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Fundamental Atmospheric Parameters of B stars in the Alpha Persei Open Cluster

Mémoire de fin d'etudes

Paramètres Atmosphériques Fondamentaux Des Étoiles B Dans l'Amas Ouverts Alpha Persée

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I dedicate this thesis to my Mom and Dad.

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Abstract

It is important to understand stellar evolution as well as the chemical composition and structure of the Galactic disk, in which B stars in open clusters play a major role as they are of the most massive and brightest objects in these clusters. The fundamental atmospheric parameters ($T_{\rm eff}$, log g) of the B stars in the Alpha Persei open cluster (190pc, 50Myrs) have been determined using the Strömgren $uvby - \beta$ photometric system, with a calibration technique by Napiwotzki et al. (1993)[65]. The method is based on fitting spectral lines of fundamental stars to synthetic spectra based on Kurucz (1979)[46] LTE model atmospheres. An echelle spectum of one of the cluster's B stars has been obtained and reduced, however without being used for analysis due to its low S/N quality and technical difficulties. Comparison between the determined parameters for our sample B stars to those obtained by previous work, allows us to put constraints on the photometric versus spectroscopic methods used to calculate the fundamental parameters of stars. Specifically, the case of emission-lines Be stars and fast rotating stars ($v$sin$i \geq$ 200km/s) whose color indices and H_β absorption lines can be contaminated by emission, as well giants and binaries whose thin atmospheres (relative to the stars radii) cannot be simply modeled using LTE's plane parallel and spherical symmetry due to the presence of convection and mixing processes, as well as mass losses in their atmospheres.

Key-words:

B stars, Open Clusters: Alpha Persei, Effective Temperature, Surface Gravity, Strömgren Photometry.

Résumé

Il est important de comprendre l'évolution stellaire ainsi que la structure et la composition chimique du disque galactique où les étoile B des amas ouverts jouent un rôle primordiale, étant les membres les plus massifs et les plus lumineux de ces amas. Les paramètres atmosphériques fondamentaux (T_{eff} et log g) des étoiles B de l'amas ouvert Alpha Persée (190pc, 50Myrs) ont été dérivés à partir des données photométrique *uvby*-β de Strömgren suivant une technique de calibration développé par Napiwotzki et al. (1993)[65]. Cette méthode se base sur la simulation des ligne spectrales observées d'étoiles fondamentales par des spectres synthétiques calculés des modèles d'atmosphère en ETL de Kurucz (1979)[46]. Nous avons obtenu et essayer de réduire un spectre échelle de l'une des étoiles de l'amas, toutefois sans possibilité d'analyse au vu du rapport S sur B tros bas et de difficultés techniques trop importante.
La comparaison des paramètres obtenus de notre échantillion d'étoiles B à ceux obtenus par d'autres auteurs, nous permet de mieux contraindre la comparaison des méthodes photométriques et spectroscopique utilisées pour déterminer ces paramètres; plus particulièrementle cas des l'étoiles Be et des rotateurs rapides ($v$sin$i \geq 200$ km/s) où les indices de couleurs et la raie d'absorption H_β se trouvent contaminés par de l'émission, ainsi les géantes et les binaires où les atmosphères ténues et minces ne peuvent simplement êtres modelées pas des modèles plan-parallèles, à symétrie sphérique et à l'ETL, dû à la présence de convection, de processus de mélange et de pertes de masses importantes.

Mots Clés: Étoiles B, Amas Ouverts: Alpha Persée, Température Effective, Gravité de Surface, Photométrie Strömgren.

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Chapter 1

Introduction

1.1 Importance of Studying B Stars.

B stars are a spectral class of stars with masses ranging between $2M_\odot \leq M \leq 16M_\odot$[1] and surface temperatures between 10,000K (B9) and 30,000 K (B0). They emit most of their radiation energy in the ultraviolet (UV) through the optical part of the electromagnetic (EM) spectrum, according to Planck's function of a blackbody:

$$B_\lambda(T) = \frac{2hc^2/\lambda^5}{e^{hc/\lambda kT} - 1} \tag{1.1}$$

which corresponds to the spectral irradiance emitted by a blackbody (in erg s^{-1} cm^{-3} sr^{-1}) as a function of wavelength λ at an effective temperature T. Figure (1.1) shows an example of the spectrum of a blackbody at an effective temperature of 25000K.

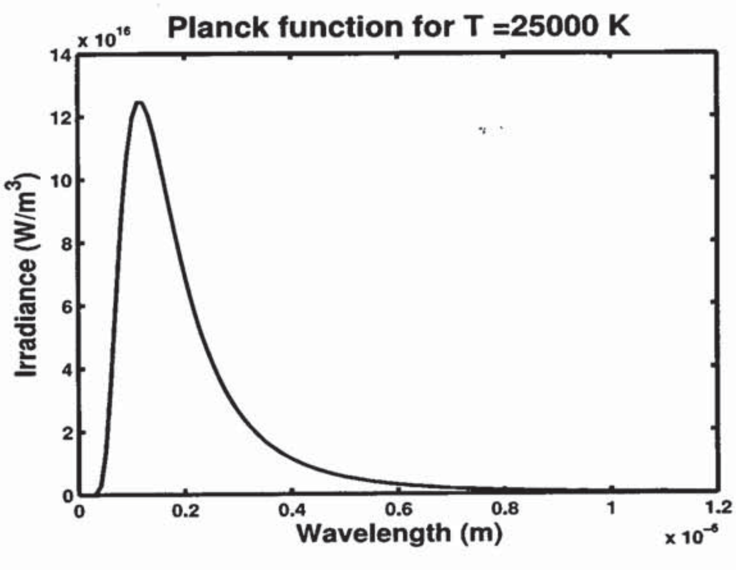

Figure 1.1: Blackbody spectrum of a B star of effective temperature $T_{\text{eff}} = 25000$K.

[1]M⊙(Solar Mass) = 1.989 x10^{33} g.

O, B and early type A stars play a central role in astrophysics studies, since they are of the most massive and luminous objects, which are at the focus of attention in several fields of astrophysics. The high-speed outflows through their stellar winds and supernova ejecta and the intense ionising radiation field emitted from massive stars can lead to the energetic and chemical enrichment, and the dynamic structuring of the surrounding interstellar medium. In starburst galaxies, the energetic feedback from massive stars can lead to the large-scale outflow of the interstellar medium in the form of a galactic wind. In addition, massive stars are the main sources of ionising photons creating H II regions.
Of those objects, Main Sequence (MS) B and early type A stars have atmospheres which can be well represented by simplifyed assumptions of Local Thermodynamic Equilibrium (LTE)[2], hydrostatic and radiative equilibrium and plane parallel geometry since convection is apparently absent, and stellar winds are very weak and many appear to have little or no photospheric microturbulence. Thus, precise determinations of their individual properties should be possible through the application of currently available and well developed astrophysical tools (Fitzpatrick E.L. & Massa D., 2005)[29].

In the sections below, the basic characteristics and properties of B stars are presented, mainly their chemical composition and its peculiarities, their rotational velocities and their fundamental atmospheric parameters as well as the importance of studying each of these parameters for these types of stars.

1.1.1 Chemical Composition

As rather young objects ($\sim$ 10Myrs), the chemical composition of (MS) B stars should reflect the present day stage of chemical evolution of the Galaxy (Luck et al., 2000)[51].
From a spectral point of view, the Balmer series of hydrogen lines are strong in B type stars, in addition to the presence of helium neutral lines. The lines of ionized Si (SiII & SiIII) are used to determine subclasses of B stars, while magnesium lines are used to distinguish between their temperature classes (Gray, Richard O. & Corbally, C. J., 2009)[32].

Chemical composition of (MS) B stars in the solar vicinity have shown inhomogeneity as well as underabundances with the respect to the solar values (Grevesse & Sauval, 1998)[33]. Al, C, N, Mg, Fe, and S elements are underabundant, while O and Si abundances are similar to solar values within uncertainties (Simón-Díaz et al., 2010)[81].

The abundances of the chemical elements, as derived from the study of stellar photospheres, have their origins in processes related to the chemical composition of the star-forming cloud, the residue of nuclear processing from within the stellar core that is dredged up to the photosphere, and physical processes within the stellar photosphere/envelope that may preferentially segregate ions or isotopes of particular elements. The first two processes have lead to our understanding of chemically normal, or solar-composition stars, while the third is considered to be responsible for creating Chemically Peculiar (CP) spectra (Adelman et

[2]LTE is the condition in a star wherein the distance over which the temperature changes significantly is large compared to the mean free path of particles and photons. In other words, it is the condition in which the material is in equilibrium with the local kinetic temperature, and that the radiation does not deviate much from its thermodynamic value $B_\nu(T)$.

al., 2004)[5].

Chemical peculiarities in B-type stars are classified into 4 sub-classes:

- **He peculiar stars:** which show periodicity in He line intensity variations (Steinitz et al., 1996)[85] are divided into:
  - He poor (B3V-B7V): In cooler B-stars, where radiation pressure on He atoms is small compared to other elements, which therefore sinks inward (Radial diffusion theory).
  - He rich (B0V-B3V): In hotter B-stars, present for narrow ranges of rotational speeds and densities.

- **Mercury Manganese (HgMn) stars:** In some late B stars, enhanced Hg and Mn abundances and several of the heaviest elements (Pt, Au, Hg, Tl, Bi) can be overabundant relative to solar values by as much as 5 orders of magnitude. These stars usually have low rotational velocities and weak or non existing magnetic fields (Dworetsky et al., 1993)[23].

- **Magnetic Bp stars:** They have stronger magnetic field strength ($\sim$ 3.35T) than normal B stars (Babcock, H. 1960)[7] and slower rotational velocities. They show over abundance of some metals such as Sr, Cr, Eu, Nd and Pr.

- **Be stars:** A Classical Be star (CBe) is a rapidly rotating B-type star with an equatorial circumstellar decretion disk, which is not related to the natal disk the star had during its accretion phase (Porter & Rivinius, 2003)[73]. Struve (1931)[88] suggested that rapidly rotating single stars of spectral class B are unstable, which eject matter at the equator, thus forming a nebulous ring which revolves around the star and gives rise to emission lines, which are then called Be stars. They have prominent emission lines of Hydrogen in their spectra as well as other atomic ions (H_α, H_β, H_γ, H_ϵ, HeI, CII, NII,II, ..). Emission lines coming from a circumstellar disk around the central B star which emitting in the UV (Lymann continuum), ionizes the disk so it reemits in the visible radiation.

1.1.2 Rotational Velocities

Unlike low-mass stars that can lose their angular momentum early in their main sequence phase, massive O and B stars are usually born with a large initial angular momentum that can last through-out their relatively short, core hydrogen-burning phase. The spin evolution of a single, nonmagnetic, massive star is driven by angular momentum loss in the stellar wind, a net increase in the moment of inertia, and an increase in stellar radius (W. Huang & D. R. Gies, 2006)[39].

Cluster B stars are faster rotators than field B-stars, due to the evolutionary spin-down of field stars with time (Abt et al., 2002)[4] or due to variation in density of birthplace environment (Strom et al., 2005)[86]. Studying the rotation of (MS) B stars in open clusters is important, since it shows how fast stars rotate close to their ZAMS, representing both the starting point of a relatively simple (MS) stage and the end of a pre-(MS) stage, in order to understand the role of angular momentum in stellar evolution.

