of the halo Li plateau. In the Yale context, the Li peak and halo Li plateau are completely analogous (see also Vauclair 1988 and Zahn 1994). (The wider extent in T_{eff} of the latter is understood specifically in terms of differences in the structure of halo dwarf models due to their lower metallicity.) Alternatively, if Li_p were instead near the observed level of the halo plateau, then Galactic Li enrichment by about an order of magnitude would be *required* to explain current Li abundances ($\sim$3.0–3.3). The increase of the Li peak level with time could then simply be reflecting the Galactic Li enrichment. We report in this *Letter* results of Li observations of a SPTLB in the old (4–5 Gyr; Demarque, Green, & Guenther 1992) open cluster M67, which distinguish between Galactic Li enrichment and stellar Li depletion as the cause for the diminished level of the Li peak in M67.

2. OBSERVATIONS AND ANALYSIS

Four 40 m exposures of the Li 6707.8 Å region in S1045 (Sanders 1977) = f-119 (Fagerholm 1906) were obtained on 1994 January 31 at the CTIO 4 m using the echelle spectrograph, folded Schmidt camera, the 31.6 l mm^{-1} grating, the GTG 181 cross-disperser (in first order), an order-blocking filter, and a preflashed TI 800 (TI 3) CCD. This configuration yielded a dispersion of 0.145 Å pixel^{-1} and a measured (from Th-Ar lines) resolution of 0.31 Å. Standard reductions (overscan subtraction, bias and preflash removal, trimming, flat-fielding, scattered light correction, extraction, and wavelength calibration) were carried out using the specialized suite of echelle reduction routines running under IRAF at the University of Texas. The four spectra were coadded to yield S/N = 130 per pixel near Li. Figure 1 shows the Li region in the co-added spectrum. The published orbit (Mathieu, Latham, & Griffin 1990; $P = 7^d.6$, $e = 0.0$) was used to ensure proper separation of the components during observation. We verify the conclusion of Mathieu et al. that the components are similar (Fig. 1). The measured Li equivalent widths before flux corrections are 47.1 $\pm$ 6 mÅ and 32.9 $\pm$ 4 mÅ.

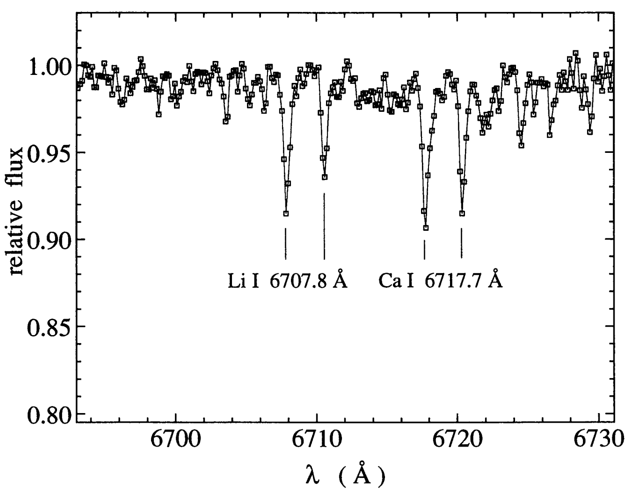

FIG. 1.—Our spectrum of the M67 short-period binary S1045 near the Li region.

Li abundances are most sensitive to T_{eff} (about 0.1 dex per 100 K), so we have placed previous M67 data on a consistent T_{eff} scale as follows. We have adopted Carney's (1983) T_{eff}–$(B-V)$ relation with the Cayrel, Cayrel de Strobel, & Campbell (1985) zero point for the Hyades. This was used by Thorburn et al. (1993, Fig. 2*b*) and gave T_{eff}'s similar to those in Boesgaard & Tripicco (1986a) and Boesgaard & Budge (1988), which were derived from different methods, for the stars in common.[4] We also took into account the metallicity dependence as prescribed by Saxner & Hammarbach (1985). Thus,

$$T_{eff} = 5040/[5247 + (0.5396)(B-V)_0] + (701.7)(B-V)_0\{[Fe/H] - [Fe/H]_{Hyades}\},$$

where we have adopted [Fe/H] = 0.0 for M67 (Garcia Lopez, Rebolo, & Beckman 1988; Hobbs & Thorburn 1991; Friel & Boesgaard 1992) and 0.15 for the Hyades (Cayrel et al. 1985; Boesgaard & Budge 1988; Boesggard & Friel 1991); we also used $E(B-V) = 0.06$ (Eggen & Sandage 1964) and 0, respectively. Values of $B-V$ were averaged from Eggen & Sandage (1964), Chevalier & Ilovaisky (1991), Schild (1983), Montgomery, Matschall, & Janes (1993), and Gilliland et al. (1991); encouragingly, the root mean square difference between 67 pairs of measures of the same star was only 0.011. We expect that the T_{eff} and Li scales are now approximately consistent for all three clusters, although some uncertainties still remain. Li abundances were calculated from the equivalent widths by constructing LTE curves of growth. Values of log $g = 4.0$ and $\xi = 1.7$ km s^{-1} were assumed, and model atmospheres were taken from the extensive new grid of Kurucz (1992). The Li abundances are shown in Table 1 and plotted in Figure 2*c* (we have taken into account the small Fe I feature at 6707.45 Å).

