BEHAVIOR OF ABUNDANCES IN CHEMICALLY PECULIAR DWARF AND SUBGIANT A-TYPE STARS: HD 23193 AND HD 170920

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ABSTRACT

To understand the origin of the abundance peculiarities of non-magnetic A-type stars, we present the first detailed chemical abundance analysis of a metallic line star HD 23193 (A2m) and an A-type subgiant HD 170920 (A5) which could have been a HgMn star on the main sequence. Our analysis is based on medium (R∼14 000) and high (R∼40 000) resolution spectroscopic data of the stars. The abundance of 18 elements are derived: C, O, Na, Mg, Al, Si, S, Ca, Sc, Ti, Cr, Mn, Fe, Ni, Sr, Y, and Ba. The masses of HD 23193 and HD 170920 are estimated from evolutionary tracks, as 2.3±0.1 M⊙ and 2.9±0.1 M⊙. The ages are found 635±33 Myr for HD 23193 and 480±50 Myr for HD 170920 using isochrones. The abundance pattern of HD 23193 shows deviations from solar values in the iron-peak elements and indicates remarkable overabundances of Sr (1.16), Y (1.03), and Ba (1.24) with respect to the solar abundances. We compare the derived abundances of this moderately rotating (vsini = 37.5 km s−1) Am star to the theoretical chemical evolution models including rotational mixing. The theoretically predicted abundances resemble our derived abundance pattern, except for a few elements (Si and Cr). For HD 170920, we find nearly solar abundances, except for C (−0.43), S (0.16), Ti (0.15), Ni (0.16), Zn (0.41), Y (0.57), and Ba (0.97). Its low rotational velocity (vsini = 14.5 km s−1), reduced carbon abundance, and enhanced heavy element abundances suggest that the star is most-likely an evolved HgMn star.

Keywords: stars: abundances — stars: chemically peculiar — stars: individual (HD 23193, HD 170920)
1. INTRODUCTION

Superficially normal A-type stars may exhibit differences in elemental abundances with respect to the Sun in considerable ranges (Adelman et al. 2015). Most of these differences can be seen in the heavy element abundances (Adelman & Unsuee 2007). Also, a group of non-magnetic A-type stars have remarkable peculiar abundances. These metallic line A-type (hereafter Am) stars are usually characterized by underabundances of some of the light elements (i.e., He, C, O, Ca, and Sc), slight/moderate overabundances of some of the iron-peak elements (Fe, Cr, Ni, etc.), and remarkable overabundances of many heavy elements such as Sr, Y, Zr, and Ba. They are divided into subclasses according to their observed properties, as classical, marginal (or mild), and hot Am stars (for details, see Kurtz 1978). However, there is no clear boundaries between these subclasses nor between normal and metallic A-type stars.

Michaud (1970) suggested diffusion processes as a mechanism for most of the observed chemical peculiarities in the atmospheres of A-type stars. He established that if the atmosphere of a star is not disturbed by convection nor any other mixing process (such as turbulence and meridional circulation) in a shorter time than the diffusion time scale (e.g., order of 10^4 years for Mn III), certain elements can move toward the top of the atmosphere by large radiative forces, causing overabundances. Diffusion processes were then studied in detail for many elements by Michaud et al. (1976) and Vauclair et al. (1978, including turbulent motions). Detailed quantitative evolution models, including 28 chemical elements and turbulent transport, were calculated by Richer et al. (2000). Despite the fact that their theoretically predicted surface abundances generally agree with those of observed Am/Fm stars, they concluded that an additional mixing mechanism was needed to explain observations. The effect of rotational mixing and mass loss on chemical abundances were also modeled/discussed in Talon et al. (2006) and Vick et al. (2010). The abundance analysis of Am stars with various v\textsubscript{sin}i may help to reveal how stellar rotation affects diffusion process.

HD 23193 is classified as an A2m: by Cowley (1968) and Cowley et al. (1969), A3 III by Osawa (1959), and A4p-Ba enhanced by Burwell (1938). Floquet (1970) states that HD 170920 might be an Am star, and its spectral type is in the range of A3-A7. Henry & Hesser (1971) perform the measurements of Ca II K line strength for 223 stars, and the authors include the 369 field stars having k-index measurements. In the study, HD 23193 is listed as an Am star with a spectral type of A2.

