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Spectroscopy of a chemically peculiar δ Scuti-type star: 60 Tau

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Abstract

In this study, a detailed spectroscopic analysis of 60 Tau is presented. 60 Tau is known to be a metallic-line (Am) star which exhibit δ Scuti-type pulsations. The pulsation mechanism of the δ Scuti stars have been thought to be well understood and it was also suggested that metallic-line stars did not exhibit pulsations. However, in recent studies, particularly after *Kepler* and *TESS* data have been released, many metallic-line δ Scuti stars have been found and it turned out that the current pulsation mechanism of δ Scuti stars including the metallic-line ones has not completely understood. Therefore, to make a reliable investigation for the driving mechanism of the δ Scuti variables, we need to know precise fundamental stellar (mass, radius) and atmospheric ($T_{\rm eff}$, log g, ξ) parameters of these variables. Hence in this study, the atmospheric parameters, projected rotational velocity and the chemical abundances of 60 Tau were obtained by using the high-resolution and high signal-to-noise spectra. The position of the star is shown in the H-R diagram and the δ Scuti instability strip using the Gaia luminosity.

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1. Introduction

Interior structures of stellar systems can be deeply investigated by using asteroseismology. Asteroseismology is a method which uses the stellar oscillations to probe the stellar interior structure [1]. There are many pulsating variables located in different parts of the Hertzsprung-Russell (H-R) diagram. These variables are the main targets of asteroseismology and they allow us to examine stars in different evolutionary stages.

The δ Scuti stars are one of the most known targets of asteroseismology. These variables exhibit radial, non-radial pressure, gravity and mixed-mode pulsations which are believed to be driven by the κ mechanism [1]. Pulsation frequency of the δ Scuti stars mostly ranges from 5 to 50 d^{-1} [2], but it was shown that most δ Scuti stars also exhibit low-frequency regime [3]. δ Scuti-type variations can be found in chemically normal and peculiar stars. There are many δ Scuti stars which exhibit chemical peculiarities in their atmospheres. However, previously it was thought that chemically peculiar stars did not oscillate [4, 5] but recent discoveries showed that those stars can also pulsate [6, 7].

Chemically peculiar stars have a spectral type ranging from late-B to early-F and they show atmospheric chemical abundance different than solar. The chemically peculiar stars are divided into different groups by taking into account their magnetic field strength and weak or strong absorption lines [8]. Among these chemically peculiar stars, there are metallic-line (Am) stars. These stars show weak CaK lines, rich iron-peak elements and also weak magnetic field [9, 10]. Am stars can be easily distinguished by a spectral classification. In their spectral classifications, we define earlier spectral type from CaK lines relative to hydrogen and metal lines. Considering the difference of spectral types between CaK and metal lines, Am stars are classified as classical and marginal Am stars. If the spectral-type from CaK and metal lines differ at least five subtypes, these Am stars are defined as classical Am stars, while others are called to be marginal Am stars.

Am stars are mostly a member of short-period binary systems [11,12]. They are also known to be slow rotators. It is thought that the reason for slow rotation is the effect of the binarity. However, it was shown that there are some single Am stars which probably was born originally as slowly rotating stars [13, 14].

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60 Tau (HD 2728, V=5.71 mag) is known as a δ Scuti-type Am star. This object was classified to be a classical Am star by [15] and its δ Scuti-type pulsations were first found by [16] during the photometric observations of the Hyades. A detailed photometric study for 60 Tau was given by [17]. In this study, five nights photometric observations of the star are presented. As a result, [17] found two pulsation frequencies of 13.0364 and 11.8521 d^{-1}. The star is also a single-lined spectroscopic binary. For years, lots of radial velocity measurements of the system were done [11, 18, 19]. The last radial velocity measurements and analysis were given by [20]. In this analysis, orbital parameters (such as orbital period, periastron passage time) of the system were determined.

