The Zeeman effect in stellar spectra

Review

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Abstract. A short biography of Pieter Zeeman is presented. The main formulae for the normal, anomalous, quadratic Zeeman effect and Paschen-Back effect are given. Instrumentation for Zeeman effect measurements in stellar spectra is described, the most important scientific achievements in magnetic star investigations with the world's largest telescopes for 50 years are demonstrated. The devices for magnetic measurements made at SAO and the main results of stellar magnetic observations obtained with the 6 m telescope are described in detail.

1 Introduction

Since the discovery of the Zeeman effect by Pieter Zeeman in 1896, it has proven to be an extremely powerful tool for the study of atoms, radiation and their interaction. The Zeeman effect has provided the most important technique for deriving new information about the physics of stars. A few decades ago the famous astrophysicist H.W. Babcock (who had discovered stellar magnetic fields in 1946) wrote: "Because of fundamental nature of the Zeeman effect and because it permits not only quantitative measurement of field strength but also determination of the direction of the field and its obliquity to the line of sight, it offers an analytical tool of tremendous importance" (Babcock, 1967).

Thanks to a remarkable contingency, in 1996 we celebrate the occasion of the 100th anniversary of the Zeeman effect discovery, the 50th anniversary of first Babcock's measurements and, finally, 20 years ago we started magnetic observations with the 6 m telescope of our observatory.

We have assembled here to recall history and discuss important problems of Zeeman effect measurements in stellar spectra and to celebrate the occasion of all these jubilees.

2 Pieter Zeeman and his discovery

(Following the address of professor A.D. Fokker at the Zeeman Centennial Conference, September 6, 1965)

Pieter Zeeman was born on the 25th of May, 1865 in a village named Zonnemaire five miles from the provincial town of Zierikzee, Holland. His father was a clergyman. He taught him French, so that he could be admitted to the secondary school in the town.

At the age of eighteen, Zeeman happened to see a magnificent aurora borealis. He described it and made a drawing which he sent to the editor of the British weekly "Nature". The editor was well pleased to take it and send a letter to Zeeman addressing it to "Professor Zeeman in the observatory of Zonnemaire".

After finishing the secondary school he had still to pass a supplementary examination in Greek and Latin for admission to the University in the city of Delft. In that period, by a fortunate chance, Zeeman met Kamerlingh Onnes, a young professor of experimental physics in Leiden. He was very much struck by the open inteligence of young Zeeman, who had already read Maxwell's Heat, and been so eager to become an experimenter.

To-day everybody is familiar with the idea that the constituents of atoms of matter are nuclei and electrons. At the time of the discovery of the Zeeman effect nothing was known about electrons. It should be kept in mind that in atoms they have been detected for the first time by means of the Zeeman effect.

The effect of spectral line splitting in the external magnetic field was discovered by Zeeman in the Laboratory of Kamerlingh Onnes in Leiden in the summer of 1896. The thing he saw was a broadening of the yellow spectral lines radiated by sodium atoms. At once professor Lorentz interpreted the effect as a modification of the motions of radiating particles under the influence of magnetic force.

Within a half-year after his discovery Zeeman was appointed a lecturer in the University of Amsterdam. In January, 1897 he started to work there. Unfortunately the rooms rendered at his disposal in the laboratory were on top of the building. The floors were ordinary timber, not at all an adequate support for the very sensitive apparatus and mounting required for making reliable observations and measurements...

Zeeman was greatly pleased when, in 1908, at the Mount Wilson Observatory Hale used with great success the Zeeman effect to investigate magnetic fields in the Sun spots. Zeeman and Lorentz were awarded Nobel prize of 1901. Pieter Zeeman died on the 9th of October, 1943.

3 General information on the Zeeman effect theory

3.1 Basic definitions

Stellar magnetic field study is based on the Zeeman effect, which consists in splitting and polarization of spectral lines in the external magnetic fields.

A single line in a magnetic field is splitted into 3 components in the simplest case. One of these components (π component) is in the unshifted position and the other two (σ components) are shifted symmetrically to the same distance on both sides of the π component. The shift is proportional to magnetic field strength H, all line components are polarized. Polarization properties depend on the angle between the magnetic field direction and the line of sight.

Full explanation of the Zeeman effect was given in the quantum theory of atom.