Table 1. Collected rotational and radial velocities of the target stars.

|       | HD 23193 | HD 170920 | References          |
|-------|----------|-----------|---------------------|
| v\textsubscript{sin}i (km s\textsuperscript{-1}) | 33        | 13        | Abt & Morrell (1995) |
| v\textsubscript{i} (km s\textsuperscript{-1}) | 21.8      | -27.3     | Duflot et al. (1995) |
|       | 27.3±0.6 | -27.3±2.9 | Gontcharov (2006)   |

Both stars are present in the Catalogue of Am stars with known spectral types given by Hauck (1973). In this catalog, the spectral classes A7 (from metallic lines) and A3 (from Ca II K line) are given for HD 170920, and A2 (from Ca II K line) for HD 23193. Both HD 23193 and HD 170920 is available in General Catalogue of Ap and Am stars (Renson et al. 1991). In the catalog, a doubtful peculiarity is noted only for HD 23193. Two stars also are included in the study of Renson & Manfroid (2009), with no any remarks on their peculiarity. The rotational and radial velocities of the stars are collected and listed in Table 1.

McDonald et al. (2012) calculated the effective temperatures and luminosities of the stars by comparing BT-SETTL model atmospheres to spectral energy distributions generated from infrared photometric data. According to their results, HD 23193 has an effective temperature of 8400 K, and a luminosity of 37.33 L\textsubscript{☉}. The fundamental parameters of HD 170920 are 7497 K, and 113.21 L\textsubscript{☉}. The distances 90.58 pc for HD 23193 and 188.32 pc for HD 170920 were also given in McDonald et al. (2012). The effective temperature of 8960 K was estimated for HD 23193 by Glagolevskij (1994) using (B2−V1)-T\textsubscript{eff} calibration of Hauck & North (1993), based on the optical photometry.

We present the chemical abundances of moderately rotating (v\textsubscript{sin}i = 37.5 km s\textsuperscript{-1}) Am star HD 23193 and a slowly rotating (v\textsubscript{sin}i = 14.5 km s\textsuperscript{-1}) A type subgiant HD 170920, to understand the origin of their abundance pattern. In Section 2, the observations and data reduction methods are given. The details of the abundance analysis are explained in Section 3. We present the evolutionary status of the stars in Section 4, and it is followed with the abundance results Section 5. Finally, we discuss and summarize the results of the study in Section 6.

2. OBSERVATION AND DATA REDUCTION

HD 23193 (α[2000]=03h44m31s; δ[2000]=+36°27′ 36″) and HD 170920 (α[2000]=18h31m57s; δ[2000]=−01°00′ 11″) are bright stars of V~5.59 and 5.94 magnitudes. The optical region spectra of the stars were obtained...
both TÜBİTAK National Observatory (TUG) with 1.5 m telescope and Ankara University Kreiken Observatory (AUKR) with 0.4 m telescope. The TUG spectra with high-resolution ($R \sim 40,000$) and high-SNR (>150) were acquired by Coude Echelle Spectrograph, covering a wavelength range of 3900 to 7500 Å with an exposure time of 3600 s on October 13, 2016. The AUKR spectra with medium resolution ($R \sim 14,000$) and high-SNR ($\sim 200$) were obtained by Shelyak eShel Spectrograph, covering a wavelength range of 4340 to 7400 Å with an exposure time of 3600 s on September 24, 2017. The medium resolution spectra were only used to analyze H$_\beta$ lines (for details see Section 3.1), since the narrow ($\sim 60$ Å) echelle orders of high resolution spectra do not cover any hydrogen Balmer lines entirely. The calibration images (bias, dark, flat-fielding, arc spectra) were also taken for each night. We performed the data reduction, wavelength calibration, and normalization of the high-resolution spectra with standard IRAF$^1$ (Image Reduction and Analysis Facility) packages, as described in the study of Çalışkan et al. (2015). For the reduction of the medium resolution echelle spectra, we used the AUKR data reduction pipeline based on the conventional reduction steps$^2$.