60 Tau has a spectroscopic study [21] in which atmospheric parameters of the system were obtained. However, to understand the real pulsation mechanism occurring in the pulsating Am stars, a more detailed spectroscopic study with higher-resolution spectra is needed. Therefore in this study, I focus on the detailed spectroscopic analysis of a metallic-line (Am) δ Scuti pulsator. The study is organised as follows. Information about the spectroscopic data is given in Sect.2.1. The spectral classification is presented in Sect.2.2. The details about the spectroscopic study are given in Sect.2.3. Consequently, the results and discussions are introduced in Sect. 3.

2. Materials and Methods

2.1. Observational data

There are five public spectra of 60 Tau in archives. One HARPS spectrum is available in the European Southern Observatory (ESO) archive (http://archive.eso.org). HARPS is an échelle spectrograph mounted on the 3.6-m telescope at ESO (La Silla, Chile). It has a resolving power of 115000 and supplies spectra with a wavelength range of about 378 – 690 nm [22]. There is also one SOPHIE spectrum of 60 Tau. SOPHIE is an échelle spectrograph attached on the 1.93-m telescope at the Haute-Provence Observatory (OHP, France). The system offers spectra with two different resolving powers of 39000 and 75000 in a wavelength range of 380 – 680 nm [23]. The SOPHIE spectrum of 60 Tau was taken with 39000 resolving power. 60 Tau also has three ELODIE spectra. ELODIE is an échelle spectrograph installed on the 1.93-m telescope at the OHP (France). ELODIE supplies a resolving power of 42000 with a spectral window of 385 – 680 nm [24]. The information for the instruments and the spectra are given in Table 1. All available spectra of 60 Tau were reduced by the dedicated pipelines for each spectrograph. They were normalized manually by using the IRAF *continuum* task [25].

Table 1. Information for the spectroscopic data.

Instrument	Observation dates	Number of spectra	S/N ratio
ELODIE	October, 2003, October, 2004, September, 2005	3	150 220 100
HARPS	December, 2014	1	160
SOPHIE	October, 2006	1	350

2.2. Spectral classification

The spectral classification is an easy way to estimate the initial information for the atmospheric parameters (such as effective temperature T_{eff}, surface gravity log g) and chemical anomalies in stars' atmosphere. To obtain this information for a star, even a low-resolution spectrum is enough. In the spectral classification, the spectra of observed stars are compared with the spectra of spectral classification standard stars. During this comparison, depending on the searching spectral type (e.g. A0, F0), there are a few important lines which should be checked [26].

As 60 Tau is a δ Scuti star, it should have a spectral type of A – F. Therefore, A – F type spectral type standard stars [27] were used and they were compared with all available spectra of 60 Tau. Detailed information about spectral classification can be found in the study of [28].

During the comparison, three different line groups, CaK, hydrogen and metal lines in the wavelength range of ~380 – 450 nm, were taken into account. The spectral types determined from these lines should agree with each other for a chemically normal star. If a star is a metallic-line star as suggested for 60 Tau, these lines give different spectral types, especially there should be a significant difference between the determined spectral types from CaK and metal lines. By applying this analysis, I determined the spectral and luminosity type of 60 Tau to be kA5hF0mF0IV. This classification shows that the spectral type from CaK lines (k) is A5 while the spectral type from hydrogen (h) and metal (m) lines is F0. This result confirms the Am feature of 60 Tau. The obtained spectral classification slightly differs than the literature A3m classification [21].

2.2. Determination of the atmospheric parameters

The atmospheric parameters (T_{eff}, log g and microturbulence ξ) of the star were determined using the hydrogen and metal lines. In the spectroscopic analysis, the spectrum synthesis method was used and the final parameters were derived considering the minimum difference between the synthetic and observed spectra.

Before starting to spectroscopic analysis, to have initial information about the atmospheric parameters, uvbyβ colors and the spectral energy distribution (SED) of the star were used. First, the uvbyβ colors were taken from [29]. The T_{eff} and log g parameters were calculated from uvbyβ using the method of [30]. During the analysis, E(b-y) value was obtained as 0.0 mag. The interstellar reddening E(B-V) value was also calculated taking into account the galactic coordinates and Gaia parallax [31] of 60 Tau. In the calculation, the galactic extinction maps published in [32] was used. As a result, E(B-V) was determined as 0.0 mag.