The mean projected rotational velocities "$v\sin i$" of the different temperature and luminosity sub-classes of B stars as worked out by Abt et al. (2002)[4] is presented in table (1.1) below:

$v\sin i$ (km/s)					
Type	V	IV	III	II	I
B0 → B2	127	84	111	62	69
B3 → B5	108	94	116	65	38
B6 → B8	152	120	74	36	52
B9 → B9.5	134	99	77	20	26

Table 1.1: Mean projected rotational velocities $v\sin i$ of different temperature and luminosity subclasses of B-type stars, after Abt et al. (2002).

1.1.3 Fundamental Atmospheric Parameters

The potential applications of the study of fundamental parameters of B stars (effective temperature "$T_{\rm eff}$" and surface gravity "log g") of different evolutionary statuses and luminosity classes is manyfold. For example, determining the stellar effective temperature $T_{\rm eff}$ is essential for the subsequent determination of the stellar radii and luminosities and thus for accurate distance determinations. Also, the primary method for deriving stellar masses is via a determination of their surface gravities log g.

Precise determination of $T_{\rm eff}$ of stars are critical for a variety of reasons, not only for direct applications such as comparisons of isochrone calculations to observed color-magnitude diagrams, but also in more indirect applications such as determinations of chemical abundances. In addition, accurate effective temperatures are needed to construct HR diagrams to test the theories of stellar structure and evolution. Effective temperatures are also necessary to study the physical processes in the stellar atmospheres, such as non-radial pulsations or stellar winds (radiative forces; changes in ionization). Regarding the stellar winds, the effective temperatures are particularly useful in discussing terminal velocities, mass loss rates, the bi-stability jump, and the wind momentum luminosity relationship (Kudritzki et al. 2003[45]; Crowther et al. 2006[19]).

$T_{\rm eff}$ and log g for B stars can be derived by means of indirect methods based on the comparison of observed quantities (such as the color indices, flux distributions and line profiles) with the corresponding computed synthetic ones by using model atmospheres for the stars. The effective temperature and gravity of the model which gived the best representation of the data are said to be equivalent to the corresponding value of the star.

For example, Becker & Butler (1990)[10], showed that Silicon lines (SII, SIII and SIV) are good diagnostics because of their sensitivity to $T_{\rm eff}$ in B-type stars. Increasing $T_{\rm eff}$ in late B-type temperature regime, results in opposite effect regarding the Equivalent Width (EW) of SII and SIII lines. In the higher temperature regime (early B-type stars), a similar effect can be observed between SIII and SIV.
Using ionization balance between the two consecutive stages of Si (SIV/SIII for early B-type stars, and

SIII/SII for mid and late B-type stars) rather than single lines, temporarily eliminates the effect of Si abundance, which affects all Si lines in the same way.
A similar behavior can be observed between the different ionization stages of Helium, i.e. HeI and HeII which are mainly only observed in the earliest B-type stars, while HeI on its own provides us with a good temperature diagnostic for the latest B-type stars, due to its strong reaction to changes in temperature.

As for the surface gravity log g, the wings of Balmer lines are Stark-broadened[3], and therefore they strongly react to changes in electron density n_e which is (almost) directly coupled to the gravitational acceleration,
[4]log g, provided that the centrifugal acceleration and the (photospheric) radiation pressure are known and correctly calculated, respectively. A change in gravity will have an influence on the wings of the Balmer lines (mainly H_γ and H_δ, as well as H_β if the mass loss rate $\dot{M}$ is not too large) since these are strong lines which are formed higher in the stellar atmosphere (see figure (1.2) below).

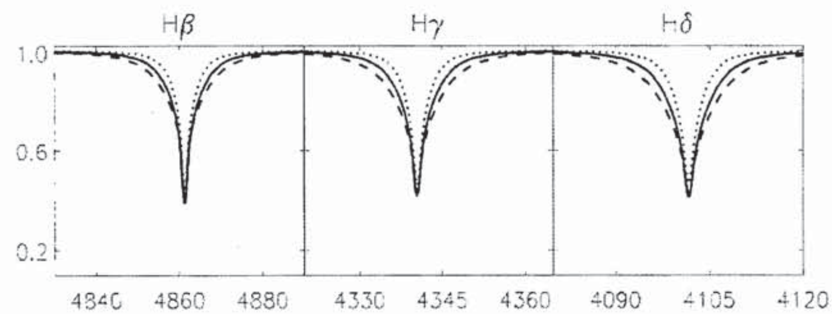

Figure 1.2: Influence of the surface gravity on synthetic Stark-broadened wings of H_γ, H_δ, and H_β. Full line is for $T_{\rm eff}$ = 22000K, log g = 3.5. Dashed and dotted lines for: $\triangle$log g = +0.5 dex and $\triangle$log g = -0.5 dex respectively.

For fast rotating objects (like some B stars), the gravity derived from Balmer wings should be corrected to account for the centrifugal acceleration due to rotation as follows: $\log g_c = \log g + (v \sin i)^2 / R_*$, where R_* is the radius of the star.

1.2 Open Clusters

Open clusters (hereafter OC) are ensembles of usually several hundred to a few thousand member stars, which are located within a volume of roughly 5 to 20 pc across. Most open clusters are significantly younger than globular clusters GC, with ages ranging from approximately 10^6 to 10^9 yrs. Another difference between OC and GC is the fact that OC are mainly located within or near the Galactic plane where there

[3]The linear Stark effect is the most important pressure broadening mechanism for hydrogenic atoms (i.e., atoms with degenerate levels) in hot stellar atmospheres, caused by the Coulomb interaction of emitting atoms with charged particles, or particles with a strong permanent electrical dipole moment.
[4]$g \equiv GM/R^2$.

is an abundance of dust and gas, whereas GC show a distribution similar to the one of the Galactic Halo. Approximately 1700 OC are known (Diaz et al., 2002)[22], half of which have been observed at least in one photometric system (UBV, Strömgren, Geveva, etc) (Mermilliod, 1999)[55].

At a first glance, star clusters are ideal objects for [5]IMF (Initial Mass Function) determinations. With all members of a cluster (more or less) formed at the same time in the same cloud and in the same volume, studies of clusters might reveal variations of the IMF with parameters such as age, location in the Galaxy and chemical composition. Therefore the study of the member stars in a cluster, is important for determining its IMF as well as its PDMF (Present Day Mass Function). In order to compute stellar masses, one would have to determine the distance, the absolute luminosity, etc. of each star individually, which is easier to do for cluster stars. Unlike field stars whose "birthplaces" and circumstances of formation are generally unknown, cluster stars are roughly at the same distance from the Sun and of similar chemical composition and in addition the difference in the apparent magnitudes between the member stars of the cluster is basically due to their different masses. Comparing the "standard" Hertzprung-Russel HR diagram, derived from nearby stars with sufficiently well known distances, with the measured HR diagram of a star cluster, provides a reliable method to determine the distance of the cluster. Comparing its HR diagram with stellar theory provides a reasonable way to estimate the age of the cluster.

In addition, reliable astrophysical and structural parameters of OC are an excellent source of information for interpreting their dynamics. From a dynamical point of view, it is found that high mass stars in an OC are concentrated toward the center of the cluster whereas the distribution of lower mass stars has a higher density toward the outer parts of the cluster, which is known as mass segregation, occuring at the formation time of the stars (Raboud & Mermilliod, 1998b)[76]. However due to the evolution of the most massive stars in the early stages of cluster lifetime, the entire cluster may be mixed up in such a way that a phase may follow in which all stars are distributed homogeneously (Lamers & Gieles, 2006)[48]. After that, the dynamics of the cluster lead to another concentration of the massive stars around the gravitational center of the cluster, whereas the lower mass stars form a corona around this region, which may extend as far as the tidal radius of the cluster.

In addition, the OC system is of great value for the study of the Galactic dynamics, because they span a relatively wide range of ages, that can be determined with more precision than any other spiral arm tracer. They are the key objects to understand the motion of spiral arms of the Galaxy and moving groups of stars, to derive the rotation curve and distinguish between star formation processes (Dias et al., 2002)[21]. The fundamental physical parameters of OC, such as distance, reddening, age, and metallicity are necessary for studying the Galactic disk. The Galactic, radial and vertical, abundance gradient can also be studied by studing abundances in OC (Hou et al., 2000)[38].

[5]IMF is a function which describes the initial dependence of stellar numbers in a population from their masses.

1.2.1 B Stars in Open Clusters

Since B (and even more the hotter O) stars have extremely high luminosities, their nuclear fuel is quickly exhausted, i.e., they are extremely short lived. Therefore, they rarely get the chance to move far from their birthplaces in the galactic plane and thus they are often found in the so called OB-associations as well as young OC.

A lot of work has been done on OC in the literature, and in particular the work on B stars in OC has taken the attention of many authors. On one hand, they are not found in GC, as these latter clusters are much older and evolved than OC, thus all their B stars must have evolved off the MS or already died. On the other hand, studying the fundamental parameters, in addition to the chemical and physical properties of cluster B stars is important to be able to compare them to field B stars of the same spectral types, and thus to put constraints on the evolutionary tracks of both.

Of the different and numerous works done on the different parameters and characteristics of B stars in OC, we mention the following:

- About 20% of B stars are Be along the B0-B8 spectral range (Zorec et al., 1997)[91]. As the formation and evolutionary enhancement of the Be phenomena is still questionable, Fabregat (2003)[24] studied the frequencies of Be stars in OC of different ages and compared that to their field population in the Galaxy, as well to their populations in the Large and Small Magellanic Clouds (LMC) and (SMC) respectively. He found that in OC that are rich in Be stars (NGC 884, NGC 663, NGC 869, ..), it was remarkable that all Be stars are of early spectral types, and he concluded that the Be stars population in young open clusters is significantly more and different than the content of the mean Galactic population. These results are shown in the histograms of figure (1.3) for two of his studied OC. This showed evidence for the evolutionary enhancement of Be phenomena during the second half of MS lifetime of B stars, which is favourable in OC.

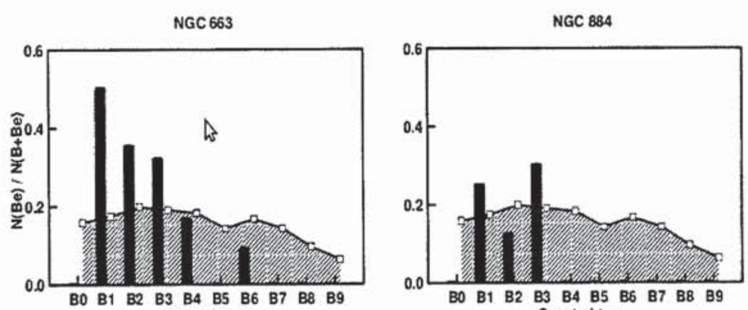

Figure 1.3: Relation between the Be stars frequencies and spectral subtypes in two OC. Bars represent the observed frequencies in the clusters. The solid line and shadowed area are the mean frequencies for field Be stars in the Galaxy, from Fabregat (2002).