In evaluating the Li abundances of S1045, it was not possible to distinguish between the case of two identical components and the case of two components with slightly different T_{eff}. We thus considered extreme cases, which turned out to give similar results. First, we assumed identical T_{eff}'s (6160 K based on $B-V$) and either adopted the average W(Li) for both stars (case 1) or took the individually measured W(Li)'s at face value (case 2). Second, since the components (with $V \sim 13.3$) are near the turnoff and lie just below the gap, one can empirically determine the lowest reasonable T_{eff} using, e.g., the excellent and thorough photometry of Montgomery et al. (1993) to identify the reddest point of the main sequence at the kink just below the turnoff gap.[5] This gives $T_{eff}(c) > 6025$ and thus $T_{eff}(h) < 6295$, where c and h are the cool and hot components, respectively. At these values of T_{eff}, we assigned the smaller W(Li) to the hotter star (case 3) or vice versa (case 4). In all cases, correction factors for the flux of the other star was calculated in a manner similar to that of Boesgaard & Tripicco (1986b). Table 2 shows the corrected W(Li)'s and derived (as above) Li abundances for each case, and Figure 2*c* shows case 1.

[4] We have revised the Li abundances of Thorburn et al. to treat the Li feature as a doublet; this lowers the abundances slightly for W(Li) > 50 mÅ, increasingly so with larger W(Li). In addition, we have checked some cooler Pleiades stars to verify that they are on the same scale.

[5] This is the gap in the color-magnitude diagram near the turnoff, after stars leave the main sequence but before they reach the (well-populated) subgiant branch. See Montgomery et al. (1993).

TABLE 1

M67 Dwarf Lithium Abundances

star	$(B-V)_0$[a]	W(Li)[b] (mÅ)	A(Li)	Ref.	T_{eff}[c] (K)	A(Li)[c]
S758 = I-29	0.571	55	2.51	1	5992	2.57
I-160	0.610	< 30	< 2.1	1	5839	< 2.08
S1256 = II-13 ...	0.598	< 15	< 1.7	1	5884	< 1.76
S1256 = II-13 ...	0.598	12	< 1.6	3	5884	1.60
S1292 = III-22 ..	0.560	19	1.9	1	6036	2.06
S1314 = III-42 ..	0.583	63	2.53	1	5946	2.61
S1092 = III-43 ..	0.571	49	2.43	1	5994	2.51
S2204 = f-130 ..	0.393	< 17	< 2.36	2	6600	< 2.44
S997 = f-124 ...	0.400	< 19	< 2.31	2	6490	< 2.41
S995 = f-127 ...	0.500	20	2.15	2	6292	2.30
S986 = f-111 ...	0.504	< 21	< 2.16	2	6274	< 2.36
S2205 = I-198 ..	0.517	< 28	< 2.23	2	6219	< 2.43
S976 = f-132 ...	0.549	< 25	< 2.16	2	6082	< 2.26
I-199 = f-129 ..	0.525	< 12	< 1.83	2	6183	< 1.95
S998 = I-11	0.504	45	2.6	3	6274	2.71
S994 = I-9	0.518	38	2.5	3	6215	2.58
S990 = I-20	0.512	67	2.8	3	6226	2.89
S747 = I-48	0.642	< 15	< 1.6	3	5720	< 1.56
S746 = I-46	0.664	< 13	< 1.4	3	5636	< 1.41
S991 = I-19	0.632	< 12	< 1.5	3	5755	< 1.43
S1045	0.530	...	...	...	6160	Table 2

[a] Averaged from sources listed in text.
[b] Includes the feature at 6707.45 Å.
[c] As revised in this *Letter* (see text).

References.—(1) Spite et al. 1987; (2) Garcia Lopez et al. 1988; (3) Hobbs & Pilachowski 1986.

