THE ASTROPHYSICAL JOURNAL, 373:250–253, 1991 May 20

THE LITHIUM ABUNDANCE OF THE T TAURI STAR BP TAURI

DOUGLAS K. DUNCAN
The Space Telescope Science Institute, 3700 San Martin Drive, Baltimore, MD 20218
Received 1990 July 12; accepted 1990 November 9

ABSTRACT

The Li abundance of the T Tauri star BP Tau is determined from both the Li I 6707 and 6103 features, using high-accuracy observations and recent model atmospheres. Other work, based solely on analysis of the λ6707 line, has found very high Li abundances in T Tauri stars. We find a significant difference between the abundances derived from the two different lines and no evidence in this star of a Li abundance significantly in excess of the typical Population I value log $n_{\rm Li} \approx 3.0$.

Subject headings: stars: abundances — stars: individual (BP Tauri) — stars: pre–main-sequence

1. INTRODUCTION

Li abundances are useful as probes of stellar structure (Michaud & Charbonneau 1990), qualitative indicators of stellar age (Duncan 1981; Soderblom 1987), and as constraints of models of primordial nucleosynthesis (Boesgaard & Steigman 1985; Reeves et al. 1990).

The large abundance of Li in T Tauri stars was first demonstrated by Bonsak & Greenstein (1960) and has been studied through the recent work of Strom et al. (1989; hereafter SWSS) and Maguzzu & Rebolo (1989). Li abundances in these stars are especially interesting because they can help differentiate between pre–main-sequence and main-sequence Li destruction mechanisms. From the cosmological point of view, they have acquired an additional significance. Studies of Li abundances in halo stars have consistently yielded values of about log $n_{\rm Li} = 2.1$ (on the scale $\log_{\rm H} = 12.00$; Spite, Maillard, & Spite 1984; Hobbs & Duncan 1987; Rebolo, Molaro, & Beckman 1988). However, maximum abundances seen in galactic cluster stars are about log $n_{\rm Li} = 3.0$. The question has arisen whether the halo stars could be uniformly depleted and the big bang the source of a universal primordial Li abundance of approximately log $n_{\rm Li} = 3$, or whether a galactic source or sources have built up the present Li abundance above a primordial value of log $n_{\rm Li} \approx 2.1$. Clear evidence of star-to-star variations in Li abundance among T Tauri stars would provide strong evidence that galactic sources of Li are significant.

The T Tauri observations of SWSS exhibit many very strong Li I 6707 lines. Their implied Li abundances range as high as log $n_{\rm Li} \approx 4.0$. The present paper undertakes a model atmosphere analysis of the particularly well-observed T Tauri star BP Tau, to see if such a high Li abundance can be substantiated for this star.

At the same time that Li abundances in T Tauri stars have become more interesting, the possibility of determining more accurate abundances in these stars has become apparent. Quantitative abundance determinations in T Tauri stars have in the past been highly suspect. The spectra of T Tauri stars show great differences from older stars of similar spectral type: Balmer and other emission lines, IR and UV excesses, and "veiling" or filling-in of lines which can range from a small amount to complete covering of the absorption spectrum. If these effects indicate disturbed stellar chromospheres and photospheres then any analysis based on normal stellar atmosphere models should be suspect. However, there is increasing evidence that many of the prominent T Tauri features arise in circumstellar material and not in the stellar photosphere (Edwards et al. 1987; Hartmann et al. 1990; Hartmann & Kenyon 1990). In particular, Hartigan et al. (1989) have given a detailed spectrum model for the T Tauri star BP Tau. They used high-resolution, high signal-to-noise observations and showed that the BP Tau spectrum could be decomposed into that of an ordinary K7-M0 dwarf plus a smooth, featureless continuum. (As distinguished from a filling in of the lines *only*, as might be expected from a very active chromosphere and extra heating in the upper photosphere.) A few very strong lines show filling in, presumably caused by chromospheric heating in excess of that in older stars. Nevertheless, the overall fit to the spectrum is quite good. One might therefore place somewhat more confidence in the use of an ordinary model stellar atmosphere of the correct temperature and gravity to obtain at least a first-order determination of abundances in such a T Tauri star, if the spectrum is first deveiled by the Hartigan et al. method.

