Magnetic Fields and Chemical Spots in HgMn Stars

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Dissertation presented at Uppsala University to be publicly examined in Håggsalen, Ångström Laboratory, Lägerhyddsvägen 1, Uppsala. Thursday, December 8, 2011 at 13:15 for the degree of Doctor of Philosophy. The examination will be conducted in English.

Abstract

Mercury-manganese (HgMn) stars belong to the class of chemically peculiar (CP) stars. It was recently discovered that some HgMn stars have spots of chemical elements on their surfaces. According to conventional picture of CP stars, magnetic field facilitates the formation and long term stability of chemical spots by controlling stratification of elements in stellar atmosphere. However, previous attempts to find magnetic field in HgMn stars set an upper limit on its strength at the level of about 20-100 Gauss. Observational evidence suggested that even weaker magnetic fields can be responsible for the formation of chemical spots. The main goal of our work was to verify this possibility.

The search for weak magnetic fields requires the use of least-squares deconvolution (LSD) technique. This method combines information from many spectral lines providing a mean line profile with increased signal-to-noise ratio. Up to now there was no extensive comparison of the LSD profile with real spectral lines. We showed that the LSD profile of the intensity spectrum does not behave like a real spectral line as a function of chemical composition. However, for circular polarization, LSD profile resembles the profile of a spectral line with mean atomic parameters.

We performed a comprehensive search for magnetic field in 47 HgMn stars and their companions, based on high-quality spectropolarimetric data obtained with the HARPSpol polarimeter at the ESO 3.6-m telescope. With the help of LSD technique, an upper limit on the mean longitudinal magnetic field was brought down to 2-10 G for most stars. We concluded that magnetic field is not responsible for the spot formation in HgMn stars.

We obtained full rotational phase coverage for the HgMn stars φ Phe and 66 Eri. This enabled us to investigate line profile variability, reconstruct surface maps of chemical elements, and perform a search for magnetic field with very high sensitivity. For φ Phe we derived surface maps of Y, Sr, Ti, Cr, and obtained an upper limit of 4 G on the field strength. We also found marginal indication of vertical stratification of Y and Ti. No magnetic field was detected in both components of 66 Eri, with an upper limit of 10-24 G. We discovered chemical spots of Y, Sr, Ba, and Ti, in the primary star. We demonstrated a relation between the binary orbit and the morphology of these spots.

Keywords: Chemically peculiar stars; magnetic fields; spectropolarimetry; Doppler imaging

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ISSN 1651-6214
urn:nbn:se:uu:diva-160308 (http://urn.kb.se/resolve?urn=nbn:se:uu:diva-160308)
To Tatjana, Vadim, Victoria, Alexander, Svetlana, and my friends
List of Papers

This thesis is based on the following papers, which are referred to in the text by their Roman numerals.


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Papers not included in the thesis:


### Contents

1. Astrophysical background .................................. 9
2. Magnetic fields and structure formation ...................... 11
3. Normal and peculiar B-type stars ............................ 13
   3.1 Normal B-type stars .................................... 13
   3.2 Chemically peculiar magnetic stars ....................... 14
   3.3 Mercury-manganese stars ............................... 14
4. Goals of this study ......................................... 17
5. Methods ................................................. 19
   5.1 Spectral lines in magnetic field ........................... 19
   5.2 Instrumentation ....................................... 20
   5.3 Least-squares deconvolution ............................ 20
   5.4 Spectrum synthesis .................................... 22
   5.5 Doppler imaging ....................................... 23
   5.6 Vertical stratification ................................... 24
6. Summary of papers ........................................ 25
   6.1 Paper I ............................................... 25
   6.2 Paper II .............................................. 28
   6.3 Paper III .............................................. 29
   6.4 Paper IV .............................................. 31
   6.5 My contribution to the papers ........................... 33
7. Future prospects .......................................... 35
8. Sammanfattning .......................................... 37
9. Acknowledgements ........................................ 41
1. Astrophysical background

Chemical elements play a crucial role in our studies of the evolution of the Universe. According to modern cosmological models, the three lightest chemical elements – hydrogen, helium, and lithium – originated during the first few minutes after the Big Bang. Other chemical elements, up to iron, have been formed in hot and dense stellar interiors during nuclear fusion processes. Chemical elements heavier than Fe are formed during s- and r-process in different generations of stars (Rauscher & Patkós 2011). Thereby, stars can be used as natural laboratories, that allow us to study the evolution of chemical elements in the Universe.

Precise studies of the chemical composition of the Universe on large scales is extremely challenging and not yet affordable. Due to the instrumental limitations, we cannot explore very distant objects at the level of detail that can be achieved for relatively close ones. The information about chemical composition of stars is imprinted in their spectra. Spectral line intensities carry the information about chemical abundances. However, the intensity of a spectral line is a function of not only abundance, but other physical parameters of a star, like temperature, surface gravity, turbulent and rotational velocities, etc. The combination of all these parameters allows for stellar classification.

Systematic abundance analysis revealed the phenomenon of chemical peculiarity: while some stars having the same temperatures and masses as “normal” exhibit dramatically different chemical compositions. We believe that these differences are superficial, reflecting atomic stratification in convectively stable outer layers caused by radiation-driven diffusion (Michaud 1970). The diffusion process as complicated and difficult to model. This makes the studies of stars important not only from the perspective of evolution of the Universe, but also from the point of better understanding of physical processes, leading to the observed abundance differences and peculiarities.
2. Magnetic fields and structure formation

The presence of magnetic field in stellar atmosphere, has significant impact on its structure, leading to formation of chemical or temperature spots. Since the first discovery of magnetic field in solar spots (Hale 1908), a giant leap was made in understanding of solar magnetism, both theoretically and observationally (Rempel et al. 2009). Thanks to the proximity of the Sun, we are able to resolve its surface (Fig. 2.1) and perform measurements of magnetic fields across the solar surface. These studies provide a better understanding of the interaction between magnetic field and gas in the surface layers of a star. It is thought that the solar magnetic field prevents the energy outflow, resulting in the formation of relatively cool zones, observed as temperature spots.