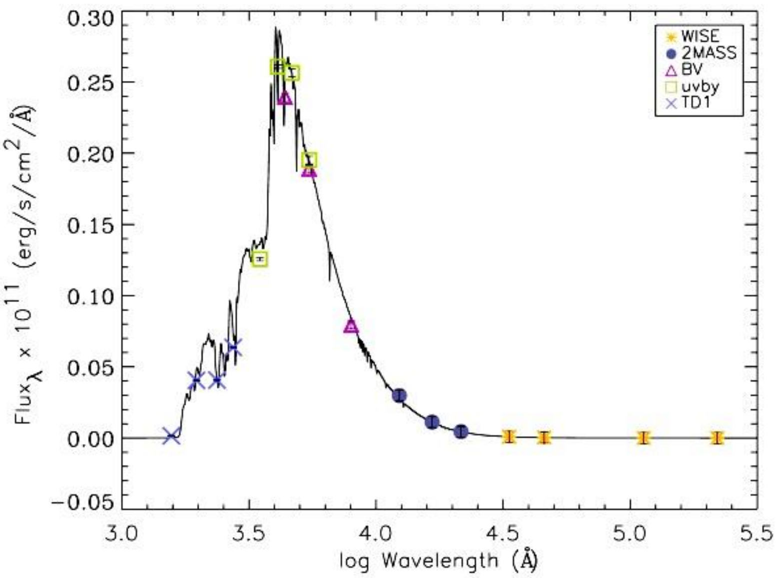

Figure 1. SED fit for 60 Tau.

The SED was constructed by using the E(B-V), Johnson [33], 2MASS [34], uvbyβ [29], the Ultraviolet Sky Survey Telescope (TD1) [35, 36] and the Wide-field Infrared Survey (WISE) [37] colors. In the analysis, the Kurucz model fluxes [38] were used. The final SED T_{eff} was determined considering the minimum difference between the model and color fluxes. During the calculation, log g and metallicity values were fixed as 4.0 and solar, respectively. The SED fit for 60 Tau is illustrated in Fig. 1. The T_{eff} values calculated from the SED analysis and uvbyβ colors are given in Table 2.

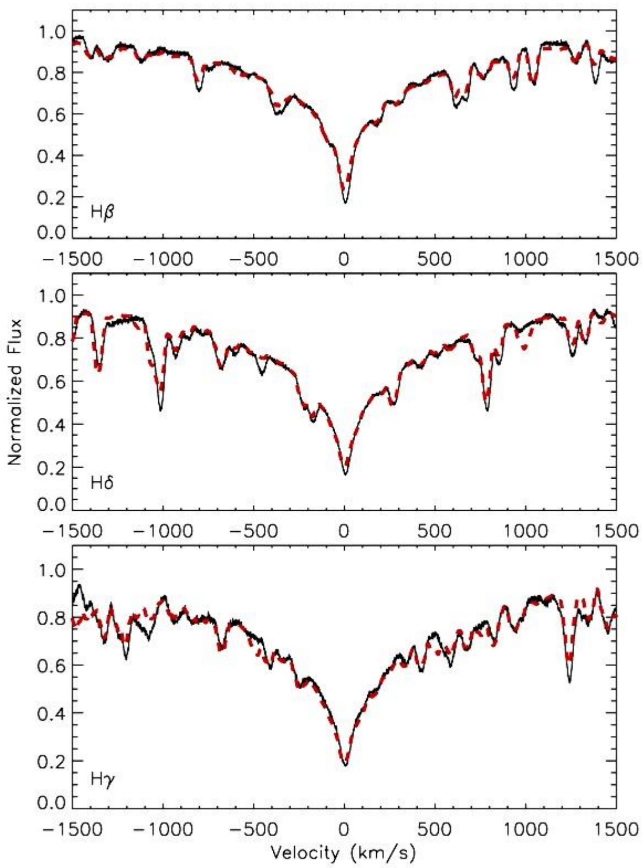

Figure 2. Theoretical hydrogen lines (red dashed) fit to the observed hydrogen (black solid) lines.