2. MODEL ATMOSPHERE CALCULATIONS

Abundance analyses of Li are usually made using the λ6707 resonance line, as it is the only Li line usually visible in the spectra of solar-type stars. Indeed, the presence of strong Li I 6707 is often taken as a characteristic of T Tauri spectra. However, this line is so strong in T Tauri stars that it is on the saturated part of the curve of growth, so that small errors in the measured line strength will lead to large errors on the derived abundance. It is formed relatively far out in the stellar atmosphere, and scattering effects and possibly even departures from LTE influence the line formation. These effects may lead to *systematic* errors in the determined Li abundance.

In the spectra taken by Hartigan et al. (1989) a line is clearly visible at λ6103.8 which they identify as a subordinate line of Li I. This line presents an excellent opportunity to obtain another determination of the Li abundance which should be more reliable than that derived from λ6707, both because the line is on the linear part of the curve of growth and because it is formed lower down in the stellar atmosphere.

New calculations were done of curves of growth for both the Li I 6707 and 6103 lines. Li I 6707 was analyzed as two components, λ6707.76, $gf = 0.99$, and λ6707.91, $gf = 0.494$. Li I 6103 was analyzed as three components, λ6103.54, $gf = 1.34$, λ6103.646, $gf = 2.38$, and λ6103.76, $gf = 0.27$, all three with a lower excitation potential of 1.847 eV. The uncertainties in the gf values are expected to be 10% for the λ6707 components and 25% for the λ6103 components (Weise & Martin 1980; Luck 1990). The program WIDTH, as installed at KPNO by Kurucz in 1985, was used for the calculations after being modified to correctly treat the fine structure of the lines. Input model atmospheres included those of Bell and Gustafsson (Gustafsson et al. 1975; Bell et al. 1976) and ones newly calculated by Kurucz (1990). The new Kurucz models are advanced over previous (1979) ones in incorporating new opacities which include the effects of $\sim$60 million discrete lines, additional continuous opacities, and an approximate treatment of convective overshooting. They incorporate 65 levels and extend to shallower optical depths than the previous models. This is important when analyzing a strong feature such as Li I 6707 which arises from the neutral state of a line which is mostly ionized, which can form high in the atmosphere. The Bell & Gustafsson atmospheres cover a range of 4500–6000 K, for $\log g = 4.5$ and 3.75; those of Kurucz cover 4000–5000 K, for $\log g = 3.75$ and 4.5. For the purposes of the present paper, the differences between the Bell and Gustafsson and Kurucz models were found not to be very significant. Calculations were done for two values of microturbulence, 1.0 and 1.5 km s^{-1}. The Doppler velocity of Li is 3–4 km s^{-1} in the region of line formation in these stars, and as expected changes of 1 km s^{-1} in the microturbulence do not have any significant effect on the curves of growth, nor do reasonable variations in the van der Waals damping constant. The present curve of growth calculations are somewhat more accurate than those of Duncan (1981), Duncan & Jones (1983), and Pallavicini, Cerruti-Sola, & Duncan (1987), especially in their treatment of the fine structure of the Li lines, and they supersede the previous calculations. Note, however, that they do not attempt to take into account the effects of the Fe I 6707.441 line which can be blended with the Li I 6707 doublet on low-resolution spectra.