3. ABUNDANCE ANALYSIS

3.1. Atmospheric parameters

As a first step for the abundance analysis of HD 23193 and HD 170920, the atmospheric parameters ($T_{\text{eff}}$ and log $g$) were determined from Strömgren, Geneva, and Johnson (only for $T_{\text{eff}}$) photometric data, using the calibrations of Napiwotzki (1997), Kunzli et al. (1997), and Flower (1996). Using the mean values of these atmospheric parameters, the initial model atmospheres were computed by ATLAS9 (Kurucz 1993; Sbordone et al. 2004), which assumes the line formation in LTE, plane-parallel geometry. No convection was used for the model of HD 23193, whereas a convection with a mixing length parameter of 0.5 was used for HD 170920. We then produced the synthetic spectra using SYNSPEC49 (Hubeny & Lanz 1995) and its SYNPLOT interface to refine the $T_{\text{eff}}$ and log $g$ values of the stars from their observed H$_\beta$ line profiles, which are sensitive both $T_{\text{eff}}$ and log $g$. In Fig. 1, we show the observed and synthetic H$_\beta$ profile fitting for both stars. The rotational velocities of the stars were derived by comparing the observed iron lines with the synthetic iron lines calculated for various $v\sin i$ values. The derived rotational velocities are in agreement with the average of the velocities given in Table 1. In order to derive the microturbulent velocity of the stars, we derived the iron abundance [Fe/H] by using 40 unblended Fe II lines for a set of microturbulent velocities ranging from 0.0 to 5.0 km s$^{-1}$. Fig. 2 shows the standard deviation of the derived [Fe/H] as a function of the microturbulent velocity. The adopted microturbulent velocity is the value which minimizes the standard deviation. The photometric $T_{\text{eff}}$ and log $g$ pairs and final adopted $T_{\text{eff}}$, log $g$, $\xi$, and $v\sin i$ of the stars are tabulated in Table 2.

3.2. Chemical abundances from spectrum synthesis

For the spectrum synthesis, we used the atomic line list of Kilçoğlu et al. (2016) compiled from Ku-

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$^1$ IRAF is distributed by the National Optical Astronomy Observatories, which are operated by the Association of Universities for Research in Astronomy, Inc., under cooperative agreement with the National Science Foundation.

$^2$ http://www.shelyak.com/dossier.php?id_dossier=47
Table 2. Derived atmospheric parameters and rotational velocities of the stars.

| Star       | $T_{\text{eff}}$ (K) | log $g$ (in cgs) | $T_{\text{eff}}$ (K) | log $g$ (in cgs) | $T_{\text{eff}}$ (K) | log $g$ (in cgs) | $\xi$ (km s$^{-1}$) | vsini (km s$^{-1}$) |
|------------|-------------------|-----------------|-------------------|-----------------|-------------------|-----------------|------------------|------------------|
| HD 23193   | 8593              | 3.78            | 8892              | 4.16            | 8727              | 3.80 ± 0.10     | 3.3              | 37.5 ± 1.2       |
| HD 170920  | 8052              | 3.15            | 8108              | 3.12            | 8670              | 3.15 ± 0.10     | 2.6              | 14.5 ± 0.8       |

$^a$The data are from Paunzen (2015) for HD 23193, and Hauck & Mermilliod (1998) for HD 170920.

$^b$The data are from Hauck & Curchod (1980).

$^c$The data are from Høg et al. (2000).

$^d$E($B-V$) = 0.07 for HD 170920.

The abundances of the elements were adjusted until the best-fit between the synthetic and observed line profiles. The synthetic spectra were broadened by the rotational velocity, microturbulence, and instrumental profile. We computed ATLAS9 model atmosphere to derive the abundances of both stars. For the chemically peculiar Am star HD 23193, we also computed an ATLAS12 (Kurucz 2005) model atmosphere based on the derived abundances with ATLAS9, and refined its elemental abundances.