- Bp and He strong/weak B stars are host to magnetic fields, which are periodically variable. In addition, these stars are found to be variable in one or more of the photometric bands (U, V or B) or in their spectra, in which the period of variability is found to be related to the rotatioanl velocity of the star *v*sin*i*. Landstreet et al. (2007)[49], observed a statistically significant sample of magnetic Bp stars in OC, for which they characterized the magnetic field structures and chemical abundances, and for which they had reasonably well-determined masses and ages. Their sample of study was able to provide valuable constraints on the evolution of magnetic fields and chemical peculiarities in these stars. Of the main results they obtained was that the magnetic field strength found is larger for B stars of more than $3M_{\odot}$.

- Huang & Gies (2006)[39] made a survey on the rotation of B-type stars in 19 OC to study the time evolution of rotational properties of massive stars. They obtained moderate resolution spectra and used fits of He_{I} λ λ4026,4387 and Mg_{II} λ4481 lines with model theoretical profiles to find projected rotational velocities of these stars. Models by Meynet & Maeder (2000)[57] predict that massive stars spin down during core H-burning at a rate that is larger for more massive stars and for those with higher initial rotational speeds. These models predict that a spin-up episode can occur very close to the terminal age main sequence (TAMS) when the core contracts prior to H-shell burning. In some situations this increase may lead to near-critical rotational velocities and induce enhanced equatorial mass outflows such as are observed in rapidly rotating Be stars. Huang & Gies found that there are fewer slow rotators among the cluster B-type stars relative to nearby B stars in the field. They presented evidence consistent with the idea that the more massive B stars ($M > 9M_{\odot}$) spin down during their MS phase. However, they also found that the rotational velocity distribution appears to show an increase in the numbers of rapid rotators among clusters with ages of 10 Myr and higher. These rapid rotators appear to be distributed between the zero age and terminal age main-sequence locations in the HR-diagram, and thus only a minority of them can be explained as the result of a spin-up at the terminal age main sequence (TAMS) due to core contraction. They suggested instead that some of these rapid rotators may have been spun-up through mass transfer in close binary systems.

In summary, one can state many motivations to study B stars in OC, of which most importantly we mention:

- They are the brightest of the cluster's members, and thus easier to detect and study with simpler instruments.
- The study of their fundamental parameters and chemical composition, and comparing them with B stars in different clusters of different ages, allows us to better understand the evolution of these stars as well as to put constraints on the present evolutionary models.
- Comparing their fundamental properties and chemical composition to lower mass, later type stars in the same cluster (mainly "normal" A and F stars), which have roughly the same chemical composition as these B stars, allows us to better understand the physical processes responsible for the chemical peculiarities (CPs) found in B stars.

- The incidence of Be stars tends to peak in open clusters with ages between 13 and 25 Myr, approximately when early B-type stars are close to the TAMS (Fabregat & Torrejon, 2000)[26], which are very important to study in order to answer unresolved questions about the origin of the Be phenomena.

- Moreover, because the analysis of higher luminosity classes (Giants and Supergiants) stars is more computationally and physically challenging (requires non-LTE modeling of atmospheres) (Fitzpatrick & Massa, 2005)[29], then the study of main sequence B stars which are associated with these more massive stars in an open cluster, provides the essential benchmark for interpreting the results for the more luminous and massive objects.

1.2.2 The Open Cluster Alpha Persei (Melotte 20)

The young open cluster **Alpha Persei** (Melotte 20) in the direction of the constellation of Perseus at right ascension $\alpha = 3^h\ 20.6^m$ (J2000) and declination $\delta = +48°\ 10'$ (J2000) is a loose cluster, of low number density (extending roughly over 60pc) and comprising about 300 members around the brightest star α Per (HD20902), an F5 Supergiant.

Because of its proximity to the Galactic plane, reliable identification of members of the α Persei cluster has often been problematic (Zuckerman et al., 2012)[92]. One of the most important works done on the cluster was published by Heckmann, Dieckvoss, & Kox (1956)[36]. In their proper motion study they determined membership probability and established cluster membership for 160 stars up to a visual magnitude V = 12. We use their ID nomenclature 'HE number' in the present work. Petrie & Heard (1970)[71] and Kraft (1976)[44] worked on the first radial velocity determinations of the cluster's stars. Stauffer et al. (1985)[83] identified 80 new members of the cluster down to V = 16.5, while Prosser (1992[74], 1994[75]) performed an astrometric, photometric and spectroscopic search of low mass members, and 130 new members were identified, raising the number of members (along with Heckman's members) to 300. Makarov (2006)[53] then reanalysed the clusters proper motions using astrometry and photometry from the Tycho-2 Catalogue and the Second USNO CCD Astrometric Catalog (UCAC2). Makarov's table of 'High-Fidelity' members lists 139 stars. Mermilliod et al. (2008)[56] undertook a radial velocity program to check for spectroscpoic binaries SB in the cluster. Their criteria for membership was threefold: proper motion (UCAC2), radial velocity and location in the color-magnitude diagram. Four of Makarov's member list were identified as non-members by Mermilliod. Most recently, Zuckerman et al. (2012)[92], created a mostly complete list of members of the cluster of spectral types G and earlier located within 3 degrees from the cluster's center, utilizing a review of the important six previously published papers concerning membership. The data in these papers are based on Hipparcos (Robichon et al., 1999)[78] and photometric distance estimates, radial velocity (Mermilliod et al., 2008)[56] measurements, proper motion information, Lithium abundances and X-ray fluxes. We used Zuckerman's combined literature results as commentary on the probability of membership of our candidate B-type stars in the cluster (Table 2.2).

Another fundamental study of α Persei was that of Crawford & Barnes (1974)[16] with four color *uvby* and H_β Strömgren photometry on 89 stars in the direction of the cluster. Hauck & Mermilliod (1998)[35] also compiled uvby-β photometry of 110 stars in the cluster which are used as entries in the WEBDA[6] Open clusters database. Peña & Sareyan (2006)[69] then performed absolute and differential *uvby*-β photometry of a sample of the cluster's stars, which yielded a total of 178 Strömgren photometrically measured stars in the direction of α Persei along with Hauck & Mermilliod's stars. They also used Nissen's (1988)[66] calibration to determine cluster membership from the $[m_1]$ vs. $[c_1]$ diagram which has already been employed in previous analysis of OC (Peña & Peniche, 1994)[70].

Alpha Persei is at a Hipparcos based distance of 190 ± 16.1 pc, corresponding to a distance modulus [7]$(M - m)_0 = 6.39$ which is based on a sample of 46 cluster stars. Mitchell's (1960)[60] UBV study of 187 stars provided a distance modulus estimate of $(m\text{-}M)_0 = 6.06 \pm 0.15$ mag and a means of further analysis and rejection of nonmembers. Cameron (1985)[12] studied 38 OC to determine their distances and metallicities, for which he determined for α Persei a distance modulus of $(m\text{-}M)_0 = 6.16$. A summary of other distance determinations to the Alpha Persei cluster are presented in table (1.2) below:

Distance (pc)	Age (Myr)
182 ± 11 (Jackson & Jeffries 2010)[40]	85 ± 10 (Barrado y Navascues et al. , 2004)[9]: Li depletion analysis.
191 ± 7 (Robichon et al. , 1999)[78]	80 (Prosser et al. 1992)[74]: Upper main sequence fitting to isochrones.
183 (Van Leeuwen, 1999)[89]	90 (Stauffer et al , 1990)[84]

Table 1.2: Different distance and age determinations for Alpha Persei.

In terms of age determinations, Maeder & Meynet (1991)[52] used models taking into account the effects of mass loss and core overshooting to determine an age of 71 Myrs. Meynet, Mermilliod & Maeder (1993)[58] then used other models taking into account overshooting and opacity tables of Rogers & Iglesias (1992)[79] and determined among 30 OC, an age of 52.5 Mys for α Persei. Makarov (2006)[53] used "isochrones" fitting after computing kinematical parallaxes of his "high-Fidelity" member stars, to plot an improved HR diagram (figure 1.4). He found a best fit at an age of 52 Myrs. Other age determinations by other authors are presented in table (1.2).

In terms of metallicity, Cameron (1985)[12] carried out a study of 38 OC to determine their distances and metallicities. The values he compiled for α Persei are $E(B - V) = 0.070$ for reddening, $[Fe/H] = 0.07$ for metallicity and a distance modulus $(m - M)_0 = 6.16$. Boesgaard & Friel (1990)[11] derived the metallicity using spectroscopy. In particular, they studied seven dwarf F-type stars in α Persei which resulted in a derived metallicity for the cluster of $[Fe/H] = 0.004 \pm 0.003$. In another spectroscopic study, Clampitt & Burstein (1997)[13] did spectrophotometry of 237 stars in seven OC. Their results for α Persei show that

[6] http://www.univie.ac.at/webda

[7] Dereddened distance modulus $(m\text{-}M)_0 = 5\log(D)-5$ is the difference between the apparent magnitude and the absolute magnitude of a star, where D is the distance to the star in units of parsec(pc).
$1pc = 3.26\ ly = 30.857\ x10^{17}$ cm.

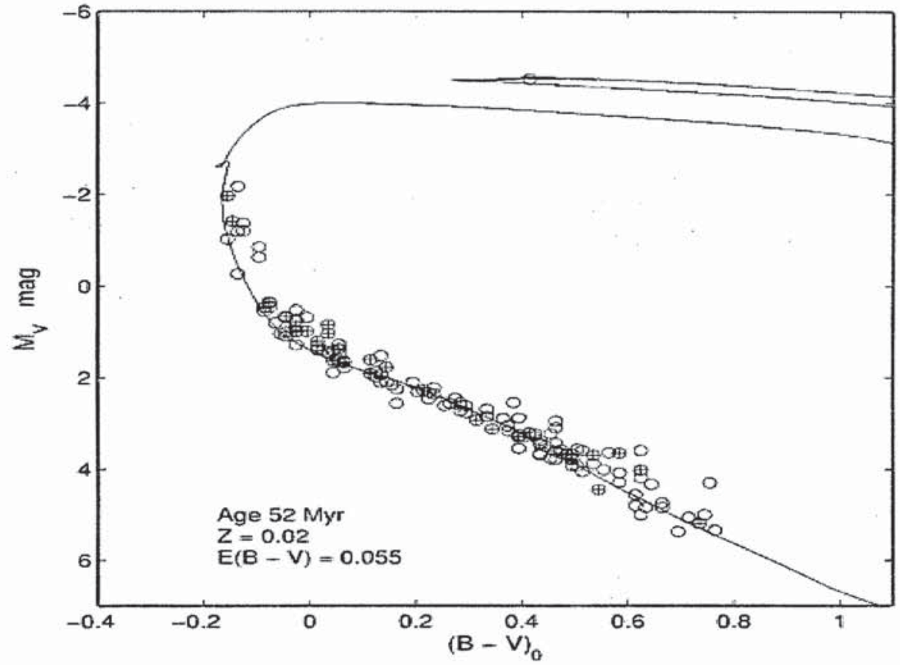

Figure 1.4: Makarov's color-magnitude HR diagram for α Persei. Solid line is 52 Myrs isochrone fit of overshooting models by Pietrinferni et al. (2004)[72]. Crossed circles are identified binaries (Abt et al., 2002).

the majority of the stars are Ap; of the five most luminous stars on the Main Sequence only one is classified as a peculiar giant. All the remaining stars in the hot part of the MS are between classes B3 and B6. They assumed a log age of 7.61 (5th ed. of Lund-Strasbourg catalogue, 1987), for which they determined a reddening E(B - V) of 0.10 and a metallicity content of [Fe/H] = 0.10.