The λ6103.54–6103.76 feature of Li I is blended with the wing of an Fe I feature centered at λ6103.19. The spectrum derived by Hartigan et al. is the difference spectrum between BP Tau and a reference star of the same temperature which appears to be Li-free. The difference spectrum, which shows only the Li I 6103 feature, is what is analyzed here. The analysis assumes linearity in the addition of line profiles, which is strictly true only for weak lines. Both lines are reasonably weak at the wavelengths of interest in BP Tau, and the analysis should introduce only small errors compared to the effects identified below.

Figure 1 presents curves of growth for Li I 6707 in both the Bell and Gustafsson and Kurucz atmospheres, for $\log g = 3.75$ and 4.0, respectively. For a line arising from a neutral species of an atom which is mostly ionized, the effect of gravity is expected to be small except when the line is saturated (which it is in the T Tauri stars). This is verified in Figure 2, which presents the Kurucz curves of growth for Kurucz atmospheres with $\log g = 4.5$ and $\log g = 4.0$. Figure 3 is like Figure 1, except that the curves are calculated for the Li I 6103 feature.

3. ANALYSIS OF BP Tau

The study of Hartigan et al. (1989) demonstrates that the spectrum of BP Tau is quite well fit by that of a K7–M0 dwarf, plus an overlying flat continuum. The largest difference in spectrum between BP Tau and the template-fitting dwarf is in fact the Li I 6103 line (the λ6700 region of the spectrum was not published by Hartigan et al.). The equivalent width of Li I 6103 was measured from the Hartigan et al. spectrum to be $\approx$57

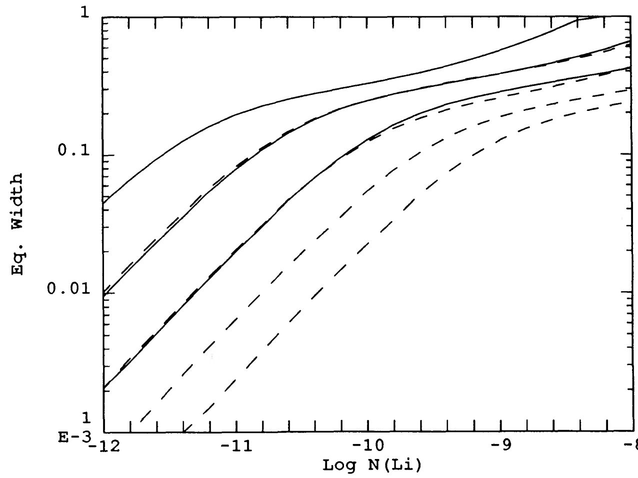

FIG. 1.—Curves of growth for Li I 6707 in Kurucz (*solid line*) and Bell and Gustafsson (*dashed line*) model atmospheres, for $\log g = 4.0$ and 3.75, respectively. Curves are shown for 500 K temperature intervals from 4000 K (*uppermost*) to 6000 K (*lowermost*).

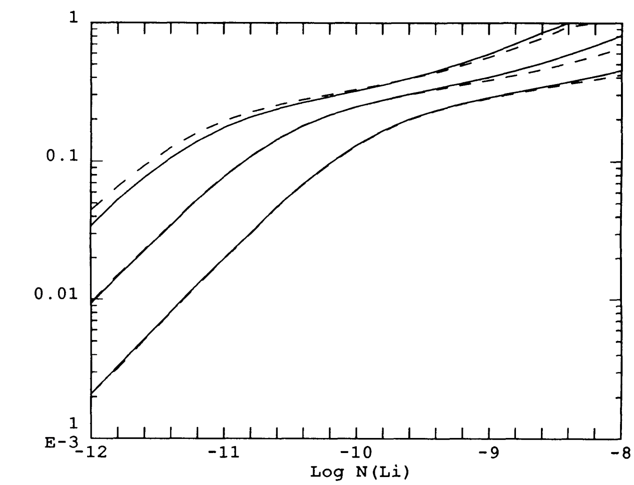

FIG. 2.—Effects of gravity on Li I 6707 curves of growth in the Kurucz atmospheres. *Dashed line*: $\log g = 4.0$. *Solid line*: $\log g = 4.5$. Temperatures from 4000 K (*uppermost*) to 5000 K (*lowermost*).