4. EVOLUTIONARY STATUS

Using the effective temperatures (derived in this study) and the luminosities (calculated from the parameters given in Table 3), we plotted the target stars on a theoretical HR diagram (Fig. 3). We used the evolutionary tracks having various masses (i.e., 2.2, 3.0 $M_\odot$) and solar metallicity to estimate the masses of the stars (Salasnich et al. 2000). For their ages, we considered the isochrones with various ages (i.e., 430, 530, 600, 665 Myr) and solar metallicity (Bressan et al. 2012). We found a mass of 2.3±0.1 $M_\odot$ for HD 23193, and 2.9±0.1 $M_\odot$ for HD 170920. The estimated age of HD 23193 is 635±33 Myr, and the age of HD 170920 is 480±50 Myr.

As shown in Fig. 3, the age (635±33 Myr) and mass (2.3±0.1 $M_\odot$) of HD 23193 shows that the star located between ZAMS$^4$ and TAMS$^5$. However, the position of HD 170920 with $M=2.9±0.1$ $M_\odot$ and $\tau=480±50$ Myr indicates that the star just left from the main sequence and it is moving into giant region. It should consequently be called a subgiant.

5. RESULTS

The derived elemental abundances for HD 23193 and HD 170920 are given in Table 4. We have indi-

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3 http://kurucz.harvard.edu/linelists/gfhyperall/gfhyperall.dat

4 Zero age main sequence

5 Terminal age main sequence
Table 3. Calculated parameters of the stars for H-R diagram.

| Star     | $m_v$   | $\pi$   | $M_v$   | BC    | $\log(L/L_\odot)$ | $\log T_{\text{eff}}$ |
|----------|---------|---------|---------|-------|-------------------|----------------------|
| HD 23193 | 5.59    | 11.04±0.31 | 0.80±0.01 | −0.085 | 1.60±0.10         | 3.944±0.005          |
| HD 170920| 5.94    | 5.31±0.45  | −0.66±0.02 | −0.014 | 2.16±0.08         | 3.916±0.008          |

Note—$m_v$, $\pi$, and BC are from Høg et al. (2000), van Leeuwen (2007), and Torres (2010), respectively.

Table 4. Derived chemical abundances with standard deviations ($\sigma$) for HD 23193 and HD 170920.

| Elements | HD 23193 [X/H] | $\sigma$ | N | HD 170920 [X/H] | $\sigma$ | N |
|----------|---------------|---------|---|----------------|---------|---|
| C        | −0.43         | 0.20    | 1 | −0.13          | 0.13    | 17|
| O        | −0.07         | 0.20    | 1 | −0.08          | 0.07    | 8 |
| Na       | 0.10          | 0.10    | 2 | −0.04          | 0.01    | 2 |
| Mg       | −0.06         | 0.15    | 5 | 0.08           | 0.30    | 4 |
| Al       | 0.55          | 0.20    | 1 | 0.00           | 0.20    | 1 |
| Si       | 0.35          | 0.17    | 3 | −0.01          | 0.19    | 3 |
| S        | 0.21          | 0.20    | 1 | 0.16           | 0.13    | 4 |
| Ca       | −0.19         | 0.24    | 5 | −0.04          | 0.14    | 24|
| Sc       | −0.10         | 0.04    | 4 | −0.06          | 0.11    | 11|
| Ti       | 0.19          | 0.17    | 16| 0.15           | 0.22    | 28|
| Cr       | 0.13          | 0.18    | 11| 0.01           | 0.14    | 24|
| Mn       | −            | −       | − | 0.03           | 0.06    | 3 |
| Fe       | 0.27          | 0.16    | 76| 0.00           | 0.07    | 40|
| Ni       | 0.42          | 0.15    | 6 | 0.16           | 0.10    | 11|
| Zn       | 0.68          | 0.20    | 1 | 0.41           | 0.15    | 2 |
| Sr       | 1.16          | 0.20    | 1 | −              | −       | − |
| Y        | 1.03          | 0.23    | 2 | 0.57           | 0.11    | 5 |
| Ba       | 1.24          | 0.33    | 4 | 0.97           | 0.38    | 4 |

Note—N is number of lines. The abundances of HD 23193 were derived from ATLAS12.