It is noteworthy to mention that in terms of binarity, Alpha Persei has a much smaller binarity rate than in nearby OC such as the Hyades and Pleiades, where a study by Morell & Abt (1992)[64] and Patience (2002)[68] stated that only 20% of the members are known or suspected spectroscopic, astrometric or visual binaries or multiple systems. These binarity results were tabulated by Makarov (2006)[53] with his 'high-Fidelity' list of members and are presented in table (2.1) for our candidate B-type stars.

Gebran et al. (2005)[30] used the Strömgren color indices to calculate the effective temperature ($T_{\rm eff}$), surface gravities and to determine the metallic abundances of some A and B stars. Whereas Klochkova et al. (1986)[43] used spectroscopy to determine $T_{\rm eff}$ and log g a sample of B stars from Alpha Persei and other nearby OC in an attempt to determine their helium abundances. Their fundamental parameters were obtained by fitting theoretical profiles of the EW of Balmer's Hγ and Hδ lines from Kurucz (1979)[46] LTE grids of stellar atmospheric models to observed ones (Gebran et al. and Klochkova et al.'s B stars members are presented in table (4.1) for comparison with our derived values.
In this work, the fundamental parameters ($T_{\rm eff}$ and log g) of all candidate B-type stars of the α Persei

cluster have been determined making use of the Strömgren photometric uvbyβ colors and their indices and using the calibration of Napiwotzki et al. (1993)[65]. These values are then compared to other published work done on the parameters of these stars (section 3.3), which are used to put constraints on the method used by us and others in terms of proper modeling of the stellar atmospheres for our B stars and B-type stars in general.

Chapter 2

Observation and Reduction

2.1 Choice of Cluster and Imaging

The main aim of this thesis was to determine via spectroscopy the fundamental atmospheric parameters of the B stars of the Alpha Persei OC, to obtain the spectra of the cluster's B stars via echelle spectroscopy, reduce them and then fit them to synthetic spectra based on Kurucz (1992)[47] ATLAS9 LTE model atmospheres. The values for effective temperature and surface gravity that would give the best fit would be those closest to the true values for the corresponding star. The starting values for $T_{\rm eff}$ and $\log g$ to be used to produce the synthetic spectra for the candidate B stars, were to be calculated using the Strömgren $uvby$-β photometric indices from Hauck & Mermilliod (1998)[35] and a calibration by Napiwotzki et al. (1993)[65].

From the list of Galactic OC that are observable in the Northern hemisphere, Alpha Persei has been chosen based on its apparent magnitude which is less than V = 8, located at a nearby distance of 190pc (Hipparcos) which can be observable with our instruments (Telescope, CCD and spectrograph) which are further described in section (2.2) below.

As compared to nearby OC such as the Pleiades (127^apc, 79^bMyrs), Eta Chamaeleon (97^cpc, 12^dMyrs) [1] and other OC whose B stars have been extensively studied in terms of chemical composition and fundamental astmospheric parameters, the fundamental parameters of Alpha Persei's B stars have not yet been all fully studied, and specifically not derived using Strömgren Photometry. And thus, another criteria for chosing this cluster is the presence of the Srömgren color indices and H_β equivalent widths (Hauck & Mermilliod, 1998)[35] for its candidate B stars.

The cluster contains 23 B-type member stars (Zuckerman et al., 2012)[92] which are good candidates for the purpose of our study. The stars were selected using the database WEBDA and they were identified in the SIMBAD[2] database where the stars parameters (apparent magnitude, coordinates, ID numbers, spectral types, etc.) have been determined. The selected stars are listed in table (2.1), in terms of their cluster HE numbers (after Heckmann et al., 1955)[36], HD numbers, BD numbers, their coordinates (J2000) (from 2MASS catalogue), visual apparent magnitudes, spectral MK types (Abt H.A., 2004)[3] and

[1](a) After Stello & Nissen (2001), (b) after Paunzen & Netopil (2006), (c) and (d) after Mamajek et al. (1999).
[2]http://simbad.u-strasbg.fr/simbad/

binarity flag (A for Astrometric, V for Visual, SB for Spectroscopic and ? for probable binarity compiled from Prosser (1992)[74], Morell & Abt (1992)[64] and Patience et al. (2002)[68]). Commentary on the membership probability of our candidate B stars as taken from Zuckerman's combined literature review (see section 1.2.2) are presented in table (2.2).

Cluster HE Number	HD number	BD number	Right ascension α	Declination δ	V	MK type	Binarity
145	19624	+51 689	+03 11 42.9	+52 09 48.4	6.88	B5V	
167	19805	+48 862	+03 13 05.2	+49 34 07.9	7.96	B9.5V	
212	19893	+49 876	+03 13 50.3	+49 34 07.9	7.16	B9V	SB
383	20365	+49 899	+03 18 37.7	+50 13 19.8	5.16	B3V	
401	20418	+49 902	+03 19 07.6	+50 05 41.8	5.04	B5V	
441	20510	+50 738	+03 20 06.2	+50 58 07.5	7.06	B9V	
557	20809	+48 899	+03 23 13.1	+49 12 47.7	5.30	B5V	
581	20863	+48 903	+03 23 47.3	+48 36 15.8	6.99	B9V	V
625	20961	+47 817	+03 24 52.1	+47 54 54.4	4.97	B5V	
675	21071	+48 913	+03 25 57.3	+49 07 14.7	6.99	B9V	
692	21091	+47 821	+03 26 10.8	+48 23 02.5	7.66	B9.5V	
747	21238	+49 936	+03 27 38.9	+49 35 59.6	6.07	B7V	SB2
774	21278	+48 920	+03 28 03.1	+49 03 46.3	7.50	B9.5V	
810	21362	+49 944	+03 28 52.3	+49 50 54.2	5.58	B6Vn	
831	21398	+47 835	+03 29 07.6	+48 18 10.4	7.37	B9V	
835	21428	+49 945	+03 29 22.1	+49 30 32.2	4.68	B3V	V
903	21540	+46 762	+03 30 26.9	+47 03 47.8	7.05	B8III	
904	21551	+47 844	+03 30 36.9	+48 06 12.9	5.82	B8V	
955	21641	+47 846	+03 31 33.1	+47 51 44.6	6.77	B8.5V	SB1?
965	21672	+48 943	+03 31 53.9	+48 44 06.5	6.63	B8V	A,V,SB1?
985	21699	+47 847	+03 32 08.6	+48 01 24.5	5.46	B8IIImnp	
1082	21931	+48 949	+03 34 12.9	+48 37 02.8	7.37	B9V	A, V?
1164	22192	+47 857	+03 36 29.3	+48 11 33.4	4.31	B5Ve	

Table 2.1: B type stars in the Alpha Persei OC.

In the duration of this thesis, the limited instruments, in addition to weather and technical constraints allowed us to have only one observing night of the cluster which was not sufficient to observe all the candidate B stars. Only one of the 23 stars, HD22192 or ψPer, has been observed for one night on April 2012 (on the 26^{th}).

Due to these unfortunate constraints mentioned above, the observed data have a very low singal to noise ratio, and thus the obtained spectrum could not be used as required in our analysis.

2.2 Instruments Used

Frames of Alpha Persei's B star was taken using a Meade LX200-GPS (14 inches = 35cm) telescope which is located and owned by the Notre Dame University (NDU) at the Zouk Mikael campus, in North Lebanon (latitude- 33° 58' 19" N ; longitude 35° 37' 08"). For CCD camera, we used the Sbig ST-2000XM of (20

Cluster HE Number	HD number	Pr?	Ma?	Rob?	Ran?
145	19624	y?	y		
167	19805	y	y	y	
212	19893	y	y	y	
383	20365	y	y	y	
401	20418	y	y		
441	20510	y?	y	y	
557	20809	y	y	y	
581	20863	y	y	y	
625	20961	y	y		
675	21071	y	y	y	
692	21091	y?	y	y	
747	21238		y	y	
774	21278	y	y	y	
810	21362	y	y	y	
831	21398	y	y		
835	21428	y	y		y
903	21540	y	y	y	
904	21551	y	y	y	
955	21641	y	y	y	
965	21672	y	y		y
985	21699	y	y	y	
1082	21931	y	y		
1164	22192	n	y	y	

Table 2.2: Membership of B stars in Alpha Persei from the literature as compiled by Zuckerman et al. (2012); Pr=Prosser 1992; Ma= Makarov 2006; Rob=Robichon 1999; Ran=Randich 1996; 'y' corresponds to listed as member; 'y?' to listed as probable member and 'n' to listed as non-member.

x 15) arcminutes field of view and $1.4e^{-}$/ADU gain. As for the spectrograph, we used the "eShel" echelle spectrograph from Shelyak of 50μm aperture and 200μm fiber optics mirror at 79 grooves/mm, a resolution of R = 11000 and wavelength range of 4300Å to 7000Å.

2.3 Reduction and Frames Processing

The reduction of the observed frames is an important step to obtain well reliable and accurate spectra which are normalized and calibrated.

In the sections that follow, I will show the steps followed in reducing and extracting the spectrum obtained for HD22192. In this work, the reduction of the data was done using IRAF "Image Reduction and Analysis Facility"[3].

In order to get rid of all of the CCD and instrumentation deficiencies as well as to calibrate our spectra, we took, in addition to the stars "raw" frames, 4 types of calibration frames namely: bias frames, dark frames, Tungsten-LED spectra as well as Thorium-Argon spectra, at every night of observation.

[3]http://iraf.noao.edu/

2.3.1 Bias Frame (Offset)

When a 0s exposure frame is taken with the camera's CCD shutter closed, a non zero reading is observed at every pixel, and that is to avoid reading a negative value. So instead, the offset (zero-level) of the camera is deliberately set to some number above zero. So 0s exposure time frames were taken every night, and then averaged into one master BIAS frame using the command **zerocombine**, to be then subtracted from the stars raw frames as well as from the calibration frames (Dark and Flatfield) using the command **ccdproc**, both found in the **ccdred** package in IRAF.

2.3.2 Dark current

Identified as the rate by which the electrons accumulate in each pixel due to thermal action. This rate depends on the temperature T of the CCD and on impurities in each pixel. This is why the CCD needs to be cooled down. For a CCD temperature, electrons due to dark current can accumulate at a constant rate for each pixel, which depends on the exposure time as well. It Can be thought of as non zero exposure-time bias frames.

Each night many dark frames were taken and averaged into one master DARK frame by using the command **darkcombine**, to be then subtracted from the stars raw frames (again using **ccdproc**).

2.3.3 Normalizing the Flat and Flat-Field Correction

The flat-field correction is important to remove pixel-to-pixel variations in the CCD which is proportional to the percentage of actual light intensity. This variation can be measured by taking "Flat-field correction frames" by exposing the camera to a uniformly bright object like a Tungsten-LED lamp in our case. This will tell us how each pixel is reacting to the incoming photons.

