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High-dispersion Spectroscopic Observations of the T Tauri-type Stars with Weak Emission Lines† ⋆

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Abstract By using the 2.16 m telescope of Xinglong Observing Station of National Astronomical Observatories and its high-dispersion spectrograph, the high-dispersion spectroscopic observations of six T Tauri-type stars with weak emission lines (i.e., weak-line T Tauri-type stars, abbreviated as WTTS) were carried out. The lithium abundances of these weak-line T Tauri-type stars are calculated and the relationships of the lithium abundances with the rotation periods as well as the amplitudes of light variations of these stars are discussed. It is found by this study that the lithium abundance for the weak-line T Tauri-type stars with fast rotations tends to be less than that of those with slow rotations. However, for all these weak-line T Tauri-type stars, the lithium abundances have no conspicuous correlation with the amplitudes of light variations of these stars in the V waveband.

Key words: star: pre-main sequence, star: abundance, star: activity

1. INTRODUCTION

T Tauri-type stars are the pre-main sequence stars which are young ($\leq 10^8$ yr) and have small masses ($M \leq 2\ M_\odot$) as well as late spectral types (the typical spectral type is G0 or later than G0). According to the equivalent width of the H_α line, the T Tauri stars can be classified into classical T Tauri-type stars (abbreviated as CTTS) and T Tauri-type stars with weak emission lines (i.e., weak-line T Tauri-type stars, abbreviated as WTTS)[1,2]. The classical T Tauri-type stars have very intense infrared emission, and this implies that

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around them there exist absorption disks. Most T Tauri-type stars with weak emission lines possess conspicuous absorption lines of lithium and exhibit very intense chromospheric activities. Besides, they possess large ultraviolet excesses, yet they are always lacking in infrared radiation[3]. All this implies that for the T Tauri-type stars with weak emission lines, the accretion disks around the stars have partially or even completely vanished.

The element Li occupies exceedingly important places in the early chemical evolution of the universe, the theory of element nucleosynthesis as well as the studies of structure and evolution of stars. From the understanding of the stellar interior structure to the constraint on the lithium abundance necessary for building the big-bang model of the early universe, the lithium abundance plays an extremely important role in many respects. Up to the present, although a comparatively complete theoretical framework of the stellar structure and evolution has been established, yet the processes of star formation and early evolution are not clear enough. The research on this aspect is nowadays a very hot field. For the study of solar-type stars, it can not only deepen our understanding of the formation and evolution of the sun-like stars, but also help us to understand the formation and evolution of the sun, the solar activity as well as the formation and evolution of the planets in the solar system. Therefore it is very necessary to observe directly a large amount of pre-main sequence and small-mass stars with various masses and various periods of rotation, to ascertain the process of lithium dissipation as well as the rate and amount of the dissipation, and to study further the relations of lithium dissipation with stellar parameters. Up to now, the observations of the lithium abundances of the G, K & M types of main sequence stars in Galactic open clusters with various ages have shown that the average lithium abundance of stars in one and the same cluster decreases toward the direction of lower temperatures. However, for the young open clusters (such as the Pleiades and α Persei cluster) and for the same colors, the lithium abundances of stars exhibit a rather large dispersion[4,5]. This kind of dispersion possesses extremely important significance for the study of the mechanism of decay of lithium abundance in stellar atmospheres and the exploration of the convection of matter in stellar interiors.

From the target sources identified by Xing et al.[6] in the BVR multi-wavelength photometric observations of T Tauri-type stars with weak emission lines, we have chosen six T Tauri-type stars which possess the BVR multi-wavelength photometric data and are rather bright ($m_V < 10$ mag). For them we have carried out new spectral observations of high dispersion and calculated the lithium abundances of these weak-line T Tauri-type stars. In combination with the BVR multi-wavelength photometric observational data, we have investigated the relations of lithium abundance with the stellar rotation period and the amplitude of light variation. We have also searched the correlations of the lithium abundances with the amplitudes of V-band light variations of these weak-line T Tauri-type stars as well as their rotation periods.

