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A More Powerful Approach For Studying the Abundances of Chemically Peculiar Stars

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Abstract
We investigate those stars in which convection and then radiation transports energy from their cores to their envelopes and atmospheres. In our previous generation of stellar analyses, we used the spectroscopic technique of fine analysis with optical region spectra mainly from the Dominion Astrophysical Observatory (DAO) with R = 67000 and S/N values close to 200 to obtain the elemental abundances of non-magnetic, solar-composition and peculiar B, A, and early F-stars and differential Strömgren photometry of the magnetic Chemically Peculiar stars from the Four College Automated Telescope. Our new analyses of high-dispersion (R = 80000) Chiron échelle spectrograms now being obtained with the 1.5-m telescope at Cerro Tololo Inter-American Observatory in Chile were coadded to achieve high S/N (>500) are beginning to enable us to study in much greater detail many properties of these stars. For example, it should be possible to investigate in greater detail the abundance differences between stars. Studies of peculiar A stars might reveal the effects of non-solar abundances on their stellar evolution. It is important to determine how homogeneous with distance from the stellar centers are the chemical compositions of these stars which might be seen in their photometric variability. We summarize the abundance studies of Chemically Peculiar stars putting their results into the broader context of stellar evolution.

Key words: techniques:spectroscopy – star:chemically peculiar – stars:abundances

1 Introduction

One way to classify stars is to compare the composition of their atmospheres which are found from analyses of spectrograms including lines originating from both ions and neutral atoms of various elements. The chemistry of stellar atmospheres is derived from the spectral lines and stellar parameters. Most stars have compositions similar to that of the Sun. However, the spectra of some stars contain spectral lines that are attributed to heavy elements such as mercury, manganese and the Rare Earth Elements which indicate that these elements are surprisingly abundant in the stellar atmospheres of chemically peculiar stars. The differences in the chemistry of peculiar stars are explained by processes that change the chemistry of the stellar atmospheres. One such process is radiative diffusion from the surface of the core through the upper atmosphere. This process counteracts the gravitational sinking of heavy metals toward the center. Once they reach the surface the atmosphere becomes rich in heavy elements (e.g. Michaud 1970).

We are interested in the middle B to the early F Main Sequence stars (see e.g. Yüce & Adelman 2014 for spectroscopic aspects; Yüce et al. 2020 for photometric aspects). These stars have some of the most quiet stellar atmospheres. Some basic questions must be answered to achieve a physical understanding of the relations of the various kinds of stars in this important part of the Hertzsprung Russell (HR) Diagram. Our stars have cores in convective equilibrium and atmospheres in radiative equilibrium. In convection the energy exchange involves atoms and ions. At any given point a slightly hotter particle moves towards outer space while a slightly cooler one move towards the stellar core. In radiative transfer it is more and less energetic photons exchanging places. In the middle F stars, convective processes replace radiative processes as the major means of transporting energy in the stellar atmospheres and envelopes while the cores become radiative.

The study of the spectra of Chemically Peculiar (CP) stars is also important in terms of the stellar evolution. Even CP stars spend most of their lives as a Main Sequence Stars. At this stage, Hydrogen atoms in the core undergoes fusion. Not much differences occur in the composition other than the changes in the abundances of light atoms. However, at some stage, processes like diffusion, convection, and rotation create new conditions under which the chemistry of the stellar atmosphere changes. The spectra of the CP stars provide experimental data that bear some information about the peculiarities.

2 History

About 1900 astronomers realized that some A type stars had peculiar spectra (Maury 1897; Cannon 1901; Lockyer & Baxandall 1906). Very intense lines belonging to unexpected elements were identified. For example, Baxandall (1913) found spectral lines of the singly ionized Rare Earth Element Eu II in the spectrum of α^2 CVn. The phenomenon of spectrum variability was also found early (Ludendorff 1906; Belopolsky 1913) as was that of light variability (Guthnick & Prager 1914).

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In 1933 Morgan showed that the relatively brighter young stars with spectral peculiarities can be regarded as a well-defined group with members showing spectral anomalies apparently correlated with the surface temperature.

Early analyses pertaining to the elemental abundances of peculiar A stars started with the work of Bunker (1941) and continued with Aller (1947). Later, other investigators (e.g. Adelman 1987; Adelman et al. 2001; Yüce et al. 2011) analyzed the spectra of individual non-magnetic CP stars and showed that the overabundances of some heavy elements inferred from the enhanced spectral lines are real. These investigators also added details about the abundances of the elements of which lines could be seen only on high dispersion spectrograms.