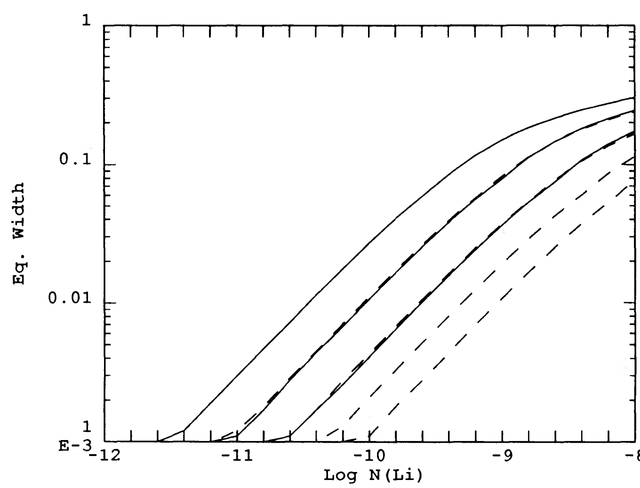

FIG. 3.—Same as Fig. 1, except for Li I 6103

mÅ. This value must be multiplied by $(1 + r)$, where r is the ratio of the veiling flux to the stellar photospheric flux, to correct to the true photospheric line strength. At $\lambda \approx 6100$ the veiling ratio was ~ 0.7 in the Hartigan et al. spectra, implying a photospheric Li equivalent width of 97 mÅ, with an uncertainty of ~ 15 mÅ.

The extensive investigation of Li ($\lambda 6707$) in pre–main-sequence stars by SWSS found equivalent widths of 0.38 and 0.50 Å for BP Tau. These values were based on echelle and Cassegrain spectra, respectively, with the echelle more accurate. SWSS correct for veiling in their stars with a relation between Hα emission strength and veiling derived from Hartmann & Kenyon (1990). This is a statistical relationship with considerable scatter. In the particular case of BP Tau, the Hartigan et al. data on spectral veiling extend to $\lambda 6600$, and they may be extrapolated to $\lambda 6700$ to give a more certain estimate of the veiling. The value so derived, $r \approx 0.6$, used with the echelle observation of SWSS, gives a corrected equivalent width of 0.61 Å. This is slightly larger than the value of 0.56 Å found by SWSS.

An additional reason for uncertainty in the veiling correction is that it can vary considerably with time, and the SWSS and Hartigan et al. spectra were taken at different times. Hartigan (1990) has measured the Li I 6707 line strength on a higher S/N echelle spectrum taken when the veiling of BP Tau was somewhat lower. He finds a veiling-corrected equivalent width of 0.53 Å. The present work adopts 0.6 ± 0.1 Å as the best estimate of the photospheric Li I 6707 line strength.

Blending of other lines in the vicinity of the strong Li I 6707.8 feature can be ignored. The total amount of blending from non-Li absorption lines may be judged from Li-free stars of similar spectral type. An example is found in Brown et al. (1989), who find a total of 0.065 Å equivalent width of blending features in the Li-weak giant HD 127700 (their Fig. 14).

The physical parameters of $T_{\rm eff}$ and log g are now required to determine abundances in BP Tau. Cabrit et al. (1990) combine optical spectroscopy and optical and IR photometry to determine photospheric, forbidden line, and IR luminosities of a large number of T Tauri stars, including BP Tau. For this star, they find a photospheric luminosity $\approx 1.0\ L_\odot$, $T_{\rm eff} \approx 4000$ K, and a spectral type of K7. These parameters are in good agreement with those of Hartigan et al. (1989). The values of luminosity and $T_{\rm eff}$ imply a gravity of log $g \approx 3.8$.