However, the Sun is not the only star that hosts magnetic field in its atmosphere. The first discovery of magnetic field in a hot star 78 Vir, which belongs to Ap-type, was made by Babcock (1947). Later, magnetic fields of various strength and geometrical complexity have been detected in Ap-Bp and He-weak stars (Borra & Landstreet 1980; Bohlender et al. 1993). Besides magnetic field, some chemically peculiar (CP) stars show variations in spectral line profiles. The explanation was suggested by Deutsch (1957), who introduced an oblique rotator model. According to this model, the spots of chemical elements produce periodic variations in spectral lines due to the rotation of a star. Subsequent development of numerical method, based on oblique rotator model, provided first two-dimensional maps of star spots (Goncharski et al. 1981). With the development of instrumentation and numerical methods, it became possible to reconstruct surface maps of chemical spots (Bohlender et al. 2010) and magnetic field (Kochukhov & Wade 2010) with high precision. The use of magnetic Doppler imaging technique showed a relation between magnetic fields and temperature or chemical spots (Lüftinger et al. 2010; Kochukhov et al. 2011b).
Figure 2.1: The image of the solar surface obtained with the help of Swedish Solar Telescope (SST). Dark regions are the temperature spots, induced by magnetic field.
3. Normal and peculiar B-type stars

The subject of our research are mercury-manganese (HgMn) stars. In this chapter we introduce the properties of stars of spectral type B, to which the majority of HgMn stars belong. The spectral type B includes stars, which cover the range of effective temperatures from 10000 to 31000 K, stellar masses vary from 2.3 to 7.2 M⊙ (Gray 2008b). Their luminosity may reach $10^4$ L⊙. In its turn, the late B stars are represented by less hot ($T_{\text{eff}} \leq 15000$ K) and less massive ($\leq 4$ M⊙) stars.

First, we will discuss the parameters of B-type stars, which are considered as “normal”. Then we will discuss magnetic B stars and the role of magnetic field in the formation of surface inhomogeneities and non-solar abundances. Finally, a detailed overview of non-magnetic chemically peculiar class of HgMn stars will be given.

3.1 Normal B-type stars

An extensive survey, focused on the fundamental parameters of late B-type stars, was carried out by Niemczura et al. (2009), where 89 stars were analysed. There were 16 CP stars among the others. Niemczura et al. (2009) determined $T_{\text{eff}}$, log g, $v_\text{e} \sin i$, and abundances of iron-peak elements, finding small underabundance of Si, S, Ti, and Fe. It was noted that the abundances of Mg and Ti increase with effective temperature. Other chemical elements show solar or slightly sub-solar abundances. The range of effective temperatures of these 89 stars is 9500 – 15200 K and surface gravities 3.2 – 4.2.

A major study of the rotational velocities of late B-type stars by Abt et al. (2002), reported that they do not exceed 150 km s$^{-1}$ on average. It was noted that lower $v_\text{e} \sin i$ is more typical for CP stars (Niemczura et al. 2009), presumably because the differential rotation of the star becomes less significant and has lesser impact on the mixing of chemical elements in hot stars (Michaud 1982). Therefore, slower stellar rotation provides better conditions for development of chemical anomalies. In this context, a normal late B-type star has rotational velocity $100$ km s$^{-1} \leq v_\text{e} \sin i \leq 150$ km s$^{-1}$. However, a low rotational velocity is not a sufficient condition for chemical peculiarity. The analysis of three slowly rotating ($v_\text{e} \sin i = 3 – 20$ km s$^{-1}$) late B-type stars ($T_{\text{eff}} = 9750 – 12800$ K and log $g = 3.5 – 3.8$) showed no evidence of peculiarities (Fossati et al. 2009). For most iron-peak elements, a small
overabundance, not exceeding the solar values by more than 0.3 dex, was reported.

From these studies we may consider late B-type star as normal if it is a moderate rotator that has chemical composition close to the solar one. One should bear in mind, that precise abundance determination in this type of stars is a difficult task due to the rotational blending and notable non-LTE effects in spectral lines of some chemical elements (Przybilla et al. 2000).

3.2 Chemically peculiar magnetic stars

Besides the general properties of stars that allow their classification on the Hertzsprung-Russell diagram, the chemical composition is used to attribute them to one or another group. When the chemical composition of a star differs from the solar values, that star is considered as chemically peculiar. CP stars may possess non-uniform distribution of chemical elements over the stellar surface. Detailed studies of these stars showed that this inhomogeneity correlates with the presence of magnetic field (Landstreet 1993).

Chemically peculiar magnetic stars exhibit a wide range of abundance anomalies and magnetic field structures. These stars may have multipolar magnetic field up to several tens of kGauss, which leads to the formation of surface inhomogeneities (Landstreet et al. 1989; Donati & Landstreet 2009). In addition, overabundance of Si, Ti, Cr, Fe, and rare-earth elements can be derived from their spectra. For instance, chemically peculiar silicon-rich stars are known to have strong magnetic fields (Ryabchikova 2004). In addition to mentioned CP stars, one has to take into account helium-type magnetic stars. These stars are sufficiently hot and have weak stellar winds (Bolton 1994). The He abundance correlates with effective temperature of a star. At hotter temperatures chemical peculiarity manifests in form of unusual abundance of helium, the so-called helium-weak and helium-strong phenomena. For the He-strong stars it was found that the periods of photometric and spectral variability are shifted relative to each other (Catanzaro et al. 1999). In some individual stars, the surface abundance pattern may have a complex structure, producing different photometric, spectral, and magnetic field phase curves (Rivinius et al. 2011). Helium stars may also possess very strong magnetic fields of complex geometry (Kochukhov et al. 2011a).

3.3 Mercury-manganese stars

As an example of CP stars lacking a strong, large-scale magnetic field, we will consider mercury-manganese (HgMn) type of stars. They are main se-
quence young stars of A0 – B5 spectral classes, which corresponds to a range of effective temperatures of 9500 – 16000 K (Dworetsky 1993). The majority of these stars are binaries and slow rotators, having $v_e \sin i \leq 50$ km s$^{-1}$, which is not typical for other stars of similar spectral type (Abt et al. 2002). Spectra of HgMn stars typically show strong spectral lines of Hg, Mn, Y, Sr, Ba, Pt, Cr, Xe, Ga, and other, mostly heavy chemical elements.

For a long time, atmospheres of this type of stars have been considered as quiet and chemically homogeneous, compared to another CP stars (e.g. Kochukhov 2004). But based on time-series observations, Adelman et al. (2002) discovered variability of the Hg II line at 3984 Å in $\alpha$ And and presented surface distribution of this chemical element. Follow-up observations of this star discovered the evolution of chemical spots over seven years (Kochukhov et al. 2007). It was unexpected because other spotted CP stars tend to maintain spot morphology over tens of years (e.g. Adelman et al. 2001). For a couple of other HgMn stars, Kochukhov et al. (2005) found variability of the mercury line, implying spotted distribution of this chemical element over the stellar surfaces. AR Aur was studied by Hubrig et al. (2006) and Folsom et al. (2010), who independently reported variability of Hg, Y, Zr, Pt, and Sr lines. Further studies showed the line profile variability of Y, Sr, and Ti in the spectrum of HD 11753. HD 53244 and HD 221507 display variability in lines of Mn and Hg (Briquet et al. 2010). HD 221507 also exhibits variations in Y lines.