3. DISCUSSION

Figure 2 illustrates three *main* features in the morphology of Li abundances of Population I clusters: (1) over a T_{eff} range of only a few hundred K, F dwarfs develop a deep Li gap on the main sequence (the "Boesgaard gap"); (2) G and K stars (the "cool dwarfs") deplete their Li with age during both the pre–main-sequence and the main sequence and develop a spread in Li at fixed T_{eff}; and (3) in between these two regions (late-F and early-G dwarfs) is the "Li peak" region, which seems to be the best preserving Li region, although its abundance appears to be progressively lower at greater ages (compare Figs. 1*a*–1*c*; Boesgaard 1991). None of these main-sequence features can be reproduced by standard stellar models, but all can be explained in terms of rotationally induced mixing (Yale models), which can also explain Be abundance patterns and detections of Li in Be-depleted stars (Deliyannis & Pinsonneault 1993).

In each of the four cases for S1045, both components lie above the mean trend of M67. Furthermore, in all four cases at least one component lies close to or more than a factor of 2 above any other star, except S990 (below), and close to or more than a factor of 3 above the mean trend. Consistent with the Yale + tidal scenario, this argues strongly that the current level of the Li peak in M67 has been depleted from a higher initial abundance. This also suggests that Li depletion rather than Galactic Li enrichment may be the dominant mechanism in producing the age dependence of Li peak abundances in open clusters, although the errors do allow for some enrichment (below).

TABLE 2

Lithium Abundances for S1045

Case	T_{eff} (K)	Corrected W(Li) (mÅ)	A(Li)
1..........	6160, 6160	80.0, 80.0	2.96, 2.96
2..........	6160, 6160	65.8, 94.1	2.85, 3.05
3..........	6295, 6025	64.0, 96.9	2.94, 2.95
4..........	6295, 6025	91.5, 67.7	3.15, 2.77

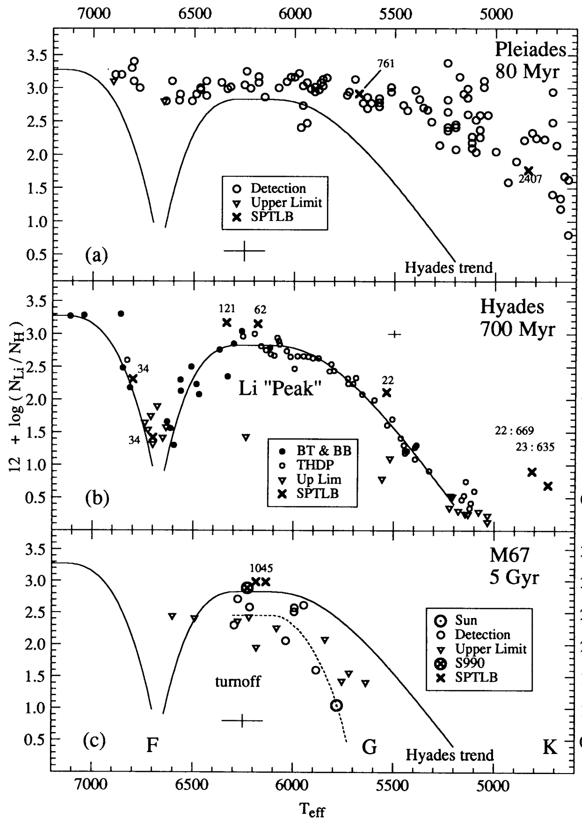

Fig. 2.—The morphology of the Li abundance as a function of T_{eff}, and its evolution in Population I clusters of different age (Pleiades: ~80 Myr, [Fe/H] = 0.0; Hyades: ~700 Myr, [Fe/H] = 0.15; M67: 5 Gyr, [Fe/H] = 0.0). Solid line indicates the Hyades mean trend, and dotted line is M67 trend. Crosses denote short-period tidally locked binaries (SPTLBs) and other short-period binaries, *on* the mean trend in the Pleiades and *above* the mean trend in the Hyades and M67, as predicted by theory (see text). The M67 SPTLB S1045 is plotted for case 1 (with $\Delta T_{eff} \neq 0$ to show both components); cases 2–4 differ slightly (see Table 2, text). Circled cross designates S990 in M67 (see text). Lithium data for Pleiades are taken from Pilachowski et al. (1987), Boesgaard et al. (1988); and Soderblom et al. (1993); for Hyades from Thorburn et al. (1993) (THDP; *open circles* and *triangles*) and from Boesgaard & Tripicco (1986a) and Boesgaard & Budge (1988) (BT and BB; *solid circles and triangles*); and for M67 from Hobbs & Pilachowski (1986), Garcia Lopez et al. (1988), and Spite et al. (1987). Li abundances were placed on approximately consistent scales (see text).

