⁶Li IN THE ATMOSPHERE OF GJ 117

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ABSTRACT

We present high-resolution VLT UVES observations of the active K dwarf GJ 117. ⁶Li enhancement has been shown for energetic solar events, one chromospherically active binary, and several dwarf halo stars. Our analysis reveals the detection of ⁶Li on this source with ⁶Li/⁷Li = 0.030 ± 0.010. We found no significant contribution from other lines, including Ti I, in the Li profile of GJ 117 and a template star of similar spectral type and metallicity. We discuss the possibility for ⁶Li production by spallation and find it to be consistent with the activity levels of the object.

Subject headings: stars: activity — stars: atmospheres — stars: individual (GJ 117) — stars: late-type

1. INTRODUCTION

Lithium is a fragile element that serves as a powerful diagnostic of stellar structure and evolution. The fragility of Li arises from the fact that it can burn at relatively low temperatures via the [⁷Li(*p*, α)⁴He] and [⁶Li(*p*, α)³He] processes. Most of the Li destruction occurs during the pre-main-sequence state, when the convection zones are deepest and for stellar models with the lowest mass. Lower mass stars arrive on the zero-age main sequence at lower temperatures, and the amount of protostellar Li that survives today in dwarf stars decreases with decreasing temperature (Deliyannis & Malaney 1995). Stellar clusters, such as α Per and the Pleiades, show a large spread of Li abundances at each effective temperature, and it has been shown that the largest Li abundances are found in fast rotating stars with the strongest chromospheric emission (Soderblom et al. 1993). This is a puzzling result as theoretical models predict that fast rotation enhances the mixing process that leads to increased Li depletion; the rotational history plays a major role in the depletion process (Pinsonneault 1997).

On the main sequence, the correlation between Li and chromospheric activity is not very strong. Stars with the same Ca II flux may have Li abundances that differ by 1 order of magnitude. Lithium is enhanced in sunspots (Giampapa 1984) where a small but notable amount of ⁶Li has been detected (Ritzenhoff et al. 1997). An investigation of active RS CVn binaries failed to show a clear correlation between photometric variations and Li abundances (Pallavicini et al. 1992). Plages and active regions could play a minor role but their effect would be to decrease rather than increase the Li λ6707.8 equivalent width (Houdebine & Doyle 1995). Russell (1996) used the Li λ6104 line, which is formed deeper into the atmosphere, to study a sample of Pleiades K dwarfs. The results showed that the derived abundances have significantly less scatter than those derived from the λ6707.8 line. If activity has an effect on Li, it seems to increase rather than decrease the equivalent width and is therefore opposite to what the chromospheric non-LTE calculations predict.

Surface activity could increase the Li abundance if extreme energetic conditions are met (see Mullan & Linsky 1999). Spal-

lation reactions from low-energy flares can increase ⁶Li/⁷Li ratios (Canal et al. 1975). Predictions for significant creation of ⁶Li in stellar and solar flares have been made (Canal et al. 1975; Walker et al. 1985; Livshits 1997), although actual measurements for the Sun have found an average ⁶Li/⁷Li of 0.01 and up to 0.04 (Traub & Roesler 1971; Müller et al. 1975).

The first detection of ⁶Li on the halo dwarf HD 84937 has been highly significant (Smith et al. 1993). Follow-up studies have confirmed this detection and have also shown the presence of the isotope in BD +26 3578 (Smith et al. 1998; Hobbs & Thorburn 1997). Unexpected ⁶Li abundances have been observed during a long flare on a chromospherically active binary (Montes & Ramsey 1998). These have been attributed to spallation reactions.

In this Letter we present high-resolution VLT UVES observations of the K star GJ 117 with emphasis on the Li λ6707.8 line profile. GJ 117 (=HD 17925) is a single chromospherically active K dwarf. The object shows evidence of photometric variability with a period of 6.5 days (Cutispoto 1992), while the weak color variations show that the star is redder at minimum light. Spectroscopic observations in the Ca II lines also show strong evidence of variability at both short and long timescales (Baliunas et al. 1995). Our observations and analysis are presented in § 2. In § 2.1 we present stellar models generated using the PHOENIX code for the temperature and gravity of GJ 117. We present the results, derived lithium parameters, and ⁶Li/⁷Li ratio in § 2.2. Discussion of the results and implications for lithium production are presented in § 2.3, and lastly we summarize our findings in § 3.