2. OBSERVATIONS AND DATA PROCESSING

On January 14∼16, 2012 and by using the 2.16 m telescope of Xinglong Observing Station of National Astronomical Observatories as well as its high-dispersion spectrograph, we carried out the spectral observations of the six rather bright ($m_V < 10$ mag) weak-line T Tauri-type stars, which were chosen from Xing et al.[8]'s BVR multi-wavelength photometric data. Our observations were made with a mid-focal length camera in the red region. After passing through the slit and the bi-color plate, the light rays were divided into red and blue regions. The spectral resolution power of the red region was $R = 37000$. The star image was formed on the spectrograph slit, and both the height and width of the slit could be adjusted. During the observation of stars, the width of the slit was chosen to be 0.5 mm and the height of the slit was adjusted to be 3 mm. The detector was the TEKTRONIX Tex 1024 CCD (1024 pixel × 1024 pixel), the dimension of each pixel was 24 μm × 24 μm, and the readout noise was 1.67 ADU.

After the acquisition of observational data, the software package IRAF (Image Reduction and Analysis Facility) was employed to make data processing. The main steps can be described as follows: (1) image preprocessing—the primary data acquired by observations with the telescope are preliminarily reduced and the hot points and dead points in images are excluded; (2) order determination—the flat field or stellar spectrum is used to determine the position of every order on the primary spectral image (generally speaking, this is the 36-th order in the red region); (3) flat-field correction—the quantum efficiencies of various pixels of the CCD device are different, even if a completely uniform illumination was yielded on the CCD, the output image will not be uniform in intensity, hence this effect has to be corrected with the flat field; (4) wavelength calibration—the spectrum of the Th-Ar lamp is used to determine the wavelengths in spectrum, so that the dispersion relation is obtained, and the spectral lines in the calibration table of the system exhibit one-to-one correspondences with various CCD pixels; (5) order extraction—along the direction of order, the pixels on the slit are added together, the 2-D spectrum is extracted to be an one-dimensional spectrum. Thus, the new high-dispersion spectra of the six weak-line T Tauri-type stars are obtained.

3. DATA ANALYSIS

The high-dispersion spectra obtained via the data analysis of six weak-line T Tauri-type stars are depicted in Fig.1.

3.1 Equivalent Widths (EWs) of Lithium Absorption Lines

At first the confirmation and normalization of continuums were carried out for the spectra obtained via the IRAF software. Then the two methods, Gaussian fitting and direct integration, were used to measure the equivalent widths. The steps are as follows:

(1) Determination of continuum and normalization treatment—Via a group of defined continuum windows and the low-order stripline interpolation and fitting, the continuum is determined. With the primary one-dimensional spectrum divided by the continuum, the normalized 1-D spectrum is obtained (see Fig.1).

(2) Measurement of equivalent widths—Mainly the two methods, namely Gaussian fitting and direct integration, are adopted to measure the equivalent widths. Generally speaking, the Gaussian fitting is suitable for the case of weak lines, and the direct integration may be used for strong lines (this is because in this case the non-Gaussian profiles of line wings have rather large contributions to equivalent widths). For the spectral lines of intermediate intensities, the weighted means of the two kinds of fitting may be adopted.

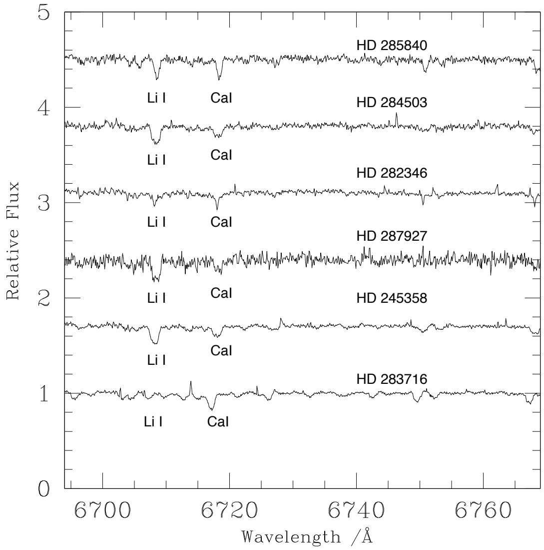

Fig. 1 High-dispersion spectra of six T Tauri-type stars in the vicinity of Li I λ 6708 Å

In Fig.2 the equivalent widths of the lithium absorption lines obtained from the high-dispersion spectroscopic observations of the six weak-line T Tauri-type stars are compared with those obtained by other observers [7−11].