The existence of magnetic fields in some CP stars was discovered by Babcock (1947) who observed the Zeeman components of the line profiles of circularly polarized spectra of the Ap star 78 Vir. Babcock (1958) later published a catalogue which he summarized observations of the magnetic fields of CP stars. Many Ap stars were found to possess measurable magnetic fields when their spectral lines are not greatly broadened by rotation. Further all spectral magnetic fields are variable, some being periodic. These magnetic periods are related to the light and spectrum variabilities. To explain the magnetic phenomena several models have been proposed. Among these, the oblique rotator model (Stibbs 1950) has been the most successful and received strong support from the measurements of the line widths of the periodic Ap stars. A series of papers entitled "The FCAPT *uvby* Photometry of the mCP Stars" by Adelman & his collaborators (e.g. Pyper & Adelman 2017; Dukes & Adelman 2018) discuss mCP stars that have spectral types between B2 and A2 and are on or near the Main Sequence of the HR diagram. The magnetic fields and light curves of mCP stars vary periodically within a range from about one-half day to decades. The photometry does not show any significant correlation between the amplitudes of variation in the *uvby* filters and the periods. The amplitudes have a Gaussian distribution, but each band has a slight skewness to large amplitudes (Yüce et al. 2020). Adelman (2002) found some evidence for the expectation that as mCP stars move away from the Zero Age Main Sequence (ZAMS) their rotational velocities decrease. He noticed that many, but not all, of the most rapidly rotating mCP stars are close to the ZAMS and some of the least rapidly rotating are the furthest from the ZAMS.

During the past 60 years several hypotheses have been advanced to account for the spectra of various CP stars. These involve both nuclear and non-nuclear processes. For example, Fowler et al. (1965) proposed that in the central cores of these stars the process of nucleosynthesis could still be operating as a continuation of the main sequence phase of evolution. Guthrie (1967) reviews the possibility of a surface contamination of the normal star by a supernova companion. Michaud (1970) discusses the possibility of an outward diffusion induced by radiation pressure. Another mechanism of a selective magnetic accretion of interstellar matter was suggested by Havnes & Conti (1971). The particulars of the processes involved in all those hypotheses can be extremely complicated. To validate of these hypotheses requires a variety of observational data besides the abundance anomalies themselves.

The light variability of magnetic CP stars have been studied in detail, especially over the last 30 years, based on systematic ground-based observations (e.g. Adelman et al. 1992; Adelman 2004a). The observed changes are accepted as the observational results of the rotational movements of stars with inhomogeneous surface element distributions. The 'rigid oblique-rotator' model, proposed by Babcock (1949) and developed by Stibbs (1950), can be used to explain the photometric variability of mCP stars (e.g. Pyper 1969; Pyper & Adelman 2021). The magnetic field is assumed to be locally constant (Adelman et al. 1992). While such variability observed in solar-like stars is due to the activity created by the spots formed as a result of dynamo motion in the stellar interior, the physical nature of the photometric variability observed in mCP-type stars is due to the spotted regions having different sources of opacity compared to other regions (Krtička et al. 2012).

Space telescopes have become important tools in the processes of determining the rotation periods of stars, as they may produce highly sensitive, uninterrupted, long-term photometric data. For CP stars, studies based on space satellite photometry included those of CoRoT, Kepler, Gaia, TESS) (e.g. Lüftinger et al. 2010; Paunzen et al. 2015; Hümmerich et al. 2018). Recently, Hümmerich et al. (2018) detect observed periods ranging from 0.84 d to 9.6 d, and effective amplitudes ranging from 0.6 mmag to 90.5 mmag based on Kepler observations of 53 confirmed or candidate mCP stars. Their targets populate the whole range from the ZAMS to the TAMS and are distributed in mass interval from 1.5 $\mathrm{M}_{\odot}$ to 4 $\mathrm{M}_{\odot}$.

3 Chemical/Spectral Classification

The spectra of CP stars are identified by anomalously strong (or weak) absorption lines corresponding to some elements that are not usual in the spectra of many other stars of the same physical parameters. The classification of these stars started over a hundred years ago and still is in progress with each successive classification tending to being more complicated than the previous one. Cannon (1901) appended a *p* (for peculiar) to the approximate spectral type. Morgan (1933) recognized that these stars, ordered by predominant peculiarity (Mn, Si, Eu, Cr, Sr), formed a luminosity-excitation temperature sequence. Jaschek & Jaschek (1958) added some details to the sequence and showed that the colors of the stars could be correlated with their type.