2. OBSERVATIONS AND DATA ANALYSIS

Measurements of ⁶Li in stellar spectra are very difficult and rely on the modeling of the increased width and red asymmetry of the λ6707.8 doublet. The problem becomes particularly difficult in active late-type stars where large rotational velocities will smear the line profiles. The problem is further complicated by the occurrence of blends, such as Ti I and CN. The observations were conducted in 2002 December with the VLT UT2 (Kueyen) and the UV-Visual Echelle Spectrograph (UVES). This setup used the 600 line mm⁻¹ red grating and MIT/LL EEV 2K × 4K CCD. With an exposure time of 150 s, this setup provided a resolution of ≈110,000 and a signal-to-noise ratio of ≈400 in the final spectrum. The VLT data were reduced with the VLT data pipeline (UVES/1.3.3), with further analysis carried out using the STARLINK-based DIPSO software. The

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FIG. 1.—VLT UVES spectra of GJ 117 showing the Li I λ 6707.8 region.

UVES spectrum of GJ 117 in the Li I λ 6708 region is shown in Figure 1.

2.1. Model Spectra

Theoretical spectra were calculated using the general stellar atmosphere code PHOENIX (see Hauschildt et al. 1995 and Allard & Hauschildt 1995). We have used the LTE atmosphere models from the NextGen series of (Hauschildt et al. 1999) for the effective temperature and gravity listed in Table 1. Given the uncertainties in T_{eff} and $\log g$, typically ± 200 K and ± 0.3 dex, respectively, we have used the directly converged models from NextGen that are sampled every 200 K in T_{eff} and 0.5 dex in $\log g$. Line blanketing is handled within PHOENIX by means of direct opacity sampling (Hauschildt et al. 2001).

The ${}^6\text{Li}$ resonance doublet has been included in PHOENIX by adding the wavelengths and gf values of Smith et al. (1993) into the master line list of Kurucz (1995), where the fraction of ${}^6\text{Li}/{}^7\text{Li}$ is introduced as a parameter (γ). In direct opacity sampling, opacity at each wavelength point is calculated as a sum of opacities from all the contributing species. The contributions from ${}^7\text{Li}$ and ${}^6\text{Li}$ are then expressed as

$$\kappa({}^7\text{Li}) = (1 - \gamma)\kappa({}^7\text{Li}_{\text{tot}}), \quad (1)$$

$$\kappa({}^6\text{Li}) = \gamma\kappa({}^6\text{Li}_{\text{tot}}), \quad (2)$$

where $\kappa({}^n\text{Li}_{\text{tot}})$ is the opacity calculated as if all lithium is in the n isotopic state. Theoretical line profiles have been calculated with γ ranging from 0.0 to 0.2. Microturbulence has been taken into account when generating the model spectra using a velocity of $\xi = 1.5 \text{ km s}^{-1}$. The $v \sin i$ of the object was derived from χ^2 analysis of several lines in the Li I λ 6707.8 region.

2.2. The ${}^6\text{Li}/{}^7\text{Li}$ Isotope Ratio

We have carried out a comparison between the observed and model profiles using χ^2 statistics. A grid of models in steps of ${}^6\text{Li}/{}^7\text{Li} = 0.01$ was developed, and the most probable model with $\chi^2 \sim 1$ was determined. Figure 2 shows the $\Delta\chi^2$ computed for the model grid and plotted with the sign preserved. The best fit has a ${}^6\text{Li}/{}^7\text{Li} = 0.030 \pm 0.007$ and $\Delta\chi^2 \sim 30$ as compared to a model with no ${}^6\text{Li}$. The observed spectrum of GJ 117 fitted with ${}^6\text{Li}/{}^7\text{Li}$ ratios of 0.0, 0.03, and 0.10 is shown

TABLE 1
STELLAR AND LITHIUM PARAMETERS

Source	$\log g$	$\log T_{\text{eff}}$	$v \sin i$ (km s^{-1})	Li EW (mÅ)	$\log \text{Li}$	${}^6\text{Li}/{}^7\text{Li}$
GJ 117	3.70	4.6	5.5 ± 0.2	211	2.45	0.030 ± 0.010

FIG. 2.— $\Delta\chi^2$ as a function of the ${}^6\text{Li}/{}^7\text{Li}$ ratio for Li I model line profiles for GJ 117 (see text).

in Figure 3; χ^2 was calculated for 35 degrees of freedom, and a sign factor was added to χ^2 to indicate whether the observational data was larger (positive) or smaller than (negative) the model.