In the framework of existing theories, it is the magnetic field, which is responsible for the formation of chemical or brightness spots (e.g. Lüftinger et al. 2010). Thus, a number of spectropolarimetric observations were initiated to search for magnetic field in HgMn stars. The first systematic attempt to detect magnetic field in these stars was undertaken by Shorlin et al. (2002). They measured the mean longitudinal magnetic field component, which is oriented along the line of sight of an observer, and set an upper limit on the field strength at 16 – 100 G. No definite detection of magnetic field was reported. There were other attempts to associate chemical spots with magnetic field. For instance, spectropolarimetric studies of $\alpha$ And performed by Wade et al. (2006) set an upper limit on the field strength at 6 – 19 G. Magnetic study of AR Aur (Folsom et al. 2010), found no field stronger than 20 – 40 G. High-precision measurements of the Stokes V profiles for three sharp-lined HgMn stars also revealed no magnetic field at the level of 1 – 3 G (Aurière et al. 2010).

A couple of space missions observed lightcurves of some HgMn stars aiming at finding variations. The observations of three HgMn stars by CoRoT spacecraft (Baglin et al. 2006) showed weak variations ($< 1.6$ mmag) in two of them (Alecian et al. 2009b). It was suggested that these variations can be caused by pulsations, but more detailed investigations are necessary to prove that. Studies in the framework of Kepler space mission also reported weak photometric variation of one HgMn star. It was
suggested that this variation corresponds to the rotational period of the star (Balona et al. 2011).

These studies illustrate that there is no clear understanding of the exact process of the formation of chemical spots in the atmospheres of HgMn stars. The commonly accepted theory that explains CP star phenomenon, was proposed by Michaud (1970). According to it, the observed surface abundance anomalies in CP stars are due to radiative pressure pushing some chemical elements to the surface, while other elements sink to deeper layers of stellar atmosphere. As the gravitational forces and radiative pressure are nearly identical in those layers, an accumulation of chemical elements may occur. However, it is not clear to what extent this theory can explain the variety of observed surface abundance anomalies in HgMn stars. Recent diffusion models suggest the existence of instabilities, which may change the atomic diffusion (Alecian et al. 2011).
4. Goals of this study

Despite that for the majority of HgMn stars no magnetic field was detected stronger than 20 – 100 G, the possibility of weaker fields was not ruled out. Therefore, the main goal of our study was to perform a magnetic field search with a high sensitivity for a statistically significant sample of HgMn stars and to answer the question about the presence of weak, possibly complex, magnetic fields.

A few HgMn stars were reported to exhibit spectral variability, indicative of a non-uniform distribution of some chemical elements over the stellar surface. This raises a number of questions. Is it a typical property of HgMn stars to have spots of chemical elements? What is the geometry of these spots? What is their relation to stellar properties? To answer these questions, we have obtained phase-resolved observations for a few HgMn stars, which enabled us to perform the spectral line variability search and investigate surface distributions of chemical elements.

Besides the magnetic field as a key mechanism responsible for spot formation, we investigated possible relation between the morphology of spots and other stellar parameters, such as binarity and chemical composition.

We assessed physical properties of the least-squares deconvolution technique. LSD has proven to be a robust approach in analysis of rather weak polarisation signal in Stokes V spectra, but the fundamental assumptions underlying this method, have not been verified numerically. The main aim of our experiments was to understand the properties of the LSD profiles and compare them with those of a real spectral line.
5. Methods

The work, presented in this thesis, is based on a number of methods, both instrumental and numerical. Here we will discuss the physical effects, observed in spectral lines, affected by magnetic field. Then we consider spectropolarimetry as a method and give a short overview of the polarimeter used in our study. This is followed by the description of numerical methods of data handling and analysis.

5.1 Spectral lines in magnetic field

Intensity is defined as energy per unit wavelength (or frequency). What is observed coming from the star in form of spectrum, is called “monochromatic flux”. Once continuum normalised, it is often called “residual intensity”. Stellar spectra contain information about stellar surface layers. By modeling the observed spectrum, we can estimate the effective temperature of a star, its surface gravity, metallicity, abundances of individual chemical elements, etc. The effects of magnetic field can be visible in the intensity spectrum if the field strength is greater than a few hundred Gauss (Anderson et al. 2010). Magnetic field leads to line splitting, known as Zeeman effect.

Normal Zeeman splitting of a spectral line is the simplest case and observed as a triplet. Magnetic field causes spectral line to split in two $\sigma$ and one $\pi$ component. “$\sigma+$” and “$\sigma-$” components characterise the blue- and redshifted parts of the line profile, respectively, while $\pi$ component corresponds to a central wavelength. In particular, when one observes along the direction of magnetic field, $\sigma-$ component will produce positive (right-handed) circular polarisation if the magnetic field points to an observer, and negative (left-handed) circular polarisation when the magnetic field has reverse orientation. Whereas the behaviour of $\sigma+$ component is the opposite. The $\pi$ component in this case will give rise to linear polarisation.

With the help of polarimeter, one can study vector characteristics of the polarised light. Photons emitted in the presence of magnetic field, have preferential behaviour of electric vectors. This behaviour depends on the configuration and strength of the magnetic field. Spectropolarimetry enables the analysis of stellar light vector properties in terms of Stokes I, V, Q, and U spectra. Stokes Q and U are the characteristics of linear polarisa-
tion, Stokes V characterise circular polarisation, and Stokes I represents the intensity.

To describe each Stokes parameter, let’s consider a coordinate system so that X and Y axes point orthogonally to each other and to the line of sight, which we assign to Z. The X axis will be our reference direction. Then the Stokes Q parameter will characterise the difference between oscillations of electric field vector along X and Y axes. Stokes U parameter characterises the difference of electric field vector oscillations along the axis, positioned at $+45^\circ$ and the axis at $-45^\circ$. Stokes V characterises the difference between clockwise and counterclockwise oscillations of electric field vector. We consider clockwise rotation of the electric vector at a reference point in space to be corresponding to right-handed polarisation, while counterclockwise rotation corresponds to left-handed polarisation (Shurcliff 1962). All the magnetic field measurements presented in this thesis are based on Stokes V spectra.