Referring to Figure 1, the Li abundance derived from the $\lambda 6707$ line is log $n_{\rm Li} = -8.95 \pm 0.25$, or 3.05 ± 0.25 on the scale log $n_{\rm H} = 12.00$. The stated uncertainty is that due to the line strength. The saturated Li I 6707 line is quite temperature sensitive, with a change of 500 K corresponding to a change of 0.8 dex in log $n_{\rm Li}$. If the photospheric temperature is off by much more than 100 K, the abundance determination could be off by more than 0.25 dex. The corresponding result using Figure 3 and the Li $\lambda 6103$ is log $n_{\rm Li} = 2.7 \pm 0.1$. The temperature sensitivity is ~ 0.45 dex for a 500 K temperature change.

4. DISCUSSION

The most important result of the present paper is immediately apparent: the Li abundance derived from the $\lambda 6103$ line is significantly smaller than that derived from the $\lambda 6707$ line and neither indicate a Li abundance significantly in excess of that seen in other Li-rich Population I objects.

A difference in abundance derived from the $\lambda 6103$ and $\lambda 6707$ lines is neither surprising nor unprecedented. In their analysis of the very Li-rich giant HD 112127, Wallerstein & Sneden (1982) derive an abundance of log $n_{\rm Li} \approx 3.0$ from the $\lambda 6103$ line, and log $n_{\rm Li} \geq 4.0$ from the $\lambda 6707$ line. The $\lambda 6707$ line is so strong that its core is formed at extremely shallow depths in the BP Tau atmosphere, $\tau_{\rm cont} \approx 10^{-3}$–$10^{-4}$ in the Kurucz models. The core will be strengthened by line scattering processes which are not taken into account in the model atmosphere analysis. These will tend to strengthen the actual line compared to the modeled one. The Li I 6103 line, on the other hand, is entirely formed at continuum optical depths greater than ~ 0.1. Although this line is weaker and more difficult to measure than the $\lambda 6707$ line, the same weakness lessens the *systematic* errors in the abundance analysis. The results from Li I 6103 are therefore to be preferred.

There are some systematic differences in the Li I 6707 curves of growth used in the present paper and those used by SWSS, whose main purpose was not to derive absolute Li abundances. Their abundances are higher, particularly for the strongest lines. The SWSS equivalent width versus abundance curves flatten out for the strongest lines. We find that for $T = 4000$–4500 K, as log $n_{\rm Li}$ increases to ≈ 3.5–4.0, the damping wings begin to make significant contributions, and the total equivalent width continues to increase. Our equivalent widths are therefore higher for the same abundance, or, equivalently, the same measured line strength implies a lower abundance. These differences are comparable in size to the differences between the Li I 6103 and 6707 abundances of the present investigation.

The abundance derived from the Li I 6103 feature may seem surprisingly low compared to the abundance log $n_{\rm Li} = 3.0$ or slightly higher shown by many Population I objects. It is possible that there is a systematic shift in abundances derived from the $\lambda 6103$ line compared with those derived from $\lambda 6707$. The differential results of SWSS, which show an order of magnitude spread in Li abundance among T Tauri stars of the same temperature, imply that some T Tauri stars suffer pre–main-sequence Li depletion, and this could have effected BP Tau. On the other hand, a difference of 0.3–0.4 dex may reflect the extent of systematic errors still present in attempting to model a T Tauri star with a conventional stellar atmosphere. It will certainly be worthwhile to attempt to model other element abundances in the star BP Tau and to determine Li abundances based on the $\lambda 6103$ feature in other T Tauri stars, including those in the SWSS sample which show stronger Li I 6707 features than does BP Tau.

It is also especially important to look for the Li $\lambda 6103$ feature in ordinary Li-rich dwarfs. The calculated $\lambda 6103$ curves of growth indicate line strengths of a few tens of milliangstroms should be present. Using the technique of subtracting the spectrum of a similar temperature Li-poor dwarf, the line should be detectable. Agreement (or lack thereof) of abundances derived from the $\lambda 6103$ and $\lambda 6707$ lines in ordinary dwarfs would reveal systematic effects in the analysis.