The ${}^6\text{Li}/{}^7\text{Li}$ ratio derived from the best fits are also given in Table 1; 1σ errors for the table were derived using $\chi^2 + 1$ (e.g., Nissen et al. 1999), and we also include a conservative 5% systematic error to account for the uncertainty in the continuum level making ${}^6\text{Li}/{}^7\text{Li} = 0.030 \pm 0.010$.

FIG. 3.—GJ 117 spectrum for the Li I λ 6707.8 region plotted as a solid histogram. Overplotted are PHOENIX models with ${}^6\text{Li}/{}^7\text{Li}$ ratios of 0.0 (dotted histogram), 0.03 (dashed histogram), and 0.10 (dash-dotted histogram) lines. The lower panel shows χ^2 from the difference of the data minus the model (see text).

FIG. 4.—Ti abundance as a function of the ${}^6\text{Li}/{}^7\text{Li}$ ratio (see text).

The influence of lines such as Fe I, Ti I, and CN on the Li I profile can potentially mimic an enhanced ${}^6\text{Li}$ abundance (Nissen et al. 1999; Reddy et al. 2002). The effects of possible CN bands near 6707.5 Å have been seen to be ≤ 1 mÅ in the solar spectrum and should have a negligible effect for GJ 117. In earlier lower resolution data, the Fe I line at 6707.4 Å was often blended with Li I; however, in the UVES observations, these are easily separable. We have tested models with enhanced Fe abundances and found that these have no effect on the Li I line profile.

The most significant blend may come from the Ti I lines in the vicinity of 6708 Å and could lead to erroneous results. Israelian et al. (2001) have claimed the detection of ${}^6\text{Li}/{}^7\text{Li} = 0.12$ in the planet-hosting star HD 82943. Reddy et al. (2002) concluded that this enhanced ${}^6\text{Li}$ could be explained by the presence of a Ti I lines near 6708.03 and 6708.1 Å. In a follow-up paper Israelian et al. (2003) revised the ratio to ${}^6\text{Li}/{}^7\text{Li} = 0.05 \pm 0.02$. The PHOENIX models used in our analysis were updated to include the atomic data for Ti I lines taken from Table 3 of Reddy et al. (2002). We have investigated the effects of Ti I on the Li line profile by constructing a grid of models with Ti abundances ranging from $\log \text{Ti} = 4.0$ to 6.0 and fitting the Ti I line at 6716.6 Å. The best χ^2 revealed an abundance of $\log \text{Ti} = 5.22$, in excellent agreement with the result of Luck & Heiter (2005). The latter value was used in the determination of the ${}^6\text{Li}/{}^7\text{Li}$ ratio. The effects of Ti abundance were investigated further by constructing an additional set of models at a given Ti abundance with ${}^6\text{Li}/{}^7\text{Li}$ ranging from 0.0 to 0.1. The best fit to the Li line profile provided a ${}^6\text{Li}/{}^7\text{Li}$ ratio at

FIG. 5.—Comparison of the VLT GJ 117 spectrum (solid histogram) to that of a K2 template star, HD 131511 (dashed line). HD 131511 was observed at the McDonald telescope in 2005 May (see text).

each Ti abundance. The results are shown in Figure 4. The Ti abundance and ${}^6\text{Li}/{}^7\text{Li}$ ratio are anticorrelated (also see Reddy et al. 2002) in the sense that for a given Li profile, a lower Ti abundance would lead to an increased ${}^6\text{Li}/{}^7\text{Li}$ ratio. However, in the case of GJ 117 studied here, in order to drive the ${}^6\text{Li}/{}^7\text{Li}$ ratio to zero, a Ti abundance of five times greater ($\log \text{Ti} = 5.92$) would be required. We emphasize that both our results and those found in the literature are consistent with $\log \text{Ti} = 5.22$.