5.2 Instrumentation

For actual polarisation measurements, we used a newly-built polarimeter, attached to the HARPS spectrograph (Mayor et al. 2003). The HARPSpol polarimeter (Piskunov et al. 2011), was built by a consortium led by Uppsala University. The polarimeter consists of two independent units equipped with super-achromatic retarder plates, $\lambda/2$ and $\lambda/4$, for linear and circular polarisation recording, respectively. Each unit has its own Foster prism, which serves as a beam splitter. The compact design of the polarimeter allowed us to mount it at the Cassegrain focus of the 3.6-m ESO telescope, thus minimising possible instrumental polarisation. Light passes through the polarimeter to the fibre heads, being fed to the HARPS spectrograph. HARPS is well-known for its intrinsic stability and a high resolving power of 115 000. The combination of all these factors enables polarimetric sensitivity down to $10^{-5}$ (Piskunov et al. 2011).

5.3 Least-squares deconvolution

In the case of weak magnetic field, the Stokes V signal in individual lines may become undetectable because noise dominates. Solving this problem in a direct way, i.e. by obtaining observational data with extremely high signal-to-noise ratio, is very costly in terms of observing time. An introduction of multi-line technique provided a compromise between exposure times and signal-to-noise (SNR) ratio, necessary for weak magnetic field search. On the one hand, the intensity of signal in individual Stokes V profile depends on the strength of spectral line in the intensity spectrum, Stokes I.
On the other hand, intensity of Stokes V also depends on the magnetic field strength and magnetic sensitivity of a spectral line, which is characterised by respective Landé factor.

The line addition technique, so-called least-squares deconvolution (LSD) (Donati et al. 1997), is based on two key assumptions.

1. All spectral lines are identical in shape.
2. Blends are added up linearly.

These two assumptions allow to represent stellar spectrum as:

\[ O(v) = \sum_i w_i \delta(v - v_i) Z(v_i), \]  

where \( O(v) \) can be either \( 1 - I/I_c \) or \( V/I_c \). \( w_i \) here is the weight of \( i \)th line, \( \delta \) is a delta function, and \( v_i \) is the respective position of a line. \( Z(v_i) \) is a mean profile. In this form, a stellar spectrum is described as a superposition of scaled and shifted mean profiles. Introducing line mask:

\[ M(v) = \sum_i w_i \delta(v - v_i), \]  

we can write the model spectrum as a product of matrix \( M \) and vector \( Z \):

\[ O_M = M \cdot Z, \]  

where \( O_M \) is a vector, having size of the number of points in an observed observed spectrum (\( N_{\text{obs}} \)). \( Z \) is a vector, consisting of the number of LSD profile points (\( N_{\text{LSD}} \)) and \( M \) is a line matrix with dimensions of \( N_{\text{obs}} \) by \( N_{\text{LSD}} \). Having observations and a line mask, we need to find \( Z \), so the problem reduces to a solution of the matrix equation:

\[ Z = (M^T \cdot S^2 \cdot M)^{-1} \cdot M^T \cdot S^2 \cdot O. \]  

\( S \) is a square matrix with diagonal elements containing the inverse of pixel variance, computed at the stage of data processing. Equation (5.4) allows to determine such LSD profile \( Z \) that it will reproduce the observations \( O \) in the best possible way. This method yields a gain in SNR between 10 and 1000, depending on available number of spectral lines and intrinsic SNR of input data (Donati et al. 1997).

LSD I and V profiles are then used for the mean longitudinal magnetic field measurements. Since HgMn stars do not possess strong magnetic field, we can employ a relation which is valid in weak line limit:

\[ \langle B_z \rangle = -7.14 \times 10^6 \frac{\int V(v - v_0) dv}{\int (1 - I) dv}. \]  

21
Written in this form, Eq. (5.5) provides result in Gauss. For normalisation we used the effective Landé factor set to unity. The integration limits are set, based on the width of LSD I profile.

We employ false alarm probability (FAP) to assess magnetic field detections in the situations when the LSD V profile is complex or symmetric, yielding zero longitudinal magnetic field. FAP is a $\chi^2$ statistics, which computes a probability that the Zeeman signature is statistically indistinguishable from noise.

5.4 Spectrum synthesis

The interpretation of an observed spectrum is done with the help of theoretically computed spectrum, based on certain assumptions regarding physical properties of a star. Besides knowledge of the stellar parameters, we need a model atmosphere and a list of spectral lines. Model atmosphere specifies the distribution of temperature, electron density, and pressure with depth in the outer stellar layers for a specific effective temperature and surface gravity of a star. In our studies, we made use of model atmospheres, provided by ATLAS12 (Kurucz 1993) and LLmodels (Shulyak et al. 2004) codes. To compute synthetic spectrum, we must specify the elemental abundances and solve the radiative transfer equation, which in general form can be written as:

$$\mu \frac{dI_\nu}{d\tau_\nu} = I_\nu - S_\nu,$$

where $\mu = 1$ is the distance from the center, if disk radius is set to unity, $I_\nu$ is the radiation intensity at a given optical depth $\tau_\nu$, affected by the source function $S_\nu$. Source function defines the ratio of emissivity ($\sigma_\nu$) and absorption ($k_\nu$) coefficients.

Utilising the model atmosphere and line list, we solve the radiative transfer equation (5.6) using column mass as the depth scale:

$$\mu \frac{dI_\nu}{\rho dx} = k_\nu (S_\nu - I_\nu).$$

In this study, we use spectrum synthesis code SYNTH3 (Kochukhov 2007) together with the information about atomic parameters of spectral lines from the line list, provided by Vienna Atomic Line Database (VALD, Piskunov et al. 1995). Specific intensities are calculated for seven $\mu$ positions. This particular number provides sufficient accuracy for disk integration. The sphericity effects are omitted in our case, since the size of stellar atmosphere is much smaller than the stellar radius.
The spectral synthesis method is the base of our work, which is used not only at the stage of spectral line identification, but also in Doppler imaging analysis and stratification calculations. A detailed description of the spectral synthesis code can be found in the publication by Kochukhov (2007).

5.5 Doppler imaging

A stellar spectrum is not only a rich source of information about fundamental stellar parameters and chemical composition, but it also may have an imprint of various surface inhomogeneities. The mechanisms that cause distortion of spectral lines are different. For instance, large-scale convective motions (Gray 2008a) or differential rotation of a star (Skelly et al. 2008) may severely change the shape of spectral lines. In the context of this work, we will consider one type of surface inhomogeneities – spots of chemical elements (Lüftinger et al. 2010).