After the initial atmospheric parameters were estimated, these values were used as input in the spectroscopic analysis. First, hydrogen lines were taken into account to derive T_{eff} value of 60 Tau. Hydrogen lines are very sensitive to T_{eff} and less sensitive to log g for the stars which have T_{eff} lower than 8000 K [12]. Therefore, hydrogen lines, H_β, H_γ and H_δ were only used to determine T_{eff} and in this analysis log g was fixed to be 4.0. In the hydrogen lines analysis and the further spectroscopic analysis, ATLAS9 model atmospheres [38] and SYNTHE code [39] were used. The hydrogen T_{eff} values were determined using the minimization method described by [40]. The theoretical hydrogen lines fit to the observed ones (for HARPS spectrum) are demonstrated in Fig. 2 and the resulting hydrogen T_{eff} value is given in Table 2. The errors in T_{eff} was estimated using the same method given in [41].

Table 2. Resulting atmospheric parameters, projected rotational velocity and iron abundance.

Parameters	Value
$T\mathrm{eff}_{uvby}$ (K)	7285 ± 220
log g_{uvby} (K)	4.08 ± 0.20
$T\mathrm{eff}_{SED}$ (K)	7190 ± 230
$T\mathrm{eff}_{Hydrogen}$ (K)	7100 ± 200
$T\mathrm{eff}_{final}$ (K)	7000 ± 100
log g_{final}	4.10 ± 0.10
ξ (km/s)	2.4 ± 0.1
Vsin*i* (km/s)	32 ± 1
Fe/H (dex)	7.73 ± 0.18

The final atmospheric parameters were determined depending on the excitation and ionization equilibrium of metal lines. In this analysis, iron (Fe) lines were used because they are more abundant for the searching T_{eff} value (~6800 – 7400 K). Therefore, all available Fe lines (~200 lines) in the HARPS spectrum were taken into account. I used the HARPS spectrum in the analysis because it has a higher resolving power. Higher-resolution spectra are more useful in the analysis of slowly rotating stars and from the literature, it is known that 60 Tau is a slowly rotating star [~31 km/s, 21].

To determine the final atmospheric parameters the method explained in the study of [41] was used. The uncertainties in the obtained atmospheric parameters were also estimated by the same method given in the same study. The obtained final atmospheric parameters and their errors are listed in Table 2.

After accurate atmospheric parameters were determined, the atmospheric chemical abundances of 60 Tau was be obtained. Taking into account the final atmospheric parameters as input, chemical abundances of individual elements were determined using the spectrum synthesis method explained in [41]. In the analysis individual lines and very narrow spectral windows (~0.5 nm) were analysed and the chemical abundances of individual elements and the projected rotational velocity (Vsin*i*) were obtained. The resulting abundances and Vsin*i* parameter were obtained considering the average values. The Vsin*i* value and Fe abundance are given in Table 2, while the abundances of the individual elements are listed in Table 3. The uncertainties in the abundances were calculated using the same method presented by [41]. The theoretical fits obtained in the abundance analysis are compared with the observed ones in Fig. 3.

Table 3. Chemical abundances of individual elements.