The main spectral characteristics enables us to distinguish the various classes of the Chemically Peculiar stars. Preston (1974) divided the CP stars into four groups: A*m* stars (CP1), Ap stars (CP2), HgMn stars (CP3), and He-weak stars (CP4). Other studies added other groups such as He-strong stars and λ Bootis stars (Sargent 1967). Kurtz (2000) gave the subgroups of CP stars as a function of temperature. These subgroups are magnetic subgroup (mCP) and non-magnetic subgroup. Adelman et al. (2003) showed that the A*m* and the HgMn stars formed a temperature sequence in the HR diagram with the mercury abundances changing as a function of effective temperature.

Stars without chemical peculiarities are regarded as chemically normal. Adelman (2004b) gave a brief description of normal A stars which have elemental surface abundances close to that of the Sun (supergiants and white dwarfs excepted). Chemically normal stars are also known not to have a detectable magnetic field, usually have an equatorial velocity $>$120 km/s, lack emission lines in their spectra, are constant photometrically, and do not to participate in a substantial mass exchange event with a companion.

Do the CP stars have other heavy elements, like Hg, in their atmosphere that with greater than solar abundances? Yüce & Adelman (2014) derived the detailed chemical compositions of non-magnetic B, A, and early F type-stars especially for 32 elements to investigate the relationship between normal and non-magnetic CP stars. The range of the abundance anomalies for a given element tends to be smaller among the A*m* stars than that among the HgMn stars. Chemical peculiarities are visible in the iron group and heavy elements of the Main Sequence A*m* stars and in the light elements of the evolved normal stars of our analyses based on DAO spectra. Most of the observed elemental abundances with Z $>$ 22 are overabundant for the A*m* stars (Yüce & Adelman 2018).

4 The HR Diagram Searching on the Peculiarity

The HR diagram based on that of Adelman et al. (2003) indicates the positions of the HgMn and the A*m* stars analyzed by Adelman and his collaborators. It shows that the coolest HgMn stars and the hottest A*m* stars are on the same stellar evolutionary tracks and hence the former must evolve into the later. The explanation of the dividing line between these two types of non-magnetic chemically peculiar stars where the Hg abundances suddenly change their degree of overabundance is a major test of the theories which try to explain the anomalous abundances of such stars. It most likely is due to diffusion. Some other important relationships are found which can also serve as tests of theories which purport to explain the properties of these stars. Additional stars have been added by Yüce et al. (2011). We add the theoretical evolutionary tracks from Claret (2004) for several stellar masses in the region of 1.5-6 $\mathrm{M}_{\odot}$ and the locations of the peculiar stars and the stars we examined in this work (see Figure 1). These tracks were calculated for a solar metallicity (Y $=$ 0.300 and Z $=$ 0.020) with an overshooting parameter $\alpha_{\rm over}$ $=$ 0.20. The names of individual stars and the corresponding derived effective temperature and surface gravity are given in Table 1 of Yüce & Adelman (2014) along with references to the optical region abundance analyses. Also shown are figure labels for additional stars.

We also compared the evolutionary paths of 11 δ Del (HD 197461, HR 7928) and 20 CVn (HD 115604, HR 5017) which are often considered to be stars whose chemical compositions are similar to those of A*m* star. In this work the atmosphere parameters ($\mathrm{T_e}, \log g$) were derived for 11 δ Del (7012 K, 3.4) and for 20 CVn (7294 K, 3.5) from the Strömgren photometry using the UVBYLIST code of Moon (1985) and homogeneous mean *uvby*β data of Hauck & Mermilliod (1998). The synthetic colours were taken from the grid computed for [M/H] $=$ 0 and microturbulent velocity ξ_1 $=$ 2.0 km/sec (Castelli & Kurucz 2003, 2006). Lemke (1989) finds that for main-sequence stars the mean accuracy of the atmospheric parameters are $\pm$150 K in effective temperature and probably not larger than $\pm$0.2 dex in surface gravity using Strömgren color indices. According to Napiwotzki et al. (1993), errors on effective temperature are of the order of 2% for $\mathrm{T_e}$ $<$ 10000 K. The accuracy of surface gravity ranges from about 0.1 dex for early A-type stars to about 0.25 dex for hot B stars. To refine the atmosphere parameters for most of stars investigated with DAO and TUG data, Adelman and his collaborators obtained the parameters also from a fit of theoretical and observed Hγ profiles and fluxes while obtaining ionization equilibrium. In this work for Figure 1 we fix the errors on log $\mathrm{T_e}$ and log g to be 0.01 and $\pm$0.15 dex, respectively. We anticipate a decrease in the errors in the effective temperatures and surface gravities when The Citadel Automated Spectrophotometer (TCAS) becomes operational (Adelman et al. 1995).