The Doppler imaging (DI) technique (Piskunov 2008) helps us to decode the information contained in spectral lines of those chemical elements, which are concentrated in spots, and thus reconstruct detailed maps of a stellar surface. As the star rotates, the spot will be observed at a different position on the stellar disk. Therefore, the availability of time-series observations with sufficient rotational phase coverage is crucial.

In this study, we use the DI code INVERS10 (Piskunov & Kochukhov 2002), which works as follows. The stellar surface is divided into a certain number of equal elements, where each of them is represented by a local profile. This profile is characterised by an individual value of Doppler velocity and depends on the abundance of a corresponding chemical element. The integration of these individual profiles should reproduce an observed spectrum at each rotational phase. The parameters (elemental abundances) of all local profiles are changed iteratively to minimise the discrepancy between the observed and integrated profiles, providing the best-fit synthetic spectra. To arrive at unique solution, we apply Tikhonov regularisation.

To perform Doppler imaging calculations, we need to specify the atomic line data and model atmosphere, needed for a spectrum synthesis, set the rotational velocity, inclination angle of rotational axis of a star relative to the line of sight of an observer, and typical abundance of chemical element we want to study. The end products are 2D maps and corresponding synthetic profiles. The latter allow to assess visually the model fit at each rotational phase.
5.6 Vertical stratification

For a normal star, we consider a stellar atmosphere having homogeneous distribution of chemical elements with depth. However, in the case of CP stars such an assumption may not be valid (Ryabchikova et al. 2002). The non-uniform vertical distribution of a certain element will have an effect on the wings or cores of corresponding spectral lines. The anomalous shape of spectral lines can be revealed by means of spectral synthesis, computed under the assumption of stratification absence. Each spectral line forms at a different depth in stellar atmosphere and is characterised by a number of atomic parameters (e.g. excitation potential, ionisation state, line strength, etc.). When we observe spectral lines that can be separated in groups of low and high excitation energies and one group cannot be fitted with a model spectrum, we may suspect the presence of stratification. One should be aware of possible interplay between effects of stratification and atomic parameters of considered spectral lines. The purpose of stratification analysis is to determine the abundance of a particular chemical element at each layer of model atmosphere. Obtained distribution of chemical elements with depth, allows for correct interpretation of the stellar spectrum and to understand the atmospheric structure of a studied object. Our stratification analysis made use of DDAFit code (Ryabchikova et al. 2005).

Stratification model is represented by a step-like function, which characterises an abundance change with the depth in stellar atmosphere. It has four free parameters: upper and lower layer abundances, the width of an abundance step on a scale log $\tau_{5000}$, and the position of a step in a stellar atmosphere. For each combination of the stratification model parameters, DDAFit computes the vertical abundance distribution of a particular chemical element and writes it into the model atmosphere. Then spectrum synthesis code utilises an updated model atmosphere to compute a theoretical spectrum for individual line profiles, selected for stratification analysis. Determination of the stratification model parameters continues until the least discrepancy between observations and theoretical line profiles is found.
6. Summary of papers

6.1 Paper I

A wide use of the least-squares deconvolution technique Donati et al. (1997) has shown its reliability in magnetic field measurements (Shorlin et al. 2002; Alecian et al. 2009a; Aurière et al. 2010). The general assumption regarding the LSD profile is its similarity to a real spectral line. Nevertheless, no numerical tests have been performed to verify this assumption. We initiated a comprehensive study of physical properties of the LSD profiles for intensity and polarisation spectra.

In Paper I we formulated the general principle of the LSD technique and considered the physical assumptions regarding line profiles in Stokes I and Stokes V, Q, U. We described in details how the line mask should be compiled for intensity and polarisation spectra. The process of numerical implementation of the LSD technique is explained step-by-step, making it rather transparent for understanding.

A couple of new features have been introduced to the LSD technique. Discussed modifications are implemented in the code called iLSD. It allows to compute multiple LSD profiles in one run, provided that the input line mask has more than one line pattern. A single line pattern will result in a mean profile, containing contribution from blends. Using several line masks allows to take into account this contribution by selective treatment of different groups of spectral lines. Another improvement consists in implementation of regularisation, which minimises the amplification of noise caused by direct deconvolution. In case when the input data is very noisy, regularisation may improve detectability of a weak signal. We provided guidelines for proper normalisation of LSD profiles, necessary for interpretation of their amplitude.

Before we proceed with the description of numerical results, it is worthwhile to mention the common scheme, which underlies our experiments. First, we simulate a theoretical spectrum, which has well-known parameters and take it as an observed one. Then we apply our iLSD code, which provides mean profiles, and compare them with real spectral lines.

In the assessment of self-similarity of spectral lines in all Stokes parameters, we simulated theoretical spectra for various magnetic field strengths and orientations for isolated spectral lines. It was illustrated that the LSD Stokes I profiles do not scale according to the central line intensities. A somewhat better similarity of the LSD I profiles can be obtained by using
equivalent widths as a scaling factor. The similarity between Stokes V and corresponding LSD profiles is reasonable as long as the field strength does not exceed 2 kG. For the Stokes Q we noted a significant line-to-line variation from similarity condition with an increasing field strength. The main conclusion here is that the similarity of Stokes V profiles is a more robust assumption in the framework of LSD technique, rather than in the case of linear polarisation or intensity profiles.

To compile line mask, one has to set a cut-off criterion for line selection. We analysed the behavior of the LSD Stokes I profiles for various cut-off values and came to the conclusion that larger values lead to more significant depression of LSD I profiles relative to the continuum level. We illustrated the performance of multi-line LSD technique by comparing computed profiles for selected chemical elements with the profiles derived for other chemical elements considered as background. We conclude that multi-profile LSD treatment of individual chemical elements yields a more realistic LSD I profile, avoiding continuum depression caused by contribution of blends.

A number of tests were preformed to estimate the accuracy of longitudinal magnetic field measurement from the LSD V profiles. For that we employed synthetic spectra of different magnetic field strength and orientation. It was shown that the LSD method is capable of recovering the true magnetic field strength value with an error of up to $\approx 7\%$ for 1 kG. The result depends on the selection of integration limits on the velocity scale of LSD profile. For stronger fields the error can be twice as large.
Next series of magnetic tests were aimed at the assessment of the LSD profiles for linear polarisation. In general, the similarity assumption of Stokes Q profiles does not provide an LSD profile that could be matched by a real spectral line. This result was obtained for a magnetic field of various strength and orientation. Therefore, in application to the linearly polarised spectra, LSD technique should be used as a diagnostic technique only.