Symbol of the elements	Abundance (dex)	Number of the analyzed spectral parts
C	8.13 ± 0.10	3
Na	6.63 ± 0.14	4
Mg	7.76 ± 0.24	8
Si	7.25 ± 0.44	20
S	7.85± 0.26	2
Ca	5.86 ± 0.26	19
Sc	2.45 ± 0.20	4
Ti	5.06 ± 0.35	54
V	4.40 ± 0.45	13
Cr	6.04 ± 0.27	53
Mn	5.52 ± 0.17	21
Fe	7.73 ± 0.18	186
Co	5.39 ± 0.24	6
Ni	6.72 ± 0.17	58
Cu	4.44 ± 0.27	2
Zn	4.63 ± 0.25	1
Sr	3.28 ± 0.49	4
Y	3.11 ± 0.25	11
Zr	3.30 ± 0.25	5
Ba	3.61 ± 0.30	2
La	1.72 ± 0.50	3
Ce	2.48 ± 0.20	8
Pr	1.24 ± 0.10	3
Nd	1.89 ± 0.26	6
Eu	1.35 ± 0.27	1
Gd	2.50 ± 0.35	1
Dy	1.72 ± 0.30	1

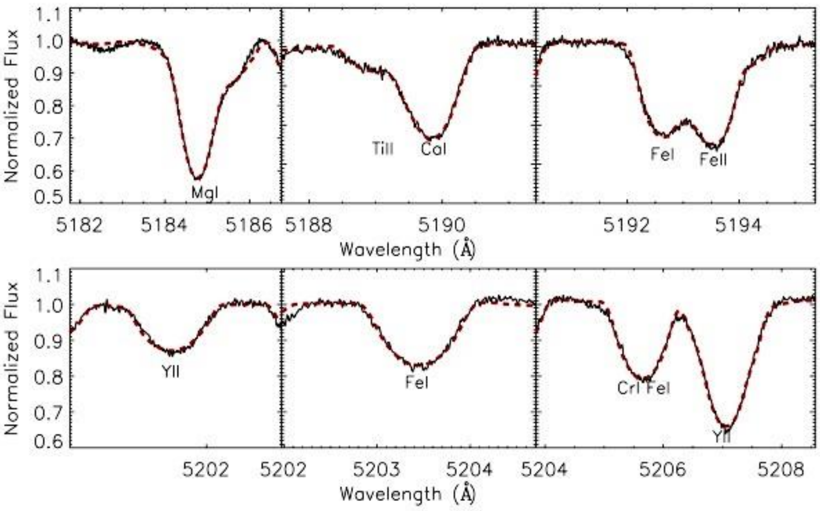

Figure 3. Comparison the theoretical lines fits (red dashed) with the observed (black solid) lines.

3. Results and Discussion

60 Tau was previously classified to be a metallic-line star and its spectral type was given as A3m [21]. According to the result of the spectral classification presented in this study, the star has a spectral type of kA5hF0mF0IV. This result confirms the Am feature of the star. However, this classification is slightly different than the previous one.

To precisely confirm the Am feature of 60 Tau, a detailed spectroscopic analysis was carried out. First, the atmospheric parameters were derived and they were found to be consistent with the spectral classification. The chemical abundances were obtained as well. The chemical abundance distribution for 60 Tau is given in Fig. 4. The Am stars exhibit overabundant iron-peak elements and some heavy elements such as Zn, Sr and Ba. Additionally, they typically show underabundant Ca and Sc [26]. According to this definition and the chemical abundance distribution of 60 Tau, Am feature of the star is confirmed.

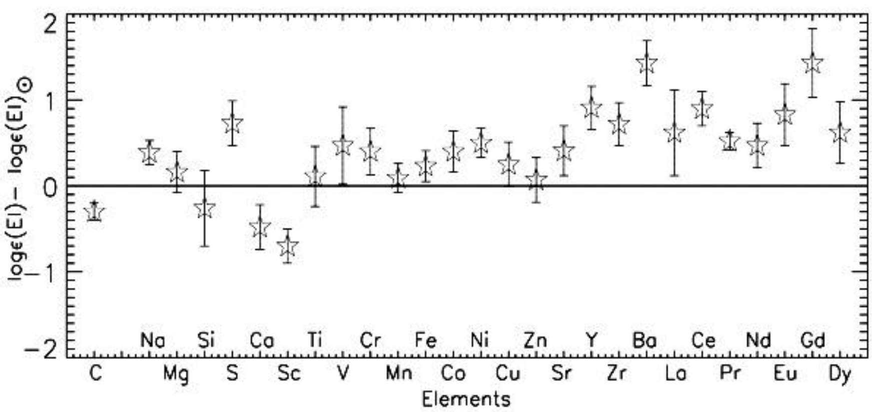

Figure 4. **.** Chemical abundance distribution of 60 Tau relative to solar abundance [42].