3.2 Effective Temperature on Stellar Surface

The UBV photometric system, also called as the Johnson (photometric) system, is a broadband photometric system. It is widely used to carry out the classification of stars according to color indices. The UBV photometric system is the first standard photometric system. Its data of stellar observations are numerous and may be easily acquired from literature and observational data. The stellar effective temperature $T_{\rm eff}$ can be obtained from the color index (B-V) in the multi-color system and via the empirical formula given by Magain[12], i.e., $T_{\rm eff}$ = 7720 - 3910(B-V). Simultaneously, on the basis of the empirical formula given by Gray et al.[13] and by using the ratio of depths of the V I 6251.83 Å and Fe I 6252.527 Å lines, we calculated the effective temperatures of the six weak-line T Tauri-type stars in the observational sample.

3.3 Gravitational Acceleration on Stellar Surface

Following Nissen et al.[14]'s method, we obtained the gravitational acceleration g on stellar surface. Via the two relations $g \propto M/R^2$ and $L \propto R^2/T_{\rm eff}^4$, we obtained $\lg\ g = \lg\ g_\odot + \lg\ (M/M_\odot) + 4\ \lg\ (T_{\rm eff}/T_{\rm eff;\odot}) - \lg\ (L/L_\odot)$, where M is the stellar mass, R is the stellar radius, L is the stellar luminosity, $g_\odot$ is the gravitational acceleration on solar surface, $T_{\rm eff;\odot}$ is the solar effective temperature and $L_\odot$ is the solar luminosity. The stellar luminosity was derived from the following expression: $L/L_\odot = 0.0813 \times r^2 \times 10^{0.4m}$, where r is the distance of the star (obtained from the observed annual parallax of the star), m

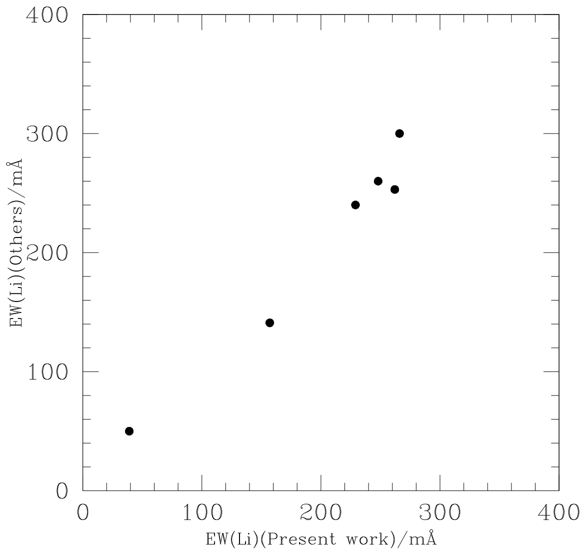

Fig. 2 Comparison of the equivalent widths of lithium absorption lines obtained by authors of this paper with those obtained by other authors

is the stellar visual magnitude, and so on. As for the stellar mass, it was obtained from the position of the weak-line T Tauri-type star on the diagram of $\lg(L/L_{\odot}) - T_{\rm eff}$, i.e., the Hertzsprung-Russell diagram.