An additional check on any significant blending that may contaminate the red wing of the lithium profile was done by comparing the spectrum of GJ 117 to the template star HD 131511 that has a similar spectral type. The two objects have similar metallicity ($\text{Fe}/\text{H} = 0.13$ to $\text{Fe}/\text{H} = 0.15$; Luck & Heiter 2005), but HD 131511 has no detectable lithium (Takeda & Kawanamoto 2005). HD 131511 was observed at the McDonald 2.7 m telescope on 2005 May 24 with a resolution of $\approx 130,000$ and a signal-to-noise ratio just over 120. The spectra of the two objects in the 6707.8–6708.3 Å region were examined on the HD 131511 spectrum and showed an equivalent width of less than 2 mÅ. We therefore conclude that our estimate of ${}^6\text{Li}/{}^7\text{Li}$ on GJ 117 is not effected significantly by other lines.

We have also analyzed the bisectors of four nearby spectral lines of Fe I and Ca I on GJ 117 and found them to be vertical with an uncertainty of about 0.004 Å (0.2 km s^{-1}). The red asymmetry in the Li profile is therefore not caused by the atmospheric effects of granulation. Our findings are consistent with Gray (2005), who analyzed the shape of the bisector of the K2 V star ϵ Eri, a star with atmospheric properties similar to our object. Our findings are also consistent with Smith et al. (1998). The lack of asymmetries can be explained by the fact that in active stars, like GJ 117, strong magnetic fields inhibit convection, and this is known to be the case in sunspots.

2.3. Can the ${}^6\text{Li}$ Abundance Be Attributed to Enhanced Activity?

Deliyannis & Malaney (1995) have suggested that flare activity may account for ${}^6\text{Li}$ production on HD 84937. However, Lemoine et al. (1997) have questioned the feasibility of this scenario on the basis of the energetics involved. We will now examine if the activity of GJ 117 can account for the detected ${}^6\text{Li}$ on this source. As already mentioned in § 1, GJ 117 has shown evidence of chromospheric activity. With a rotational velocity of 5.5 km s^{-1} , GJ 117 is rotating faster than the Sun and has a deeper convection zone. Its X-ray luminosity is at least 1 order of magnitude higher than the X-ray luminosity of

the Sun at solar maximum (Mathioudakis & Doyle 1989; Hempelmann et al. 1995). Its X-ray emission implies a total average flare energy of $\approx 5 \times 10^{29}$ ergs s^{-1} and a corresponding total average *U*-band flare energy of $\approx 5 \times 10^{28}$ ergs s^{-1} (Doyle & Butler 1985; Whitehouse 1985). The most energetic solar flares are the X class with energies of at least 10^{32} ergs. The *GOES* database shows that in 2000, a solar maximum year, 17 X-class flares were observed. Assuming that these values also hold for GJ 117, they imply a total energy of $E \approx 5 \times 10^{49}$ ergs over 1 Gyr. With a production efficiency of 10^{-3} atoms erg^{-1} , we have 5×10^{46} atoms (Livshits 1997). The mass of the convection zone of GJ 117 is $0.06 M_{\odot}$ (Pinsonneault et al. 2001). With an estimated $\log \text{Li} = 2.45$ and ${}^6\text{Li}/{}^7\text{Li} = 0.03$, we obtain $\approx 5 \times 10^{44}$ atoms. In the largest solar flares, the number of protons with energy over 30 MeV is more than 10^{33} . This value implies 3×10^{29} ${}^7\text{Li}$ atoms s^{-1} (Livshits 1997) and 7×10^{28} ${}^6\text{Li}$ atoms s^{-1} (Canal et al. 1980), or 2.2×10^{45} ${}^6\text{Li}$ atoms in 1 Gyr. Our estimates are therefore consistent with the ${}^6\text{Li}$ generation by spallation processes in flare events.

3. CONCLUDING REMARKS

High-resolution VLT UVES observations of the dK1 star GJ 117 show the detection of ${}^6\text{Li}$ at the 3% level (${}^6\text{Li}/{}^7\text{Li} =$

0.030 ± 0.010). Our spectral analysis included the Ti I transitions and atomic data used by Reddy et al. (2002) for similar studies of the planet-hosting star HD 82493. GJ 117 is considerably more active than the Sun. We have examined the possibility of Li production by spallation in stellar flares and concluded that the energetics involved are sufficient for this process to take place. Future work on this subject could include the study of the Li profile during flare events where an enhanced ${}^6\text{Li}$ may be expected.

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