S990 (=I-20; Eggen & Sandage 1964) has the peculiarity that of rotates faster ($v \sin i \sim 15$ km s^{-1}) than any other M67 dwarf observed by Hobbs & Pilachowski (1986; $v \sin i < \sim 9$ km s^{-1}, Sun rotates at 2 km s^{-1}). Its high Li is then also consistent with the expectation from Yale models that stars that have not fully spun down will have mixed less and thus have preserved more Li.

Consistent with Yale + tidal, two short-period binaries in the Hyades (vB 121 and vB 62) also lie above the Hyades Li peak itself (Fig. 2*b*). Note that the Hyades and to a lesser extent M67 lie above the mean trend for the evolution of the Li peak shown in Boesgaard (1991); if vB 121 and vB 62 from the Hyades and S990 from M67 are removed from the calculations, then the two clusters fall closer to the mean trend.

There are some complications that must be emphasized. SPTLBs are not, in general, expected to preserve their initial Li abundance intact. For example, cool dwarf SPTLBs will burn Li at the base of the convection zone, and cool subgiant

SPTLBs will dilute their Li. Most notably, even in the Li peak region, where neither of these effects is likely to apply, SPTLB's may deplete their Li as follows: In the context of Yale + tidal, after initial synchronization in the early pre–main sequence, Zahn & Bouchet (1989) predict an episode of spin-up followed by spin-down, which could lead to mixing and Li depletion. The degree of depletion may depend on the initial configuration, though will likely be less than in single stars for most cases. (We refer the reader to Ryan & Deliyannis 1994 for more details on this and other important complications.) Therefore, S1045 might not be exhibiting its pristine abundance. Indeed, the two Hyades stars, vB 121 and vB 62 seem to have a marginally higher Li abundance than cases 1–3 (but not case 4) for S1045, although systematic effects (e.g., errors in the Fe dependence of the $T_{\rm eff}$ scale) might remove this difference (or augment it), and the Hyades binaries might be depleted as well (the meteoritic abundance is 3.31 ± 0.04; Anders & Grevesse 1989). Even if the difference is real, either Li depletion or Galactic Li enrichment could be its cause. Hopefully, a sufficiently large sample of Li peak SPTLBs will yield a better estimate of the initial abundance. Li abundances for the additional SPTLBs in M67 (Mathieu et al. 1990) should be determined. If the Li peak SPTLBs have different abundances, then they have almost certainly suffered some depletion, and the M67 initial abundance could have been as high as that of the Hyades in the case of *no* Galactic enrichment. If, on the other hand, all M67 SPTLBs have the same abundance, this could conceivably reflect the undepleted initial abundance. In any case, the initial Li abundance in M67 must have been at least as high as ~ 3.0, as shown by the S1045 pair.

The high Li abundances in S1045 provide support for the Yale + tidal models which ascribe the same cause for the Population I Li peak and the Population II halo Li plateau, namely rotationally induced mixing, in which case a higher primordial Li abundance would be inferred. Evidence of this might yet be found in the form of *Halo* SPTLBs lying *above* the Population II Li plateau. Indeed, short-period binaries with high Li have been observed in *a variety of contexts*: in young cool disk dwarfs (vB 22, BD +22°669, and BD +23°635 in the Hyades; Fig. 2*b*) and old cool intermediate metallicity dwarfs, in young (vB 121 and vB 62 in the Hyades; Fig. 2*b*) and old (S1045 in M67; Fig. 2*c*) Li peak dwarfs, and in old cool intermediate metallicity and *halo* subgiants (Balachandran et al. 1993; Ryan & Deliyannis 1994), consistent with Yale + tidal. And some are *not* above the mean trend in very young dwarfs (H II 761 and 2407 in the Pleiades, Fig. 2*a*; T Tauri stars, Lee, Martin, & Mathieu 1994), again consistent with Yale + tidal. Unless halo plateau dwarfs somehow uniquely avoid Li depletion (regardless of whether Yale + tidal is the real cause) in contrast to all these other classes of stars that do undergo Li depletion as evidenced by the high Li in corresponding SPTLBs, one might expect that Li_p is above the currently observed halo Li plateau value, although direct evidence of this has not yet been obtained. Clearly, identification of *suitable* (e.g., appropriate metallicity-dependent and mass-dependent period, zero eccentricity, no evolved companions) halo SPTLBs and study of their Li can enrich our knowledge of both stellar evolution and cosmology. A large sample of suitable halo SPTLBs will be required before they yield confident conclusions about the primordial Li abundance.