In order to improve (S/N) ratio, each night we took many "Tungsten-LED" lamp spectra and then averaged them into one master FLAT using **flatcombine**. Flat fielding of the object data are made by dividing the object (star) frame by the flat frame using **ccdproc**. Before that, however, the flat frame is usually normalized for the count, in order to keep the count of the object data. Before normalizing the FLAT, the locations of the echelle orders/appertures (20 orders in the case of our 'eShel' spectrograph) need to be mapped on the CCD frame which can be done by using the **apall** task in the **echelle** package which detects the orders, resizes, fits and traces them. After that, the FLAT is normalized using the **apflatten** task. Finally, the object frames are "flat-fielded" by dividing them by this normalized FLAT using **ccdproc** again.

2.3.4 Extraction of Spectra and Wavelength Calibration

The stars spectra are extracted using the **apall** task again, this time using the extracted FLAT spectrum as a reference. The spectra then have to be wavelength calibrated which is made by using comparison spectrum (Thorium-Argon arc lamp) of well known individual spectral lines, obtained by the same setup of the spectrograph as applied to the object. The calibration is done by using the tasks **ecidentify** in which the spectral lines of ThAr are identified using a reference ThAr ATLAS and then the wavelength calibration is attached to the object extracted spectra using **dispcor**, where the correct wavelengths are assigned to pixel numbers.

Finally, the orders have to be combined, using **scombine**, and normalized using **continuum** to get a calibrated complete spectrum to be used for analysis.

However, as mentioned before, the extracted spectrum of HD22192 had a very low signal to noise ratio that could not be used for the analysis and fitting to determine the fundamental paremeters of the star as was intended to. Two main reasons have led to the low signal to noise spectrum obtained for the observed star:

- The apparent position of the Alpha Persei cluster in the Perseus constellation during the night of observation, was observed at a large airmass during that night for a total of 3 hours before descending below the observable horizon. This affected largely the quality of the object frame obtained by the spectrograph for the star, which was the main reason that led to the low signal to noise spectrum of HD22192 when extracted using **apall** (figure 2.1).

- The echelle spectrograph "eShel" was being used for the first time during the night of observation without being put to test before, and thus during the reduction process, and after defining the apertures (orders) of the spectrograph using the TUNGSTEN-LED frame using **apall** task in **echelle** package, the normalization process of the obtained "FLAT" in **apflatten** using the formerly defined apertures as reference, may have lead to unwanted features and edge effects that rippled along the dispersion direction. In addition, combining the overlapping spectral orders using **scombine** is known to add additional noise especially at the edges of the orders where those latter edges are averaged upon combining. To show this effect, the same reduction procedure applied to ψPer was applied to *Regulus*, a standard bright B star, which was observed on the same night using the same spectrograph and with the same exposure time as that of ψPer for the aim of using its spectrum for comparison with the spectrum of our sample B star. Figure (2.3) shows the sixth spectral orders of *Regulus*, which clearly shows the absorption features and thus the success of the extraction process used in this work, and asserts the problem we faced upon combining the spectral orders probably due to systematic errors from the spectrograph itself, i.e. a problem in the overlapping of the orders (see figures 2.1 and 2.2).

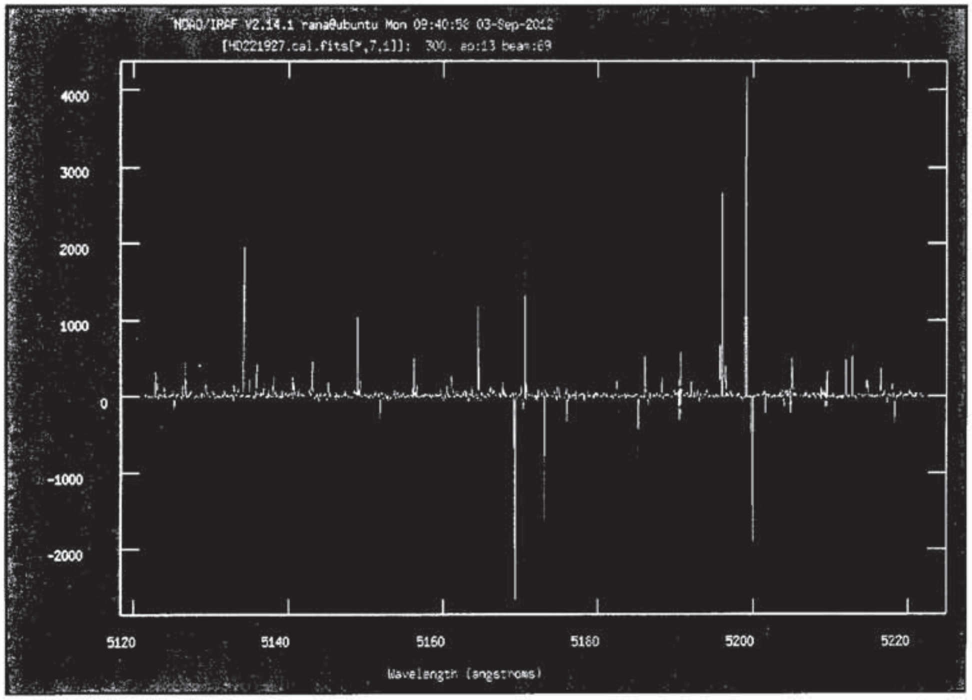

Figure 2.1: Sixth extrated spectral order for HD22192 before combining.

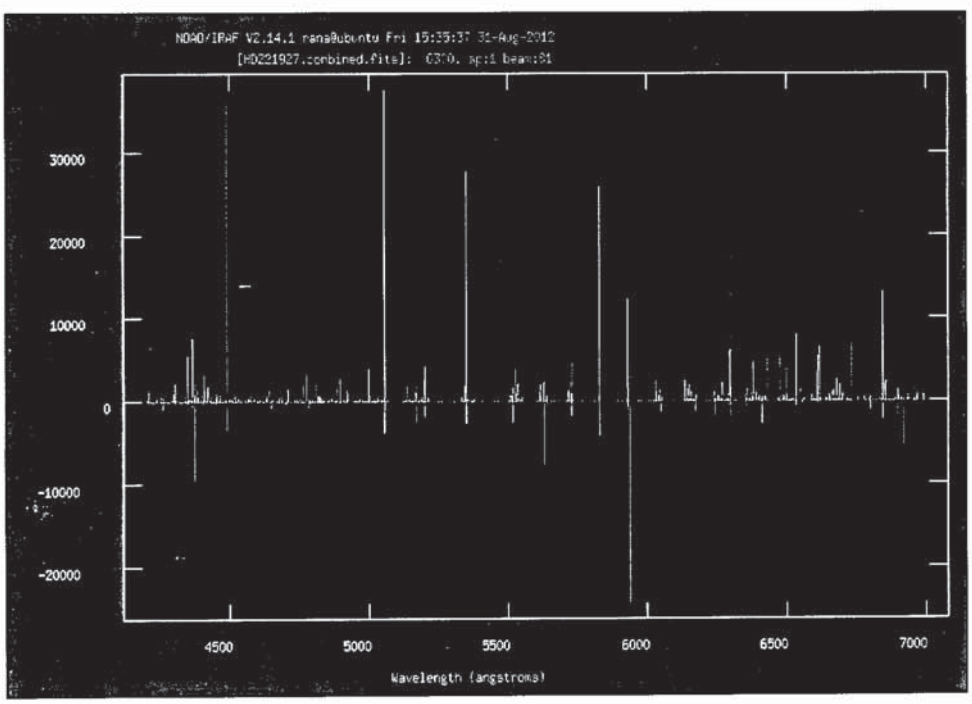

Figure 2.2: Combined spectrum of HD22192 in the visible range of wavelength.

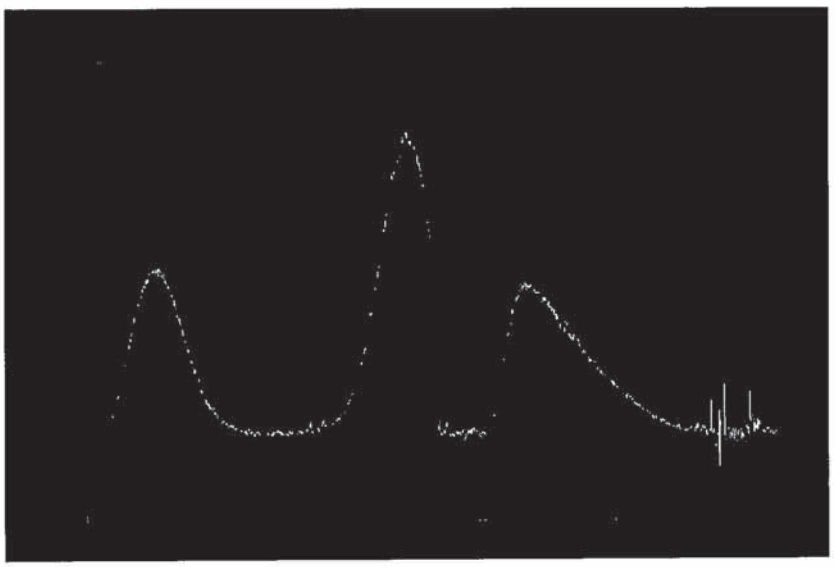

Figure 2.3: Sixth extracted spectral order for Regulus before combining.

Chapter 3

Determination of Effective Temperature and Surface Gravity using uvbyβ Strömgren Photometry

The effective temperatures and surface gravities of stars can be measured through their influence on the spectral flux distribution by a variety of different photometric methods. At their core, all of these methods rely on fitting the observed spectral distribution of the star, as photometric colors or fluxes, to expected fluxes from theoretical models or real "standard" stars with known atmospheric parameters. The variation of interstellar extinction with respect to wavelength can also influence the observed spectral flux. Therefore, the accuracy of all of these methods relies on quantifying the effects of interstellar extinction.

The table (3.1) below shows these photometric methods and their sensitivity to calculating the fundamental atmospheric parameters of the stars (effective temperature, surface gravity or both) depending on the properties of their corresponding filter passbands.

Method	Sensitivity
Johnson UBV photometry	Temperature
Strömgren Photometry	Temperature & Gravity
Geneva Photometry	Temperature & Gravity
TD1 UV Photometry	Temperature
ANS UV Photometry	Temperature & Gravity
Balmer fitting	Gravity
IUE flux fitting	Temperature

Table 3.1: Photometric methods used for determining stellar atmospheric parameters.

The success of correctly deriving the values of the temperature and gravity relations depends on properly accounting for the effects of interstellar extinction. Photometry and fluxes are corrected for extinction using the curve of Fitzpatrick (1999)[28] for the far IR through the UV wavelength range (Figure (3.1)). The Geneva and Strömgren photometric systems however, have built in reddening free parameters which are independent of these corrections (Cramer & Maeder, 1979)[14] and (Crawford & Mandwewala, 1976)[18] which makes them important tools to use for deriving the fundamental parameters of stars.