3.4 Calculation of Lithium Abundance

The abundance of the element lithium in stellar surface layer (the abundance of the element hydrogen was taken to be $\lg N(\rm H) = 12.00$) was obtained from the curve of growth of Li I λ 6708 Å. The model of stellar atmosphere is the mathematical model used to describe the physical structure of stellar atmosphere and the energy spectrum of continuum. In this paper we adopted the Kurucz model (ATLAS9), which is based on the hypotheses of local thermodynamic equilibrium, plane-parallel stratification and stationary fluid equilibrium, as the stellar atmospheric model for abundance analysis. Besides, we calculated as well the lithium abundances of the six weak-line T Tauri-type stars with the curve of growth that was given by Pavlenko et al.[15] under the assumption of non-local thermodynamic equilibrium (NLTE), as shown in Table 1. In this table, the first column lists the star names; the second column gives the spectral types of stars; the third column indicates the color indices of stars; the fourth column gives the amplitudes of light variations in the V waveband; the fifth column lists the stellar effective temperatures obtained with the empirical formula given by Magain[12] and the color indices of stars; the sixth column lists the stellar effective temperatures obtained simultaneously by using the empirical formula of Gray et al.[13] and using the ratio of depths of the V I 6251.83 Å and Fe I 6252.527 Å lines; the seventh column shows the equivalent widths of stellar lithium absorption lines; the eighth column gives the stellar lithium abundances obtained by computation; the ninth column gives the logarithms of gravitational accelerations with the base 10; and the tenth column shows the periods of stellar rotation. On the basis of the curve of growth of NLTE, Pavlenko et al.[15] used the the atmospheric model with the following main parameters: the metal abundance of the sun, the logarithm of gravitational acceleration lg $g = 3.0\sim4.5$, the stellar effective temperature $T_{\rm eff} = 3500\sim6000\,$K, and the velocity of microscopic turbulence $V_{\rm TURB} = 2.0$ km $\cdot$ s^{-1}. Fig.3 shows the curve of growth in the case of NLTE.

Table 1 Photometric results and other parameters of our sample of WTTSs

Name	SpT	B-V	$\Delta m_{\rm V}$	$T_{\rm eff}^{C}$/K	$T_{\rm eff}^{R}$/K	EW(Li)/mÅ	lg N(Li)	lg g	$P_{\rm rot}$/d
HD 245358	G5	0.713	0.093	5589	5576	266	3.32	4.09	0.736
HD 287927	G5	0.709	0.138	5594	5608	248	3.28	4.19	0.772
HD 283716	K0IV	0.769	0.077	5403	5422	39	1.89	4.33	1.48
HD 284503	G8	0.872	0.150	5109	4997	161	2.61	4.36	0.741
HD 282346	G8V	0.798	0.110	5309	5297	209	2.76	4.07	0.730
HD 285840	K1	0.702	0.160	5604	5598	253	2.77	4.29	1.558

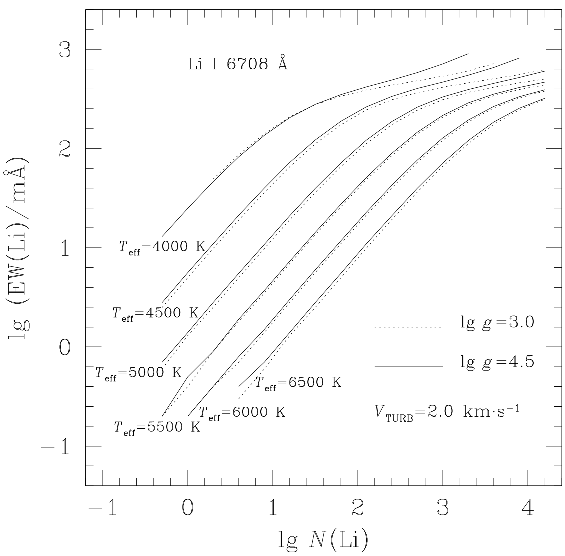

Fig. 3 Curve of growth of LiI λ6708$\AA$ for temperatures of 3500$\sim$6000 K [15]

The errors of abundance analysis have two main sources, i.e., the errors of spectral processing and those due to the uncertainties of stellar atmospheric parameters. The upper limit of the errors of measured equivalent widths is 5%, and this leads to the upper limit of abundance error of about 0.07 dex. The error of abundance of iron caused by the temperature variation of 100 K is 0.06 dex, and the increase of surface gravity by 0.1 dex may lead to the decrease of abundance of 0.01 dex. Another uncertainty comes from the description of stellar atmosphere with the model. The influence of the effect of non-local thermodynamic equilibrium on the abundance is very complex. For the stars with various metal abundances, the degrees of influence differ with the particular element. So far, there is no systematic analysis of the effects of non-thermodynamic equilibrium on the various elements in metal-poor stars. However, for certain specified elements the analysis has achieved certain progress. For the intermediately metal-poor (-1 $<$ [Fe/H] $<$ 0) dwarfs of the F and G types, the abundance error caused by the non-local thermodynamical equilibrium is approximately 0.001$\sim$0.1 dex. From this we can estimate that for the majority of elements in sample stars the influence of non-thermodynamic equilibrium should be less than 0.1 dex.