Comparisons with the theoretical evolutionary tracks of Claret (2004) in the log g and $\log \mathrm{T_e}$ diagram lead to the following conclusions:

a. Metallic line stars (A*m*) of our DAO series have masses between about 2 and 3.0 $\mathrm{M}_{\odot}$ while the HgMn stars have values between 2.5 and 5.0 $\mathrm{M}_{\odot}$. Both HgMn and A*m* stars occur along the same evolutionary tracks for 2.5 to 3 $\mathrm{M}_{\odot}$ stars. Most of the A*m* stars evolved from the coolest HgMn stars.
b. HR 6455 (A3 III, log $\mathrm{T_e}$ $=$ 3.94, log g $=$ 3.25) is the hottest and most highly evolved A*m* star of the sample, Its mass near is 3 $\mathrm{M}_{\odot}$. Its abundance pattern shows that it is the most rare earth rich A*m* star (Yüce et al. 2011).
c. Adelman & Yüce (2010) determined the effective temperature and surface gravity of ν Cnc (A0 III) and of 11 Per (B8 IV) using the spectra taken from the Coude Échelle Spectrograph of the 1.5-m Russian-Turkish Telescope of the TÜBİTAK National Observatory (TUG) as (10250 K, 3.60) and (14054 K, 4.15), respectively. The stars exhibit Hg II λ3984 lines and somewhat diverse abundance patterns. The observed values obtained from both the DAO series of Adelman (1989) and Adelman & Yüce (2010) show ν Cnc is located between the other HgMn stars and the hottest A*m* stars. Here 11 Per, which is close to the hottest HgMn stars and ZAMS, is the unevolved star of the sample while ν Cnc is most evolved HgMn star.
d. θ Aql B (B9.5 III) is near the boundary of the HgMn and A*m* stars. It has not begun to evolve away from the ZAMS which is in agreement with the abundance anomalies obtained from high resolution analyses of θ Aql B and its being a weak metallic line (A*m*) star (Adelman et al. 2015). Its abundance characteristics are similar to most of hotter A*m* stars in Table 1 of Yüce & Adelman (2014) which are underabundant in Ca, nearly solar in Fe and Si, and overabundant in S, V, Ni, Zr, and Ba.
e. The effective temperature and surface gravity estimates indicate that both components for δ Del are evolved from ZAMS, consistent with our HR Diagram result obtained from non-magnetic CP stars and normal stars of DAO series. δ Del, 20 CVn and δ Sct are located on the coolest side of the DAO A*m* stars.
The metallicity of prototype δ Sct is greater than the solar value and its abundance pattern is similar to those of A*m*-F*m* type stars (Yushchenko et al. 2005). Reimers (1976) reported that both components of the system have identical peculiarities and are close together in the HR Diagram and hence are in similar evolutionary stages. Recently, Gardner et al. (2018) point out the component stars have evolved to late A- or early F-type positions and were most likely originally late A-type stars.

5 Conclusion

When the effective temperature, surface gravity, and elemental abundance distributions are investigated, some stars have similar positions in the HR Diagram. However, the chemical composition may differ in some stars with similar effective temperatures and surface gravitational fields. The angular momentum/velocity profiles in the interior regions of stars can