For HD 170920, all elements are nearly solar except for Carbon which is slightly underabundant, S-Ti-Ni which are slightly overabundant, and Zn-Y-Ba which are overabundant. For HD 23193, we found overabundances in Al-Si-Fe-Ni-Zn-Sr-Y-Ba, slightly overabundances in S-Ti-Cr, slightly underabundances in Ca-Sc, and underabundance in C while the other elements are nearly solar. We note that the abundance of C-O-Al-S-Zn-Sr for HD 23193 and Al for HD 170920 are derived from only one line and the values must be taken with caution. The Na abundance of both stars are derived from Na I lines at 5682 and 5688 Å. The Na I lines at 5890 and 5895 Å were not used due to the strong non-LTE effects and interstellar absorption (Takeda et al. 2009).

6. DISCUSSION AND CONCLUSION

We derived the abundances of 18 elements from the high resolution spectra of HD 23193 and HD 170920. The abundance pattern of both stars are shown in Fig. 4. Also, we estimated their masses and ages. The mass and age of HD 23193 are $2.3\pm0.1 M_\odot$ and $635\pm33$ Myr. For HD 170920, the predicted mass and age are $2.9\pm0.1 M_\odot$ and $480\pm50$ Myr.

In the pattern of HD 23193, the abundance of the elements heavier than Mn roughly tend to increase with atomic number while C, Ca and Sc elements are slightly underabundant. The chemical abundance analysis of the star thus confirms its Am characteristic. This star (with $v\sin i=37.5$ km s$^{-1}$) is one of the good examples of Am stars having relatively higher rotational velocities.

The detailed abundance analysis of HD 170920 have revealed that C and O are marginally underabundant, S-Ti-Ni are slightly overabundant, Zn-Y-Ba are overabundant and the other elements do not significantly deviate from the solar abundances. Considering the main-sequence position of the stars with $2.9 M_\odot$, this star originally comes from the $T_{\text{eff}}$-$\log(L/L_\odot)$ domain where HgMn stars are found (e.g., primary component of $\chi$ Lupi, Le Bouquin et al. 2013). The low rotational velocity, reduced light element abundances, and enhanced heavy metal content suggest that this star is most-likely an evolved HgMn star. The present abundance pattern...
thus represents residual peculiarities when it reaches to the subgiant domain.

We qualitatively compare the derived abundance pattern of the Am star HD 23193 (with 2.3 $M_\odot$, and 635 Myr) with that of predicted from Montreal code by Talon et al. (2006, Fig. 12) for a mass of 2.5 $M_\odot$. As predicted by the model at 600 Myr, we indeed derived sub-solar abundances for C-Ca, and super-solar abundances for Al-Ti-Fe-Ni in the atmosphere of HD 23193. However, the star does not show a remarkable overabundance for Cr, and it shows an overabundance for Si, which are in contradiction with the model prediction indicating nearly solar values. On the other hand, both elements Cr and Si are quite solar in the atmosphere of the A-type subgiant HD 170920. The theoretical abundances predicted by the model for a rotational velocity of 50 km s$^{-1}$ (denoted as 2.5P1 and 2.5P3 in their Fig. 12) are in better agreement with the observed abundances of HD 23193 than the model with a rotational velocity of 15 km s$^{-1}$ (denoted as 2.5P2). We thus conclude that the reduced overabundance of iron peak elements in the atmosphere of HD 23193 might be the result of its slightly high $v\sin i$ (37.5 km s$^{-1}$). In order to understand how stellar rotation reduces the effects of diffusion process, the abundance analysis of more Am stars with various $v\sin i$ are needed.

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REFERENCES

Abt, H. A., & Morrell, N. I. 1995, ApJS, 99, 135
Adelman, S. J., Gulliver, A. F., & Kaewkornmaung, P. 2015, PASP, 127, 340
Adelman, S. J., & Unsuree, N. 2007, Baltic Astronomy, 16, 183
Bressan, A., Marigo, P., Girardi, L., et al. 2012, MNRAS, 427, 127
Burwell, C. G. 1938, ApJ, 88, 278
Çalıskan, Ş., Kılıçoğlu, T., Elmash, A., et al. 2015, New A, 34, 6
Cowley, A., Cowley, C., Jaschek, M., & Jaschek, C. 1969, AJ, 74, 375
Cowley, A. P. 1968, PASP, 80, 453
Duflot, M., Figon, P., & Meyssonnier, N. 1995, A&AS, 114, 269
Floquet, M. 1970, A&AS, 1, 1