5. CONCLUSION

The Li abundance derived from the Li I 6103 feature in BP Tau, using the most recent stellar atmospheres, does not support the very high abundance inferred from the $\lambda 6707$ line in previous studies. Despite the good fit to the BP Tau spectrum found by Hartigan et al. (1989) by combining an ordinary dwarf spectrum plus a continuum, an ordinary dwarf or subgiant model does not give consistent results for the two lines, when the line formation is treated in LTE. The abundance indicated by the weaker $\lambda 6103$ line is likely to be the more accurate, and one must conclude that in the case of BP Tau there is no conclusive evidence of a Li abundance in excess of the typical Population I value log $n_{\mathrm{Li}} \approx 3.0$. Similar investigation of other T Tauri stars and Li-rich main sequence dwarfs is certainly indicated.

I would like to thank S. Strom for the original question which prompted this investigation, and K. Strom, R. Cayrel and R. E. Luck for useful comments. I thank R. Kurucz for providing model atmospheres in advance of publication, and P. Hartigan for providing data.

REFERENCES

Bell, R. A., Eriksson, K., Gustafsson, B., & Nordlund, A. 1976, A&AS, 136, 65
Boesgaard, A. M., & Steigman, G. 1985, ARA&A, 23, 319
Bonsak, W. K., & Greenstein, J. L. 1960, ApJ, 131, 83
Brown, J. A., Sneden, C., Lambert, D. L., & Dutchover, E. D. 1989, ApJS, 71, 293
Cabrit, S., Edwards, S., Strom, S. E., & Strom, K. M. 1990, ApJ, 354, 687
Duncan, D. K. 1981, ApJ, 248, 651
Duncan, D. K., & Jones, B. F. 1983, ApJ, 248, 651
Edwards, S., Cabrit, S., Strom, S. E., Heyer, I. Strom, K. M., & Anderson, E. 1987, ApJ, 321, 473
Gustafsson, B., Bell, R. A., Eriksson, K., & Nordlund, A. 1975, A&A, 42, 407
Hartigan, P. 1990, private communication
Hartigan, P., Hartmann, L., Kenyon, S. J., Hewett, R., & Stauffer, J. 1989, ApJS, 70, 899
Hartmann, L., Calvit, N., Avrett, E. A., & Loeser, R. 1990, ApJ, 349, 168
Hartmann, L., & Kenyon, S. J. 1990, ApJ, 349, 190
Hobbs, L. M., & Duncan, D. K. 1987, ApJ, 317, 796
Kurucz, R. L. 1979, ApJ, 40, 1
———. 1990, private communication
Luck, R. E. 1990, private communication
Maguzzu, A., & Rebolo, R. 1989, Mem. Soc. Astr. It., 60, 105
Michaud, G., & Charbonneau, P. 1990, Space Sci. Rev., in press
Pallavicini, R. Cerruti-Sola, M., & Duncan, D. K. 1987, A&A, 174, 116
Rebolo, R., Molaro, P., & Beckman, J. E. 1988, A&A, 192, 192
Reeves, H., Richer, J., Sato, K., & Terewasa, N. 1990, ApJ, 355, 18
Soderblom, D. R. 1987, IAU Symp. 132, The Impact of High S/N Spectroscopy on Stellar Physics (Dordrecht: Kluwer), p. 381
Spite, F., Maillard, J.-P., & Spite, M. 1984, A&A, 141, 56
Strom, K. M., Wilkin, F. P., Strom, S. E., & Seaman, R. L. 1989, AJ, 98, 1444
Wallerstein, G., & Sneden, C. 1982, ApJ, 255, 577
Weise, W. L., & Martin, G. A. 1980, NSRDS-NBS 68