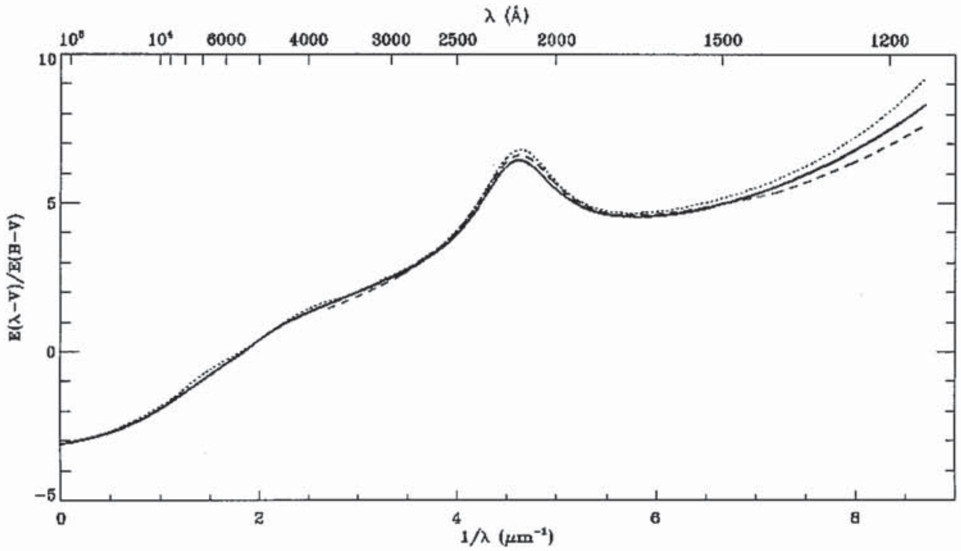

Figure 3.1: Interstellar extinction curve from the Far-IR through the UV, from Fitzpatrick (1999).

Our main aim of this study was to use our observed spectra and to fit them to synthetic spectra based on LTE model atmospheres from Kurucz et al. (1992)[47] to obtain the best fit for the fundamental parameters of our candidate stars, namely $T_{\rm eff}$ and log g. However our observations turned out to have very low signal to noise values from which we could not extract any useful spectra due to both technical and weather problems we faced from February till June 2012. For that reason, we calculated $T_{\rm eff}$ and log g of our candidate stars using the availabe Strömgren uvbyβ photometric indices and applied a calibration method by Napiwotzky et al. (1993)) based on LTE model atmospheres (Kurucz, 1979). We then compared our results to available previous determinations by other authors of the same parameters for some of these stars.

3.1 Introduction to Strömgren Photometry

Strömgren (1966)[87] used uvbyβ photometry, with *uvby* filters (corresponding to ultraviolet, violet, blue and yellow respectively) and their corresponding photometric color indices, in addition to the measure of the EW of the narrow-band H_β centerted at 4861Å line, which can be used by applying a calibration technique to determine the fundamental properties of stars without the need of knowing their absolute magnitude and/or distance modulus $(m - M)$.

The Strömgren photometric system is better than the Johnson UBV photometry for determining the effective temperatures and gravities of stars because it is comprised of a series of narrower passband filters that better sample optical to UV wavelengths. The characteristics of the Strömgren photometric filters are presented in table (3.2) below, and their transmission percentage as a function of wavelength in figure (3.2).

The widths of these filters and the H_β EW were chosen because of their important features, mainly due

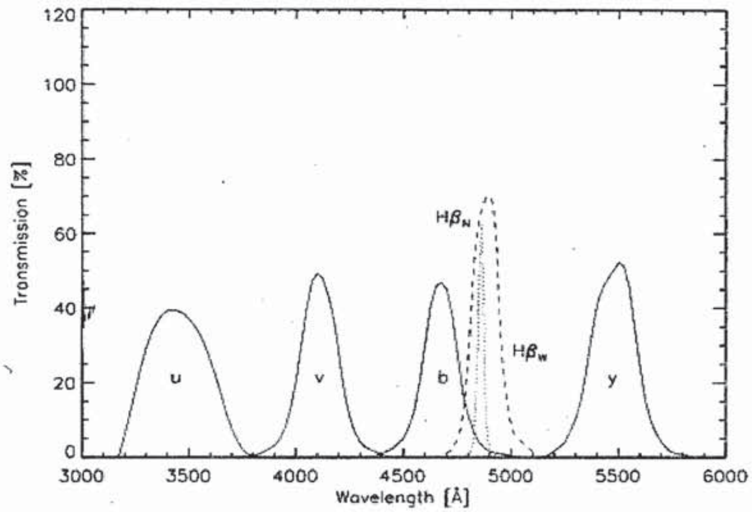

Figure 3.2: Transmission of the Strömgren uvby-β color bands as a function of wavelength, from Önehag et al. (2009)[67].

to:

I- Their color differences, which are highly sensitive to surface gravity and effective temperature differences.

II- The Balmer discontinuity $\beta = \beta_{\ Narrow}$ - $\beta_{\ Intermediate}$, the difference in magnitude strength between two passbands, intermediate and narrow, both centered at [1]H_β, which roughly measures the absorption in the wings of that line.

III- Blanketing absorption[2] due to heavy elements in stars is quite small in the uvbyβ system.

Filter	λ (Å)	$\Delta\lambda$ (Å)
u	3500	340
v	4100	200
b	4700	160
y	5500	240
β	4861	30 and 50

Table 3.2: Strömgren filters characteristics.

Strömgren introduced color differences and color indices, known as the uvbyβ Strömgren colors, are related to the fundamental parameters of B-type stars in the following manner:

[1]Balmer discontinuity (jump): The drop in the continuum of the spectrum of a star due to absorption of photons by Hydrogen atoms at 4861Å.

[2]Line blanketing: Dimming of star's spectrum by the presence of many hundreds or thousands of weak absorption lines too faint and close together to be resolved.

- **(u-b)** is an indicator of T_{eff} for B stars.
- **(b-y)** measures the slope of the Paschen continuum which is sensitive to T_{eff} as well, and it is rather free from blanketing effect.
- **c1=(u-v) - (v-b)** color index which measures the Balmer discontinuity at 3647Å which is sensitive to changes in log g for stars hotter than 9000K.
- **m1 = (v-b) - (b-y)** color index which measures line blanketing, used for determining abundance differences.
- β Indicator of effective temperature or surface gravity (for B-type stars) depending on spectral type of star, and insensitive to ISM (interstellar medium) reddening.

3.2 Conversion of Strömgren Color Indices into Stellar Atmospheric Parameters

The relations of Moon & Dworetsky (1985)[62](**MD85**), Balona(1994)[8](**B94**), and Napiwotzki, Schönberber & Wenske (1993)[65](**NSW93**), were used to convert the Strömgren photometric indices into effective temperatures and surface gravities.

The **MD85** temperature and gravity relations are derived from synthetic *uvby* colors calculated by Relyea & Kurucz (1978)[77] LTE model atmospheres, which were then calibrated to fit the observed uvbyβ indices, and used synthetic H_β indices from Schmidt (1979)[80]. They published grids for the determination of T_{eff} and log g as a function of the Strömgren photometric indices, by comparing the photometric indices of fundamental stars (stars of well known T_{eff} and log g) to theoretical photometric indices in the temperature range:

$$6000K \leq T_{\text{eff}} \leq 20000K \tag{3.1}$$

Their results show that:

- For stars earlier than B9 ($T_{\text{eff}} \geq$ 11000K), β plays the role of a gravity indicator and c_0 (dereddened value of c_1) is a temperature parameter.
- For stars later than A3 ($T_{\text{eff}} \leq$ 8500K), β and c_0 have reversed roles to that of the above.
- For stars between B9 and A3 (8500K $\leq T_{\text{eff}} \leq$ 11000K), it was important to introduce two new parameters:

$$a_0 = 1.36(b-y)_0 + 0.36m_0 + 0.18c_0 - 0.2448 \tag{3.2}$$

$$r^* = 0.35c_1 - 0.07(b-y) - (\beta - 2.565) \tag{3.3}$$

in which a_0 is a $T_{\rm eff}$ indicator and r^* a surface gravity parameter.

MD85 obtained good accordance in $T_{\rm eff}$ and log g values, between those obtained using their constructed grids and the ones already known for stars of spectral types B2 to G0. The error between theory and observation in their method was $\triangle$ $T_{\rm eff}$ = -10 ± 260K and $\triangle$ log g = -0.01 ± 0.1 dex.

The **B94** temperature and gravity relations are based on the Strömgren indices computed by Lester, Grey & Kurucz (1986)[50] and calibrated using the surface gravities of eclipsing binaries from Andersen (1991)[6]. On the other hand, the **NSW93** temperature and gravity relations were calibrated empirically using $T_{\rm eff}$ and log g of fundamental stars from a variety of sources, and compared them to those determined with different calibrations (**MD85**, Lester et al., 1986).

The corrections **NSW93** made on the **MD85** calibrations were the following:

- The **NSW93** surface gravity relation is a function of the **MD85** surface gravity relation, recalibrated by fitting theoretical Balmer line profiles computed using the LTE model atmospheres of Kurucz (1979) and the Hβ standards published by Crawford & Mander (1966)[17]. The relation they obtained is:

$$\log \mathrm{g} = \log \mathrm{g}_{\mathrm{MD85}} - 2.9406 + 0.7224 \log \mathrm{T}_{\mathrm{eff}} \tag{3.4}$$

where $g_{\rm MD85}$ is the value of the surface gravity as obtained by **MD85**.

- The **NSW93** calibration of $T_{\rm eff}$ for normal B stars is:

$$\Theta = 0.1692 + 0.2828\,[u-b] - 0.0195\,[u-b]^2 \tag{3.5}$$

where

$$\Theta = \frac{5040}{T_{\rm eff}} \tag{3.6}$$

and

$$[u-b] = (u-b) - 1.53\,(b-y) \tag{3.7}$$

The **NSW93** uncertainties on $T_{\rm eff}$ are up to 2.5% for T $\leq$ 11000K, and 4% for T $\geq$ 20000K, in addition for a 0.25 dex uncertainty on log g.

The computer code used in this thesis, based on the **MD85** grids and the above calibrations of **NSW93** to determine the fundamental atmospheric parameters $T_{\rm eff}$ and log g is Napiwotzki's **UVBYBETANEW** (an updated version of the **UVBYBETA** by Napiwotzki et al. (1993)). In order to determine these fundamental parameters, the following indices and magnitudes have to be known for a certain star:

- Apparent magnitude V.
- (b-y) metal-blanketing free color index.

- m_1 color index.
- c_1 color index.
- $H\beta$ line equivalent width.

Once the parameters above are entered into the former code in addition to the spectral type of the star, these indices are dereddened by applying an average dereddening law of the Galaxy (Crawford (1978)[15] for B0 $\rightarrow$ A0 for III to V luminosity classes, and Zhang (1983)[90] for B0 $\longrightarrow$ A0 for I and II luminosity classes). Then a calibration is applied (**NSW93**'s calibration) and by successive iterations it the determines iso-$T_{\rm eff}$ and iso-log g curves closest to the representative point of the star of corresponding indices. The uncertainty on $T_{\rm eff}$ in this method is $\pm$250K and that on log g is $\pm$0.25 dex.