Finally, we assessed the similarity of intensity profiles and their corresponding LSD. We computed mean profiles from theoretical spectra of different abundances assumed for one chemical element, and measured their equivalent widths. It was noted that the curve of growth for LSD profiles is less steep than those of the real spectral lines (see Fig. 6.1).

Then we compared profiles of the real spectral line, whose curve of growth was the closest to the one of LSD, with the corresponding LSD profiles. As the abundance increases, the LSD I profiles become wider, showing lesser central depth, compared to the real spectral lines. LSD profiles also get more offset from the continuum level at higher abundances, while at lower ones, they appear to be stronger in central depth, relative to the profiles of the real spectral line (see Fig. 6.2).

Therefore, we conclude that the assumption of similarity between the LSD profile and a real spectral line is not fully correct for the intensity spectrum. Hence, LSD cannot be used for a direct estimate of the abundances in a stellar spectrum.
6.2 Paper II

The presence of magnetic fields in HgMn stars has been debated over the last decade (Hubrig et al. 2001; Shorlin et al. 2002; Wade et al. 2006; Aurière et al. 2010; Folsom et al. 2010). This discussion is closely related to the discovery of spectral line variability in HgMn star $\alpha$ And by Adelman et al. (2002), who showed a non-uniform surface distribution of mercury in the form of chemical spots. Later, for the same star Kochukhov et al. (2007) discovered the evolution of chemical spots over seven years. Such a phenomenon was not observed earlier in any star of similar type.

Generally it is believed that the formation of temperature and chemical spots is caused by magnetic field (e.g. Lüftinger et al. 2010). Attempts to find magnetic fields in HgMn stars set an upper limit on the mean longitudinal magnetic field at $16 – 100$ G (Shorlin et al. 2002; Folsom et al. 2010). For a few stars, an upper limit on the field strength was set at $1 – 19$ G (Aurière et al. 2010; Wade et al. 2006). Besides these few precise magnetic field measurements, no extensive survey was performed previously for other HgMn stars.

Making use of Ap, HgMn, and Am catalogue compiled by Renson & Manfroid (2009), we selected a list of HgMn stars whose rotational velocities do not exceed $70$ km s$^{-1}$ and visual magnitude is brighter than $m_v = 7$. Employing newly built polarimeter HARPSpol (Piskunov et al. 2011), installed at the 3.6-m ESO telescope, we obtained high-quality circularly polarised observations of 41 targets. Spectra have SNR = $150 – 400$ and resolving power $R = 115000$.

To measure the magnetic field, we used the LSD technique, which provided $S/N$ gain factor of $5 – 17$, depending on the number of available spectral lines. We estimated the mean longitudinal magnetic field, using the relation (5.5). For one star, HD 71066, we reached the $\langle B_z \rangle$ error of 0.81 G, while for majority of other HgMn stars we set an upper limit on the mean longitudinal magnetic field strength at $2 – 10$ G. We detected no longitudinal magnetic field in any of these stars. Our results are presented in Fig. 6.3.

In some cases, the geometry of magnetic field may be rather complex, leading to zero value of the Stokes $V$ integral. To exclude such situations, we employed false alarm probability (FAP), which is a $\chi^2$ statistics. The larger the FAP number, the higher the probability that the analysed signal is just a random noise, while smaller FAP numbers characterise a real signal. For all LSD profiles we obtained FAP numbers that $> 10^{-3}$, which corresponds to no detection.

In Paper II, we have demonstrated that HgMn stars do not show globally organised magnetic fields stronger than $\approx 10$ G. FAP analysis also confirmed no detection of signal presence in the LSD Stokes $V$ profiles. On the other side, the equipartition field strength, which would be sufficient to influence
gas in the line forming region has to be 60 – 180 G. Our measurements show much lower limit of possible magnetic fields and hence, completely rule out the magnetic field as the main mechanism responsible for the formation of observed inhomogeneities.

6.3 Paper III

This paper presents a detailed study of HgMn star, 66 Eridani, which is a binary with two stars of nearly identical parameters. The primary star is HgMn, while secondary seems to have no significant overabundances of the chemical elements.

The magnetic field measurements in both stars were performed with the help of LSD profiles. We set an upper limit on $\langle B_z \rangle$ at 14 G for the HgMn star and 20 G for the secondary. FAP analysis revealed no presence of magnetic signal.
To search for the line profile variability, we had to disentangle the orbital motion from the intrinsic variability of spectral line profiles. The routine of spectral disentangling, described by Folsom et al. (2010), provided individual spectra of the primary and secondary components. In addition, we have obtained a set of high-precision measurements of the radial velocities of two stars. Combination of our RV measurements with those that have been published earlier, allowed to improve the orbital parameters significantly.

We have redetermined fundamental parameters of two stars, using Padova evolutionary tracks (Girardi et al. 2000). Evolutionary masses and radii allowed us to determine the angles of the orbital and rotational inclination. We found the orbital motion and rotation of two stars to be synchronised and corresponding axes to be aligned.

Figure 6.4: Orbital motion and rotation of the components in the binary system 66 Eri. The star with spots (of yttrium) represents 66 Eri A and the other filled with a solid colour represents 66 Eri B. The radii and the separation between the two stars are shown to scale.
The line profile variability search showed that Y, Ti, Sr, and Ba seem to be distributed non-uniformly over the surface of the primary star. No line profile variations have been detected for the secondary. To reconstruct surface maps of variable chemical elements, we employed Doppler imaging (DI) code INVERS10 (Piskunov & Kochukhov 2002). For better interpretation of the line profile variability, the code was used in a multi-line mode for the first time for HgMn stars. It was discovered, that the spots of chemical elements show relative overabundance on the hemisphere, which is directed away from the secondary. On the other hand, the spot of relative underabundance was found on the hemisphere facing the secondary (see Fig. 6.4). The fact that orbital motion and rotation are synchronised, suggests that such a distribution may be due to the tidal effects and illumination by the secondary.

### 6.4 Paper IV

The fourth paper is dedicated to a detailed study of HgMn star, $\varphi$ Phoenicis, for which chemical spots were investigated by (Briquet et al. 2010), but it has not been previously studied with spectropolarimetry. We have obtained 17 observations in Stokes I and V, which provided us full rotational phase coverage.

The abundances of most chemical elements were unknown for $\varphi$ Phe before our study. The parameters of model atmosphere were redetermined with the help of Strömgren photometric indices and calibration by Moon & Dworetsky (1985). The weights for Stokes I mask were recomputed after the adjustments of abundances of the individual elements to match the observed spectral lines.