4. DISCUSSION

The relationship between the lithium element abundances of the six T Tauri-type stars with weak emission lines and their effective temperatures are depicted in Fig.4. In the figure no conspicuous correlation between the abundance of lithium element and the stellar effective temperature can be found.

For the weak-line T Tauri-type stars, due to the stellar rotation the large spots or groups of spots enter or leave the visible disks, then the light variations of stars are produced. The larger the areas of the spots or groups of spots on stellar surfaces, the larger the amplitudes of light variations of stars. Conversely, the smaller the areas of the spots or groups of spots on stellar surfaces, the smaller the amplitudes of light variations of stars. In Ref.[16], the variations of the equivalent widths of lithium absorption lines of the WTTS V410 Tau with the phase of stellar rotation were investigated (Namely, the variations of the equivalent widths of lithium absorption lines with the entering or leaving of large spots or groups of spots into or from the stellar disk were studied). It was discovered that for the star V410 Tau such variations are very small, or there is no variation al all. By using a simple model (namely, for a given model of stellar atmosphere and a temperature of stellar photosphere) and by changing the areas or temperatures of spots or groups of spots on the stellar surface, Soderblom et al.[4] calculated the influence of spots or groups of spots on the lithium element in stellar envelope. As discovered by them, although the equivalent widths of lithium absorption lines exhibit conspicuous variations with the entering into or leaving out from the visible disk, yet such variations of area or temperature have almost no influence on the abundance of the lithium element.

By using a sample of multiple weak-line T Tauri-type stars with different amplitudes of light variations, we may study as well the relation between the amplitude of light variations and the abundance of lithium and investigate the influence of the areas of spots or spot groups on stellar surfaces upon the lithium abundance of stellar surface layers. In order to study the influence of the spots or spot groups on the surfaces of WTTSs upon the abundance of the lithium element, we in Fig.5 draw the figure of the lithium abundances in the surface layers of the six recently observed WTTSs and the amplitudes of light variations of these stars in the V waveband obtained via the BVR multi-color photometry. The amplitudes of V-band light variations of the six WTTSs are taken from Xing et al.[6]'s multi-wavelength photometry of WTTSs. As may be seen in Fig.5, between the lithium abundances in the surface layers of these six WTTSs and the amplitudes of light variations in the V waveband, no obvious correlation can be found.

Namely, the sizes of areas of spots or spot groups on the surfaces of these six WTTSs have no obvious influence on the lithium abundances in the surface layers of these stars. This completely agrees with Ref.[16] and the result of Soderblom et al.[4], and implies that