The Strömgren photometric color indices (b-y), m1 , c1 as well as the visual magnitude V and the $H\beta$ equivalent width (after Hauck, B. and Mermilliod, M. (1998)[35]) of our candidate B-type stars in the Alpha Persei cluster are presented in table (3.3) below.

Cluster member	HD number	V	$b-y$	m_1	c_1	β
145	19624	6.88	0.046	0.083	0.730	2.772
167	19805	7.96	0.074	0.137	0.945	2.887
212	19893	7.16	0.046	0.106	0.865	2.807
383	20365	5.16	0.002	0.076	0.361	2.681
401	20418	5.04	-0.005	0.082	0.402	2.673
441	20510	7.06	0.030	0.143	0.821	2.816
557	20809	5.30	-0.009	0.088	0.407	2.696
581	20863	6.99	0.024	0.115	0.821	2.813
625	20961	4.97	0.086	0.128	0.940	2.871
675	21071	6.99	-0.029	0.103	0.444	2.727
692	21091	7.66	0.028	0.136	0.947	2.856
747	21238	6.07	-0.019	0.138	0.847	2.892
774	21278	7.50	-0.028	0.096	0.407	2.705
810	21362	5.58	0.000	0.089	0.500	2.691
831	21398	7.37	0.021	0.126	0.831	2.828
835	21428	4.68	-0.026	0.088	0.373	2.686
903	21540	7.05	0.107	0.115	0.729	2.714
904	21551	5.82	0.002	0.101	0.683	2.746
955	21641	6.77	0.014	0.109	0.718	2.743
965	21672	6.63	0.019	0.096	0.662	2.747
985	21699	5.46	-0.041	0.111	0.369	2.696
1082	21931	7.37	0.034	0.126	0.847	2.829
1164	22192	4.31	0.003	0.063	0.369	2.490

Table 3.3: Strömgren color indices of B stars in Alpha Persei cluster.

Using the values of the color indices for our candidate stars in table (4.3), and using Napiwotzki at al.'s code **UVBYBETANEW**, we determined the values of $T_{\rm eff}$ and log g of our candidate B stars, based on uvbyβ Strömgren photometry, which are shown in table (3.4).

Cluster member	HD number	T_{eff}	log g
145	19624	12169	4.04
167	19805	10173	4.37
212	19893	11258	4.04
383	20365	16387	3.92
401	20418	15646	3.67
441	20510	11447	4.21
557	20809	15515	3.98
581	20863	11457	4.18
625	20961	10259	4.29
675	21071	14778	4.25
692	21091	9605	1.44
747	21238	10764	4.26
774	21278	15415	4.09
810	21362	14254	3.64
831	21398	11332	4.28
835	21428	16048	3.93
903	21540	12274	3.44
904	21551	12483	3.86
955	21641	12247	3.74
965	21672	12660	3.96
985	21699	16010	4.08
1082	21931	11252	4.25
1164	22192	13451	0.54

Table 3.4: Effective temperature and surface gravities of B stars in Alpha Persei.

Using the values obtained from this work's results for effective temperature for the cluster's B stars, in addition to the absolute magnitudes M_V based on the Hipparcos distance of 190pc (Robichon et al., 1999)[78], the HR-diagram of Alpha Persei has been plotted (figure 3.3). It can be seen that the position of most of the stars lie near or close to the Main Sequence except for ψPer (HD22192) which lies slightly above the main sequence (shown on the figure), raising a question regarding its debatable spectral type which has been classified as a B5IIIe giant by Slettebak et al. (1982)[82] and as a B5Ve main sequence star by Abt (1978, 2004)[2], [3]. The analysis and interpretation of the results obtained by us and other authors for ψPer are discussed furthermore in section (4.3).

3.3 Comparison of Our Results for Fundamental Parematers to that of Preceding Work

It is important to compare our results to previous published work in the literature for the same fundamental parameters of the same stars, obtained by either the same or different method as ours, to be able to put constraints on the method used by us, in case of the presence of a vast difference in values.

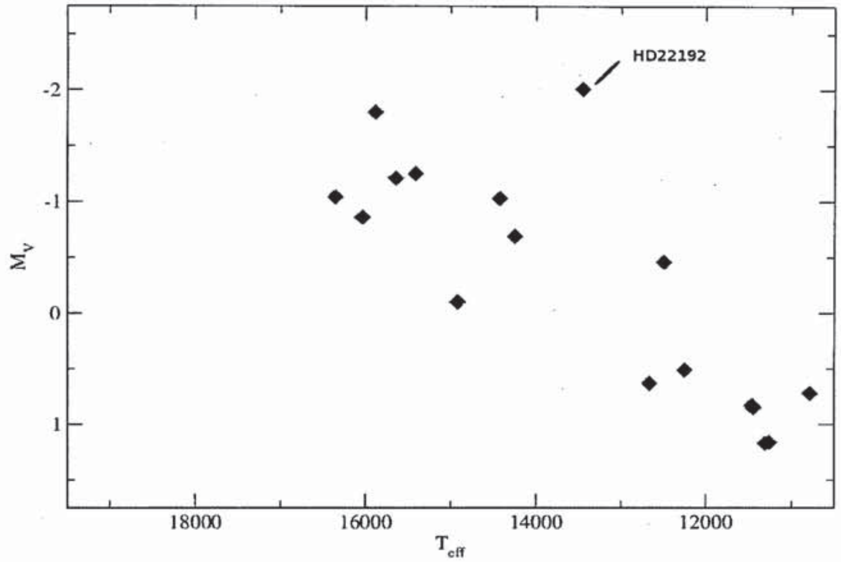

Figure 3.3: Alpha Persei's HR diagram compiled from this work's resulting effective temperatures $T_{\rm eff}$, and absolute magnitudes M_V based on Hipparcos' 190pc distance for the cluster's B-type stars.

In the case of Alpha Persei's candidate B stars, the comparison was made to the results of some stars obtained by Gebran et al. (2005)[30] and to that of Klochkova et al. (1986)[43].
In Gebran et al.'s (2005) article, the authors derived their temperature and surface gravity using the Strömgren color indices from Hauck & Mermilliod's (1998) catalog, and using Napiwotzki et al.'s (1993) calibration with his FORTRAN code UVBYBETA, whereas in this work we used Napiwotzki at al's updated version of that code UVBYBETANEW. The difference between the values obtained by us and that of Gebran et al. have an average of $\pm$127K for $T_{\rm eff}$ and $\pm$0.025 dex for log g, which lies within the error bar proposed by their paper which is $\pm$250K and $\pm$0.1 dex respectively.

On the other hand, the values obtained by Klochkova et al. (1986) were obtained by fitting theoretical profiles of the EW of Balmer's H_γ and H_δ lines from Kurucz (1979) LTE grids of stellar atmospheric models to observed ones, along with the measurement of the (U - B) color indices corrected for interstellar reddening. The difference between our work and their's has a large average value of 1026K for $T_{\rm eff}$ and 0.185 dex for log g. The comparison between the values of $T_{\rm eff}$ and log g obtained by this work to that of Gebran et al. (2005) and Klochkova et al. (1986) available for some of the stars are presented in table (3.5).

HD19805	T_{eff}(K)	log g	HD20961	T_{eff}	log g
This work	10173	4.37	This work	10259	4.29
GE2005	10294	4.33	GE2005	10386	4.27
HD21699	**T_{eff}(K)**	**log g**	**HD20365**	**T_{eff}**	**log g**
This work	16010	4.08	This work	16387	3.92
GE2005	16101	4.11	KL1986	17300	3.8
HD20809	**T_{eff}(K)**	**log g**	**HD21278**	**T_{eff}**	**log g**
This work	15515	3.98	This work	15415	4.09
KL1986	16500	3.7	KL1986	16200	3.8
HD21071	**T_{eff}(K)**	**log g**			
This work	14778	4.25			
GE2005	14945	4.26			
KL1986	16200	4.3			

Table 3.5: Comparison between T_{eff} and log g obtained by this work, Gebran et al. (2005) (GE2005) and Klochkova et al. (1986) (KL1986).

Chapter 4

Results and Interpretation

4.1 Interpretation of Results.

In what follows, the results obtained for some of the stars for which comments exist regarding their obtained values or those which show discrepancies to previous results are presented, with some possible explanations for the discrepancies and peculiarities their results show:

HD19805 and HD20961. HD19805 is classified as a 'A0Vp' He-weak peculiar star by Gray et al. (1987)[31], and a 'B9.5V' by Morgan et al. (1971)[63], while HD20961 is classified as B9.5V by Morgan et al. (1971) and a 'A1V' by Petrie et al. (1970)[71]. These slow rotating ($v\sin i \leq 50$km/s, Kraft 1967) stars has been studied in terms of their funadamental parameters and abundances by Gebran et al. (2005)[30] using the same photometric method we used, for which there was found to be an accordance with our results for T_{eff} and log g within acceptable error bars (table 3.5).

HD21699 and HD21540. HD21699 is classified as a 'B8III' by Morgan et al. (1971)[63], this star is found to be a giant variable (period = 2.49 days) of spectral type 'B8IIIp' and of He-weak peculiarity by Molnar (1972)[61] in his study for nearby bright B8 stars, and of a Hg-Mn peculiarity in the 2MASS catalogue of bright point sources (2003). Also known as "V439 Per", this star has been studied in terms of its fundamental parameters by Gebran et al. (2005)[30] by the same uvby-β method we used, and their values were in accordance with ours within error bars. HD21540 is also classified as a B8III giant by Abt (2004)[3]. However, since giants have expanded over the size they had while on the main sequence, then their surface gravity should be lower which is not the case for these two stars as obtained by the photometric method applied in this work (log g = 4.08 for HD21699 andlog g = 3.44 for HD21540) and also Gebran et al.'s work (log g = 4.11). Two types of explanations might arise in this case: The first has to do with fact that giant stars have thin atmospheres relative to their radii and they have strong mass loss and rich nucleosynthetic processes resulting from convection (Josselin E. & Plez B., 2003)[41]. Thus non-LTE effects have to be accounted for in modeling their atmospheres and in producing their synthetic spectra which was not the case in this work or Gebran et al.'s work in which Kurucz (1979)[46] LTE models were used in the calibration of the uvby-β indices into fundamental parameters. The second, might have to do with the fact that spectral classification is very heterogeneous and for a lot of stars spectral types are uncertain, which is shown by the discripancies in the stars spectral classifications mentioned above.

HD20809 and HD20365. HD20809 is classified as a B5V star by Morgan et al. (1971)[63], this fast rotating star ($v\sin i$ = 250 km/s by Millward et al., 1985[59]) is also classified as variable known as "V575 Per" by the General Catalog of Variable Stars (GCVS) (2007-2012). Whereas HD20365 is classified as a B3V by Morgan et al. (1971)[63] and a B4IV by Abt (1978)[2], is also a fast rotator ($v\sin i$ = 208km/s by Millward et al., 1985 and $v\sin i$ = 145km/s by Abt, 1962[1]). Their parameters have been studies spectroscopically by Klochkova et al. (1986), whose results show a large difference ($\sim$ 900K and 0.2 dex respectively) from the value of $T_{\rm eff}$ and log g obtained by this work. The reason for this difference might be due to the effects of rotation on the β index called 'incipient emission' effect as stated by Mcnamara (1962)[54], in which rotation changes total absorption of the line, and the effect is not due to broadening because when using a filter with a larger half width, the effect on β did not change much with increasing $v\sin i$. Thus a lower value for β might affect the obtained values for $T_{\rm eff}$ and log g.