In the literature, there is a spectroscopic study of 60 Tau [21]. In this study, the atmospheric parameters and Vsin*i* parameters are given. While T_{eff}, log *g* and Vsin*i* values are consistent with the results obtained in the current study within error, the ξ value differs around 1.3 km/s. This is probably the effect of the resolving power of the used instruments. In the present study, a higher resolution spectrum (R~115000) was used and for such slowly-rotating stars, higher resolution spectra are more suitable to be used in a comprehensive spectroscopic analysis.

The position of the star in the δ Scuti instability strip was found. The Gaia luminosity of 60 Tau was calculated using the bolometric corrections for the star's $T_{\rm eff}$ value [43], Gaia parallax [31] and extinction coefficient. As a result, the location of the star in the H-R diagram and in the δ Scuti instability strip is demonstrated in Fig. 5. [44] found that pulsating Am stars mostly confine a specific area in the H-R diagram and 60 Tau is also found in this region.

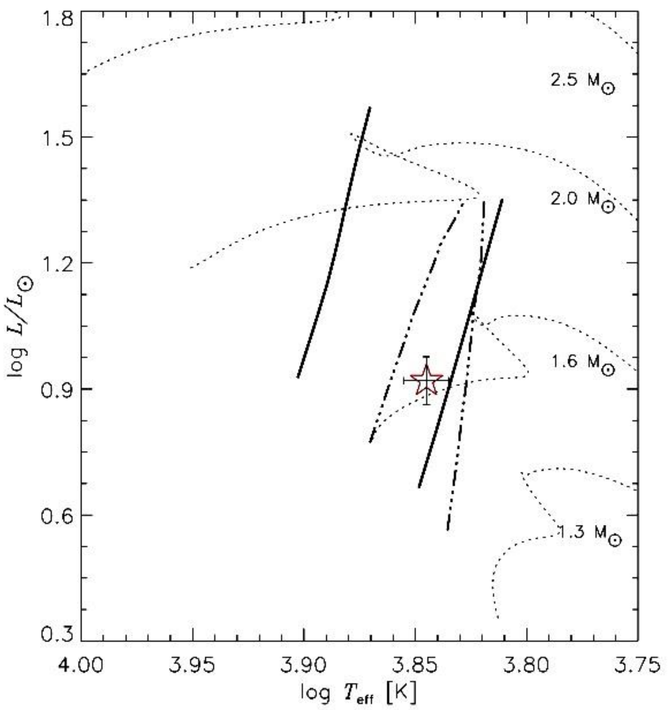

Figure 5. The position of 60 Tau in the H-R diagram. Solid and dashed-pointed lines represent the δ Scuti and γ Doradus instability strips [45], respectively. The evolutionary tracks (dotted lines) were taken from [41].

In this study, the Am characteristic of 60 Tau was confirmed with a comprehensive spectroscopic study. An updated spectral classification of the system was obtained. The $T_{\rm eff}$, log g, ξ and Vsin$i$ parameters were derived and the star was found to be a slowly-rotating object as expected for the Am stars. The obtained chemical abundance distribution of 60 Tau also exhibit a typical Am feature.

The current pulsation mechanism in the δ Scuti stars unfortunately is not completely understood. Especially, the driving mechanism in the pulsating chemically peculiar stars is needed more explanations. Therefore, accurate fundamental stellar and atmospheric parameters of this kind of objects are needed. This study will supply good input data for the future theoretical studies to understand the available pulsation mechanism in the normal and chemically peculiar δ Scuti stars.

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Conflicts of interest

The author states that did not have conflict of interests.

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