It is a pleasure to thank the Cerro Tololo InterAmerican Observatory for the provision of time on their 4 m telescope. We are grateful to R. Mathieu for sharing his data with us ahead of publication, and for informative discussions. C. P. D. and J. R. K. gratefully acknowledge support from NASA through grant HF-1042.01-93A and HF-1046.01-93A (respectively) awarded by the Space Telescope Science Institute which is operated by the Association of Universities for Research in Astronomy, Inc., for NASA under contract NAS 5-26555. S. G. R. gratefully acknowledges support from the Australian Research Council. This research has been supported by NSF grant AST 90-16778 to A. M. B. University of Hawaii.

REFERENCES

Anders, E., & Grevesse, N. 1989, Geochim. Cosmochim. Acta, 53, 197
Balachandran, S., Carney, B. W., Fry, A. M., Fullton, L. K., & Peterson, R. C. 1993, ApJ, 413, 368
Boesgaard, A. M., & Budge, K. G. 1988, ApJ, 332, 410
Boesgaard, A. M., Budge, K. G., & Ramsay, M. E. 1988, ApJ, 327, 389
Boesgaard, A. M., & Friel, E. D. 1991, ApJ, 351, 467
Boesgaard, A. M. 1991, ApJ, 370, L95
Boesgaard, A. M., & Tripicco, M. J. 1986a, ApJ, 302, L49
———. 1986b, ApJ, 303, 724
Carney, B. W. 1983, AJ, 88, 623
Cayrel, R., Cayrel de Strobel, G., & Campbell, B. 1985, A&A, 146, 249
Chevalier, C., & Ilovaisky, S. A. 1991, A&AS, 90, 225
Deliyannis, C. P. 1990, Ph.D. thesis, Yale Univ.
Deliyannis, C. P., Demarque, P., & Kawaler, S. 1990, ApJS, 73, 21
Deliyannis, C. P., Demarque, P., Kawaler, S. D., Krauss, L. M., & Romanelli, P. 1989, Phys. Rev. Lett., 62, 1583
Deliyannis, C. P., & Pinsonneault, M. H. 1993, in IAU Colloq. 137, Inside the Stars, ed. W. W. Weiss & A. Baglin (ASP Conf. Ser., 40), 174
Demarque, P., Green, E. M., & Guenther, D. B. 1992, AJ, 105, 151
Eggen, O. J., & Sandage, A. 1964, ApJ, 140, 130
Fagerholm, E. 1906, Inaug. diss., Uppsala
Friel, E. D., & Boesgaard, A. M. 1992, ApJ, 387, 170
Garcia Lopez, R. J., Rebolo, R., & Beckman, J. E. 1988, PASP, 100, 1489
Gilliland, R. L., et al. 1991, AJ, 101, 541
Hobbs, L. M., & Pilachowski, C. P. 1986, ApJ, 311, L37
Hobbs, L. M., & Thorburn, J. A. 1991, AJ, 102, 1070
Kurucz, R. L. 1992, private communication
Lee, C. W., Martin, E. L., & Mathieu, R. D. 1994, ApJ, submitted
Mathieu, R. D., Latham, D. W., & Griffin, R. F. 1990, AJ, 100, 1859
Montgomery, K. A., Matschall, L. A., & Janes, K. A. 1993, AJ, 106, 181
Pilachowski, C. A., Booth, J., & Hobbs, L. M. 1987, PASP, 99, 1288
Pinsonneault, M. H., Deliyannis, C. P., & Demarque, P. 1992, ApJS, 78, 179
Pinsonneault, M. H., Kawaler, S. D., & Demarque, P. 1990, ApJS, 74, 501
Ryan, S. G., & Deliyannis, C. P. 1994, ApJ, submitted
Sanders, W. L. 1977, A&AS, 27, 89
Saxner, M., & Hammarbach, G. 1985, A&A, 151, 372
Schild, R. E. 1983, PASP, 95, 1021
Soderblom, D. R., Jones, B. F., Balachandran, S., Stauffer, J. R., Duncan, D. K., Fedele, S. B., & Hudon, J. D. 1993, AJ, 106, 1059
Spite, F., Spite, M., Peterson, R. C., & Chaffee, F. H. 1987, A&A, 171, L8
Thorburn, J. A., Hobbs, L. M., Deliyannis, C. P., & Pinsonneault, M. H. 1993, ApJ, 415, 150
Vauclair, S. 1988, ApJ, 335, 971
Walker, T. P., Steigman, G., Schramm, D. N., Olive, K. A., & Kang, H.-S. 1991, ApJ, 376, 51
Zahn, J.-P. 1994, A&A, in press
Zahn, J.-P., & Bouchet, L. 1989, A&A, 223, 112