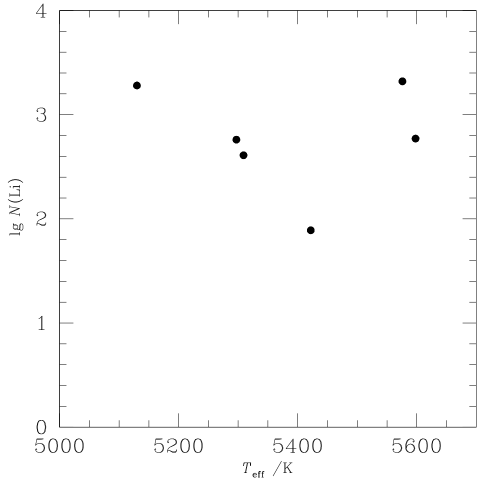

Fig. 4 Relation between lithium abundances and effective temperatures of stars

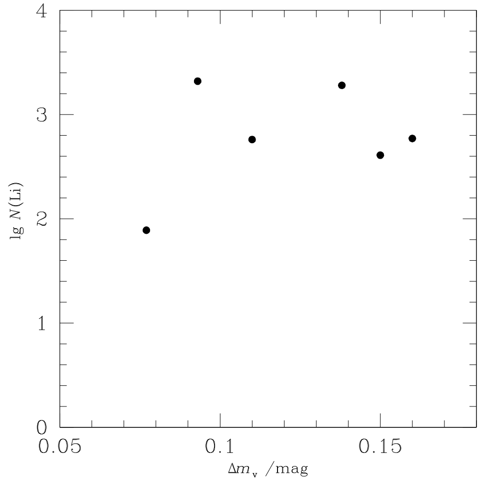

Fig. 5 Relation between the lithium abundances of weak-line T Tauri-type stars and their amplitudes of light variations in the V waveband

the size of areas of spots or spot groups has a very small influence on the lithium abundance in stellar surface layers. The magnitude of the lithium abundance in the surface layers of WTTSs is very probably determined chiefly by the stellar age.

In order to study the influence of rotational velocity of pre-main sequence stars on the lithium abundance of stellar surface layers, in combination with the 13 WTTSs in the star-forming regions of the constellations Taurus, Auriga and Orion, excluding the binary systems in which (see Table 2 of Reference [6]), the relationship between the lithium abundances of the 19 WTTSs and their rotation periods is depicted in Fig.6. From this figure, it is found that between the lithium abundances in the surface layers of WTTSs and the periods of rotation of these stars there is a conspicuous correlation. Namely, with the increase of stellar rotational velocity (or with the decrease of stellar rotation period) the lithium abundance evidently decreases.

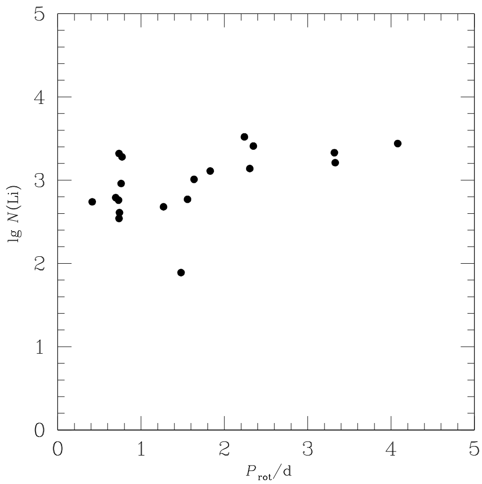

Fig. 6 Relationship between the lithium abundances of WTTSs and the stellar rotation periods

However, as demonstrated by the model of stellar evolution and a large amount of observational results, the main evolutionary characteristics of the pre-main sequence, late-type and small-mass stars are as follows. With the increase of stellar age, the rotation evidently accelerates. Namely, for the T Tauri-type stars and with the increase of stellar age, the stellar rotation becomes conspicuously faster (according to the law of conservation of angular momentum, with the contraction of a star in volume, the radius decreases and the rotation becomes faster). The weak-line T Tauri-type stars with smaller velocities of rotation are still younger than those with larger velocities of rotation. Our result confirms the model proposed by Piau et al.[17] which advocates that the lithium abundance of stellar surface layer evolves with the stellar age. It also supports the proposition of Drake et al.[18] that the lithium element may be taken as the "clock" of stellar evolution.

From another side, the relation between lithium abundance and rotation period illustrates that for small-mass stars, the dissipation of lithium commences before the main sequence. This result supports the theory of lithium dissipation proposed by Piau et al.[17].

5. CONCLUSION

Via the high-dispersion spectroscopic observations of six weak-line T Tauri-type stars, we have calculated the lithium abundances of these stars, discussed the relations among their lithium abundances and the rotation periods as well as the amplitudes of light variations. It is found that the lithium abundance of the fast rotating weak-line T Tauri-type stars tends to be less than that of slowly rotating ones. However, there has not been found a conspicuous correlation between the lithium abundances of the surface layers of these T Tauri-type stars and the amplitudes of their light variations in the V waveband.

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