HD21071 and HD21278. HD21071 is classified as a 'B7V' by Morgan et al. (1971)[63] and a 'B7Vsn' by Abt (1978)[2], is also a variable star known as "V576 Per" listed in the (GCVS) (1971-1996). Studied by both Gebran et al. (2005)[30] and Klochkova et al. (1986)[43] in terms of its fundamental parameters. HD21278 is classified as a B5V, slow rotating star (50km/s, Abt 2002[4]) which has been studied by Klochkova et al. (1986) as well. The results for these two stars show a large difference in values between this study and that of Gebran et al. with that of Klochkova et al. (a difference of $\sim$1400K in $T_{\rm eff}$), which might be due to the difference between the spectroscopic and photometric methods used in determining their parameters.

HD22192. Also known as ψ Per, this bright Be star (V = 4.31 mag) has been classified as a 'B5IIIe+shell' star by Sletteback (1982)[82] and a 'B5Ve+shell' by Abt (1978)[2]. It is fast rotator ($v\sin i$ = 385km/s, Abt 1962[1]) as most Be stars are. The low value obtained for the surface gravity (log g = 0.54) in this work shows controversy considering that it is listed as a 'B5Ve' star in many literature papers, which should not be the case considering that it is a Main sequence star. The most probable reason for that could be, that Be stars have Hβ in emission, which affects the value of β color index used in the Strömgren photometric method. Where the core of Hβ is slightly refilled by emission, the line would appear much weaker, implying a lower log g value. This interpretation is shown as well when entering a zero value for the β index as stated by Napiwotzki in his 'UVBYBETANEW' code for "unknown" values for β which then automatically inserts an average value of β depending on the inserted spectral type of the star (between 2.55 and 2.88, for B0-A0 classes III-V). The result obtained showed a higher value for log g (log g = 3.82) which clearly demonstrates the effect of inserting a lower value for β on the results.

Note on Be stars: Fabregat et al. (1996)[27] stated that Be stars occupy anomalous positions in the photometric color-magnitude diagrams, laying above the main sequence, which can be explained in terms of the circumstellar continuum radiation contribution to the photometric indices. In their study of

Be stars in eight OC and two OB-associations, Fabregat et al. (1996) found that in the ((b - y)$_0$ - M_V) plane, Be stars appear to be redder than non-emission B stars, due to the additional reddening caused by the hydrogen free-bound and free-free recombination in the circumstellar envelope. In the (c_0 - M_V) plane, the earlier Be stars present lower c_0 than absorption line B stars, which is caused by emission in the Balmer discontinuity, while later Be stars deviate towards higher c_0 values, indicating absorption in the Balmer discontinuity of circumstellar origin. Lower β index were observed for these Be stars as well, due to Balmer line emission.
Dachs et al. (1986)[20] and Kaiser (1989)[42] however, showed that the emission in the Paschen continuum of the circumstellar envelope is closely related with the equivalent width of the Hα line. By measuring the Hα emission line strength, the underlying star contribution to the photometric indices can be decoupled from the circumstellar disk contribution, and then the usual uvby-β calibrations can be applied (Fabregat & Regbero, 1990)[25], which unfortunately could not be measure for ψPer due to the star's very low S/N spectrum which could not be used for analysis.

Binaries: A final note on the cluster's B stars binaries should be made (table 2.1) since LTE models of stellar atmospheres used in our calibration method to determine the fundamental parameters of the stars are based on assumption of their plane-parallel or spherical symmetry. However, violation of this assumption by tides and rotation in close binaries leads to incompatibility of hydrostatic and radiative equilibrium. Therefore, an improvement of model atmospheres in this respect is desirable for simulation of light curves and line profile changes. Moreover, atmospheres of contact components of interacting binaries determine initial conditions of dynamics of gaseous streams and in this way influence the behaviour of the binary system (Hadrava, 1987)[34].

4.2 Model Atmospheres of B stars.

Virtually all our knowledge about stars and their evolution is derived by quantitative analysis of their spectra. These are based on model atmosphere techniques which have reached a high degree of sophistication in the recent years. The majority of the work has been performed under the assumption of local thermodynamic equilibrium (LTE), where the thermodynamic state of the atmospheric plasma is described via the Saha-Boltzmann equations as a function of the *local* temperature and electron density alone. However, this approximation strictly holds only in the limit that collisions, i.e. thermalising processes, dominate, and that photon-mean-free-paths are small. For a more accurate physical description the $non-local$ nature of the radiation field and its interaction with the stellar plasma has to be accounted for. This requires consideration of the detailed atomic processes for excitation andionization, as expressed in the rate equations of statistical equilibrium (the non-LTE case).

A "good" model atmosphere should include not only the behaviour of pressure $p(r)$, temperature $T(r)$, density $\rho(r)$ and velocity $v(r)$ with depth r in the atmosphere, but also a prediction of the emergent spectrum, which is a direct and observable diagnostic of the underlying atmospheric properties. We thus need a code that can predict how the spectrum would look like when the star has a certain effective temperature, surface gravity, etc. This code should be sophisticated enough to give an accurate approximation of the real observed spectrum, but at the same time it should be approximative enough to produce a synthetic spectrum within a reasonable computation time.

In stars of the upper main-sequence, the increasing effective temperatures cause the ionisation zones of hydrogen and helium to be shifted more and more towards the stellar surface. As a result the outer convection zones of these stars become thinner and less turbulent. But this absence of turbulent convection does not necessarily lead to ideal, static atmospheres. Some A and B stars show spectroscopic signatures of microscopic and macroscopic transport processes. The diagnostics of these processes yield valuable information about the behaviour of an element under the influence of gravitation and radiation. Even in nonmagnetic stars this leads to a variety of abundance patterns (Hempel & Holweger, 2003). Whereas on the hot end of the main-sequence, radiative processes are dominant and lead to massive radiatively-driven stellar winds in O stars and early-type B stars (Kudritzki & Hummer, 1990)[37].
The transition between the diffusion-accretion dominated atmospheres and the wind-driven atmospheres lies in the region of the late B stars.
Rough values of surface gravity log g, effective temperature T_{eff} and abundances are frequenty derived by assuming LTE model atmospheres. However when the continuous absorption coefficient κ_ν varies as strongly with frequency as in B stars, the usual "gray-atmosphere" solution, formed by replacing the actual absorption coefficient κ_ν by some "mean" value κ independent of frequency, is only an approximation.

So what does that mean?

It means that depending on the ionisation stage and the line strength, deviations from LTE can become significant, and neglecting non-LTE effects (as usual in the case of A and late B stars) can conceal abundance patterns and make correlations insignificant.
Thus it should be noted that the one-dimensional, plane-parallel, assuming LTE and hydrostatic equilibrium Kurucz (1979) ATLAS9 models, which were used by Napiwotzki's (1993) calibration technique to determine the fundamental parameters of the stars using Strömgren photometric indices, and also used in this thesis, could not be a well representative of the atmospheres of our sample B stars. Kurucz (2005) stated that in his ATLAS9 and ATLAS12 codes, the models have only radiative-convective energy transport, no waves, no magnetic energy or pressure, and assume time and horizontal-space averaging. But in fact real stars do not look like that. In real stars convection produces waves that heat the temperature minimum and the chromopshere wherein the spectrum would have chromospheric and non-LTE effects. Therefore, uncertainties on the obtained values of T_{eff} and log g in this work exist due to Kurucz (1979) LTE models which are used in Napiwotzki's calibration to determine the atmospheric parameters of our candidate B stars, in addition to the uncertainties obtained by Napiwotzki's method itself as explained in chapter 3.

Chapter 5

Conclusion

This thesis has been intended to study the fundamental atmospheric parameters of B stars in the Open Cluster Alpha Persei, namely their effective temperatures and surface gravities. The general properties of B stars in terms of their chemical compositions and their peculiarities, rotational velocities and fundamental parameters have been presented in chapter (1), as well as a description of the chosen cluster and the work done on its stars from the literature has been highlighted. Echelle spectroscopy has been obtained for one of the cluster's B stars and the brightest among them (ψ Per), whose frame has been reduced and its spectra extracted in chapter (2). However, due to technical problems we faced in the duration of preparation for this thesis, the data obtained has not been good enough (very low Signal to Noise ratio) to be used in the analysis to derive the parameters of the star as intended. Therefore, the only approach to determining the parameters of these stars has been based on the Strömgren *uvby*-β photometric method and a calibration by Napiwotski et al. (1993) to determine these parameters, which is based on the stars photometric color indices taken from Hauck & Mermilliod (1998) which are sensitive to the temperature and gravity of the star as explained in chapter (3). Napiwotski's code UVBYBETANEW has then been used to derive the parameters of the candidate B stars in the cluster.

The results obtained in this work were then compared to previous work in the literature available for some of these stars, which allowed us to put constraints on the method used by us to determine these parameters in chapter (4). It was found that the results obtained for the B stars which are classified as giants or Be are controversial for their either higher or lower values than expected for surface gravity, since Be stars show emission in the β index which can contaminate its true value, and thus affect the obtained value for surface gravity. In addition, giant stars which have thin atmospheres compared to their radii and thus mixing processes and high mass loss rates can lead to deviation from LTE conditions (Hydrostatic and Radiative equilibria in plane parallel and spherically symmetric atmospheres). Therefore, non-LTE effects need to be taken into account for more accurate modeling of their atmospheres to determine better values of their parameters. However, the model atmospheres used in the calibration of the Strömgren indices into fundamental parameters by Napiwotski et al. (1993) were based on Kurucz (1979) ATLAS9 LTE models, which might have resulted into the higher than expected surface gravity values obtained for the B giant stars in our sample.

Also it was noted that the fast rotation of stars can affect the absorptiom of their β index by what is called an 'incipient emission', which in turn can affect our values obtained for the surface gravity. On the other hand, the color indices of binary stars which are obtained from the combined light of their components imply larger uncertainties and require decoupling of the combined light of their light curves to determine more accurate temperature and surface gravity values.

Finally, we may conclude that photometry can generally lead to an over or under estimation of the surface gravity of stars, since photometric colors are too rough a measure to provide an accurate estimate of the stellar gravity and cannot compete with accurate line fitting through high resolution spectroscopy. Strömgren photometric method and Napiwotski's calibration used alone to determine the fundamental parameters for stars can be used as a rough estimate for normal non-emisson, slow rotating main sequence B stars, which can be a useful method for further abunadance determinations without the need of accurate distance measurements for these stars, however within uncertainties. These uncertainties rise due to the LTE model atmospheres by Kurucz (1979) which are used in Napiwotzki's calibration which may not accurately represent the atmospheres of B stars, since they do not include the effects of convection and mixing processes actually present in stellar atmospheres, specifically for CP stars. Additional uncertainties rise from Napiwotzki's calibration method itself initially based on the Moon & Dworetsky (1985) grids.

For an improvement on the results obtained in this thesis, future spectroscopic observations need to made to fit to synthetic model atmospheres for better determination of the stars fundamental parameters.

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