Magnetic field measurements were performed using the LSD I and V profiles, yielding $<B_z> < 4$ G. We tested a hypothesis, suggesting that it is more likely to detect magnetic field in spots of chemical elements. Using our iLSD code, the mean profiles were computed for individual chemical elements, known to be variable. Magnetic field measurements confirmed no signal presence in Stokes V, setting an upper limit on the mean longitudinal field at 8 – 15 G. We ruled out the possibility for magnetic field to concentrate in spots of chemical elements for this particular star. The line profile variability search showed changes in the shape of Y, Sr, Ti, and marginal variations in Cr lines. To check that variability of Cr lines is not a spurious effect, the LSD technique was employed. It was found that indeed Cr varies very weakly.

A few studies suggested that $\varphi$ Phe is a binary with the orbital period of 40 days (Dworetsky et al. 1982; Leone & Catanzaro 1999). To examine this, we computed the LSD I profiles for non-variable chemical element – Fe. Using their gravity centers, the value of radial velocity was determined for each
Figure 6.5: Surface maps of Y, Sr, Ti, and Cr. The abundance scale is normalised to the Sun. Darker colour denotes relative overabundance, while brighter zones show relative underabundance.

observation. We found no trend in radial velocity that could suggest its possible change over the period of 40 days.

The Doppler imaging code INVERS10 (Piskunov & Kochukhov 2002) was employed, providing surface maps of Y, Sr, Ti, and Cr. We noted a somewhat similar spot morphology, compared to 66 Eri. All four chemical elements show a relative overabundance on the same hemisphere, but appear to be much more compact (Fig. 6.5). We also noted the presence of the second, less pronounced chemical spot in maps of Ti and Cr. The smallest abundance difference between over- and underabundance zones, $\Delta = 0.15$ dex, was found for Cr.

It was suggested that chemical spots in HgMn stars may float only in the upper layers of stellar atmosphere, forming “chemical clouds” (Michaud et al. 1974). This hypothesis implies a non-uniform distribution of chemical elements with depth in atmosphere. Probing vertical stratification based on the optical part of a spectrum is rather challenging task for hot stars, since most of the necessary information contained in the UV. However, we were able to identify a few spectral lines of Y and Ti, useful for the stratification analysis.

We used the stratification model, discussed in Sect. 5.6. Assuming that Y and Ti concentrate only in the upper layers, we allowed the code DDAFit
(Kochukhov 2007) to vary abundance in the upper layers. The analysis, performed for various positions of the abundance step in the stellar atmosphere, showed a marginal indication of the vertical stratification for Ti. The fit of observed spectral line profiles improves by 0.02%, compared to the homogeneous distribution. Whereas for Y, the stratification model produces systematically worse fit than vertically homogeneous model. These results lead to a conclusion that $\phi$ Phe possesses no notable vertical stratification of chemical elements.

6.5 My contribution to the papers

In Paper I I have shown that the LSD profile of the intensity spectrum does not depend on the abundance as it does a real spectral line. This paper was mainly written by Oleg Kochukhov, except Sub-section 3.5, in which I describe studies of the LSD profile properties as a function of chemical composition. The rest of numerical experiments and their interpretation was done by Oleg Kochukhov.

In the framework of Paper II, I have compiled the target list and carried out the observations with the 3.6-m ESO telescope in La Silla, Chile. I did data processing and analysis. I computed the LSD profiles and measured the magnetic field in 98 individual spectra. I performed the analysis and interpreted results. Paper II was written by me and significantly corrected by Oleg Kochukhov and Nikolai Piskunov.

Paper III is based on my observations and presents a detailed study of the HgMn star 66 Eri. I processed the data, computed LSD profiles, estimated the magnetic field, and performed spectral disentangling. The fundamental parameters of 66 Eri were determined from the evolutionary tracks by Oleg Kochukhov. He also provided the orbital solution and Figs. 4 and 5 (see Sect. 5 and 6 in Paper III). I performed the search for variable spectral lines, which were later utilised by Oleg Kochukhov in DI calculations. I interpreted DI maps for Ti, Sr, Y, Ba, and suggested a relation between the observed spot topology and binarity. Figures 7–10 (see Sect. 8 in Paper III) were produced by Oleg Kochukhov. Paper III was written by me.

Paper IV the analysis was based on the data collected by me at the 3.6-m ESO telescope. I reduced the data, computed LSD profiles and measured the mean longitudinal magnetic field. I did estimates of the magnetic field in spots of chemical elements, based on LSD profiles of variable spectral lines. I searched the whole spectral range of our data for variable spectral lines, computed Doppler maps and interpreted them. I also performed stratification analysis in the atmosphere of $\phi$ Phe and interpreted results. This paper was written by me.
7. Future prospects

This study has addressed some of the most important questions about physics of HgMn stars. We showed that strong magnetic field does not have to be the main mechanism of spot formation. Current theoretical study suggests that the atomic diffusion in the atmospheres of HgMn stars may become unstable under the influence of some physical mechanisms (Alecian et al. 2011). It is possible to assume that weaker magnetic fields located in higher layers of atmosphere, may somehow change the diffusion. Recent measurements of extremely weak magnetic fields (Petit et al. 2010, 2011) suggest a similarly sensitive magnetic field survey of selected HgMn stars, in particular, slowly rotating.

Yet another open question about HgMn stars concerns the phenomenon of surface inhomogeneities. Namely what we need to know, is can this be considered as a short-time evolution mark or is this a property gained by HgMn star at its birth and carried during the life on a main sequence. Understanding of the time-scales of spot evolution is connected to the instability of atomic diffusion.

We have shown that there is a connection between spot morphology and binarity. However, such connection is poorly studied and further investigation should be helpful in confirming or disproving such relation.

As for the future projects, one may consider useful the time-series spectroscopy of HgMn stars aimed at spectral line profile variability search in UV and optical parts of the spectrum. Each of the studied star must have sufficient rotational phase coverage, necessary for interpretation of line profile variability. The success of systematic studies will be based on following conditions:

• Identical instrumental setup during the whole project;
• Consistent data processing algorithms;
• Repeated observations of individual targets after 1–2 years break;
• High signal-to-noise ratio of the data (>500) and resolving power (>60000).

The combination of all these points will ensure the detection of weak spectral line variability and will allow to model surface distribution of chemical elements for significant fraction of HgMn stars. This should be sufficient to constrain the physical conditions that may favor unstable atomic diffusion.
Universum innehåller många olika typer av stjärnor som jag studerar för att förstå deras egenskaper och universums utveckling. Ett sätt att göra detta är att studera deras grundämnessammansättning. Denna information är kodad i stjärnornas spektra och kan tas fram och analyseras med hjälp av astronominiska instrumenten och datorer. Här kommer jag först att diskutera de observationstekniker som denna studie baseras på och sedan fokusera på de viktigaste vetenskapliga resultaten.