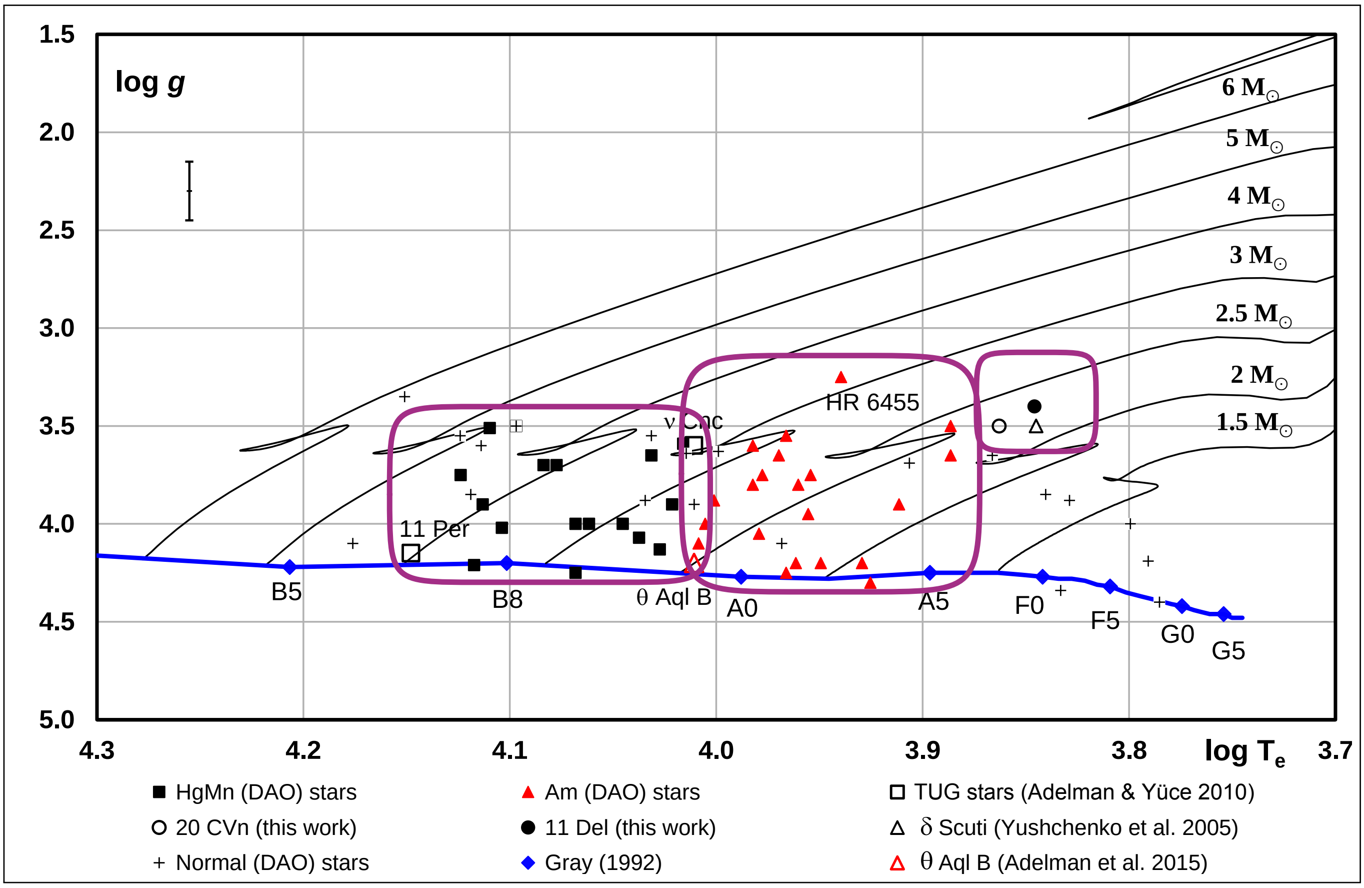

Figure 1. Locations of 11 Del and 20 CVn from this work, along with HgMn and A*m* stars and normal stars from the spectral analyses of our DAO series, on the theoretical evolutionary paths of Claret (2004). The solid line at the bottom represents the empirical Main Sequence stars of Gray (1992).

lead to somewhat different element abundances. We found that the physical properties changes, and chemical structure separation occur close to log $T_e = 3.88$ and 4.02 K. The theory of CP stars in these regions needs to be modified to predict this important finding.

Adelman et al. (2003) demonstrated that the HgMn and A*m* stars occur on the same evolutionary tracks in the mass range of 2.5 to 2.9 $M_\odot$ with the HgMn stars being closer to the ZAMS and the A*m* stars simultaneously populating the same evolutionary tracks. The boundary between the two types of non-magnetic CP stars is the locus on the HR diagram where the Hg abundances changes from greatly overabundant in the HgMn star region to not detectable in the Am star region. A possible explanation is this is where on the hot side of the boundary the Hg atoms in the evolving cool A*m* stars are first substantially pushed by diffusion from the stellar interior into the surface layers so that their Hg abundances are greatly increases. Similar loci for other elements should also be found by investigating the spectra of HgMn and A*m* stars if this idea is correct.

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