Ämnet för denna avhandling är en-typ av ”kemiskt pekuljära” stjärnor, som kallas kvicksilver-mangan-stjärnor. Framträdande spektrallinjer av Hg och Mn är grunden för klassifikationen. Senare har ovanligt kraftiga spektrallinjer av yttrium, strontium, gallium, platina, barium och andra mestadels tunga grundämnen också upptäckts i spektra av dessa stjärnor. Trots att dessa objekt har studerats i mer än 50 år har tidsvariationer i dessa spektrallinjer inte upptäckts förrän för ett decennium sedan. Mer detaljerade studier visade att orsaken är en ojämna fördelning av olika grundämnen över
stjärnornas ytor i kombination med att stjärnorna roterar och visar olika sidor mot Jorden.

De flesta forskare är överens om att de kemiska inhomogeniteterna, som vanligtvis observeras i form av fläcker, orsakas av magnetfält. Men ett antal försök att mäta magnetfält i HgMn-stjärnor, vilket alltså förväntades förklara fläckfenomenet, har inte lyckats upptäcka dem ens på en relativt låg nivå. Studier av andra stjärnor med fläcker gav vid handen att svaga magnetfält ändå kunde vara ansvariga för stjärnytoras olikformigheter. Å andra sidan hade inga statistiskt signifikanta observationer av svaga magnetfält i HgMn stjärnor gjorts tidigare.

Vi har därför inlett en omfattande spektropolarimetrisk undersökning av HgMn-stjärnor för att söka efter svaga magnetfält med hjälp av ett av de bästa instrumenten i världen. Vi har också studerat variationer i spektrawninvariationerna hos några HgMn-stjärnor för att försöka förstå sambandet mellan fläckmorfologen och stjärnornas individuella egenskaper.


Artikel II beskriver vi sökandet efter magnetfält i HgMn-stjärnor som tidigare inte visat spår av magnetfält ens vid extremt låga nivåer. Dessutom visar vi också att styrkan av magnetfältet måste vara betydligt högre än våra övre gränser för att orsaka bildandet av kemiska fläcker.

Artikel III är tillägnad en detaljerad studie av HgMn-stjärnan 66 Eridani som är en dubbelstjärna och därför upvisar två spektra. Baserat på observationer som omfattar hela rotationsperioden i detta system utförde vi en fasupplöst magnetfältanalyser och sökte efter variationer i linjeprofiler hos båda komponenterna. Inga magnetfält upptäcktes i någon av stjärnorna. En analys av variabiliteten avslöjade en ojämn fördelning av yttrium, strontium, barium, och titan på ytan av den ljusaste av stjärnorna vilken är HgMn-stjärnan, medan den ljussvagare verkar vara normal. En analys av dubbelstjärnans banparameter visar att banrörelse och rotation för de två stjärnorna är synkroniserade. Detta innebär att stjärnorna alltid vänder samma sida mot varandra. Vi rekonstruerade ytor och forskningen av grundämnen med hjälp av doppleravbildningsteknik och upptäckte att koncentrationerna av yttrium, strontium, barium, och titan på HgMn-stjärnan är lägre på den sida som vetter mot den ljussvagare stjärnan, medan den andra sidan visar ett relativt överskott av dessa grundämnen. Vi tror att tidvatteneffekter i kombination med
strålningen från den mycket närbelägna ljussvagare stjärnan kan förklara
den observerade fördelningen av grundämnen.

Artikel IV presenterar en analys av HgMn-stjärnan \( \varphi \) Phoenicis för vilken
förekomsten av kemiska fläckar tidigare hade rapporterats. Inga tidigare
spektropolarimetriska observationer hade dock gjorts för att söka efter
magnetfält. Vi observerade Stokes I och V spektra som sträcker sig över alla
rotationsfaser och använde LSD-teknik för att försöka mäta magnetfältet.
Inga magnetfält upptäcktes heller i denna stjärna. Linjeprofilernas
variabilitet bekräftade tidigare resultat och visade också extremt svaga
variationer i profiler av grundämnet krom. Våra kartor över stjärnans yta
visade en liknande morfologi av fläckar som vi funnit för 66 Eridani, även
om de på \( \varphi \) Phoenicis upptar en mindre yta. Vi drar slutsatsen att detta
beror på att \( \varphi \) Phoenicis inte är en dubbelstjärna.

De mekanismer som leder till de observerade fläckarna på ytan av vissa
HgMn-stjärnor är fortfarande okända. Nya teoretiska studier tyder på att
atomär diffusion i dessa stjärnor kan påverkas av någon icke-magnetisk
fysikalisk process. Vi har ännu inte statistiskt tillräckligt omfattande data för
hur typiskt är det för HgMn- stjärnor att ha kemiska fläckar och hur dessa
fläckar kan vara relaterade till dessa stjärnors fysiska egenskaper. Mer de-
taljerade studier av dessa objekt kommer att sprida ljus över fysiken bakom
de observerade fenomenen.
I thank my supervisors Oleg Kochukhov and Nikolai Piskunov for offering such a fantastic possibility to pursue astrophysical studies with world-class instruments. I am indebted to them for all their support, which made these fascinating results being available to scientific community and general public. My gratitude to Andreas Korn and Bengt Gustafsson for their scientific advises and interesting discussions, which changed my life. I thank Ulrike Heiter for teaching me how to use SME code. Bengt Edvardsson is thanked for helping me to make “Swedish” summary really Swedish. I really appreciated help by Samuel Regandell, who was always ready to help with the library queries. My gratitude is expressed to Vladimir Pavlenko, who, besides interesting discussions, contributed to the improvement of my presentation skills. I thank all other people from the Department of Astronomy and Space Physics, who made the working environment pretty stimulating. I believe, this will continue.

Apart from local people, I thank all my co-authors for their valuable comments to the papers. Perhaps, I would not consider a scientific career without my uncle, Vadim. Being an astronomer, he showed me all the beauty of science and I am endlessly indebted to him for it. I thank my wife, Tatjana, for her infinite love, care and support. I thank my parents Alexander and Victoria for bringing me up the way I am. I thank my grandmother, who despite all the obstacles in her life, made it to this day to see me becoming the Doctor of Philosophy.

Finally, I am thankful to my friends, who have been by my side, when we both needed support.

21 of October 2011, Uppsala
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Acta Universitatis Upsaliensis

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