In the case of weak magnetic field (when L-S coupling is assumed) two kinds of Zeeman effect are present: normal (simple) effect with the triplet splitting of a spectral line and anomalous (complex) effect, when a spectral line is split into a large number of π and σ components, while the Paschen-Back effect and the quadratic Zeeman effect are observed in very strong magnetic fields (when L-S coupling is broken).

3.1.1 Normal Zeeman effect

The triplet splitting is realized for singlet lines only. Singlet levels of atom (spin S = 0) are split in a magnetic field into 2J+1 sublevels, where J is the full angular momentum. Every singlet line with the frequency ν_0 is split into 3 components: π component with the same frequency ν_0 and two σ components with frequencies ν:

$$\nu = \nu_0 \pm 1.4 \cdot 10^6 \cdot H \qquad [\mathrm{Gerz}] \tag{1}$$

(H is the magnetic field strength, Gauss). All line components are elliptically polarized. Two extreme cases are of special interest: observations along and across the magnetic field direction. When we observe along the magnetic field direction (longitudinal Zeeman effect), the central π component is absent while the two σ components of the same intensity are circularly polarized in opposite directions. In the observations across the field direction (transverse Zeeman effect), the components are linearly polarized: however the π component is polarized in the direction parallel with that of the magnetic field, while the σ components — in the direction perpendicular to the magnetic field.

The line splitting in the Zeeman effect is very small: around 0.01 Å in a magnetic field of 1000 Gauss in the generally observed spectral range near λ 5000 Å.

3.1.2 Anomalous Zeeman effect

Most stellar spectral lines (more than 80%) show the anomalous Zeeman effect (for example, see Romanyuk, 1984).

Here we will not consider the line splitting in the anomalous effect in detail, we recommend papers of Mathys and Stenflo (1987a,b).

We will restrict ourselves to some general remarks.

In the case of small field when the Russel-Saunders (L-S) coupling is assumed (Beckers, 1969), *the* spin $S \neq 0$ and each atomic level is split into 2J+1 sublevels with energies E_M:

$$E_M = E_0 \pm 9.27 \cdot 10^{-21} \cdot H \cdot q \cdot M \quad [\text{erg}], \tag{2}$$

where:
E_0 is the level energy in a zero field (erg),
H — magnetic field strength (Gauss),
q — Lande factor of the level,
M — J projection on the direction of H.

Lande factor for each level is determined as:

$$q = 1 + \frac{J(J+1) + S(S+1) - L(L+1)}{2J(J+1)}, \tag{3}$$

where L, S and J are the orbital, spin and total momenta, respectively.

A spectral line in the anomalous effect can be split into a few tens of π and σ components. The splitting picture is fully determined by electron configurations in the atom and is fully explained in the quantum theory in the vector model of the atom. The theory of Bohr is verified by the experimental investigation of the Zeeman effect which can be found in the text-books of physics.

3.1.3 Paschen-Back effect

In very strong (more than 10 kG) fields, when the magnetic splitting becomes stronger than the multiplet splitting, the complex Zeeman splitting gradually gets more simple. This phenomenon, known as the Paschen-Back effect, is the result of L-S coupling broken in a very strong field.

In this case, the energy of level splitting E_M is:

$$E_M = E_O \pm 9.27 \cdot 10^{-21} \cdot (M_L + 2M_S) \cdot H \quad [\text{erg}], \tag{4}$$

where M_L and M_S are the orbital and spin magnetic momenta, respectively.

The Paschen-Back effect for various lines appears in the fields of different strengths, depending on the multiplet structure. The partial Paschen-Back effect needs to be taken into account in all the cases when fields are stronger than 10 kG (Mathys, 1990a; Mathys and Stenflo, 1987a,b). We will consider the influence of the partial Paschen-Back effect a little later.

3.1.4 Quadratic Zeeman effect

Real measurement of the quadratic Zeeman effect may be expected in superstrong, 10^6 - 10^9 G, magnetic fields of white dwarfs and neutron stars as a shift $\Delta\lambda$ of lines shortward of the wavelength scale. For hydrogen lines this shift is as follows:

$$\Delta\lambda = -4.98 \cdot 10^{-23} n^4 \cdot \lambda^2 (1 + M^2) H^2 \quad [\text{Å}], \tag{5}$$

where:
n is the main quantum number,
M — magnetic quantum number,
H — magnetic field strengths.

Unfortunately, the spectra of white dwarfs and neutron stars are very deficient in spectral lines, and magnetic measurements present a problem. The circular polarization of thermal radiation (Kemp, 1970) was used for strong magnetic field detection in white dwarfs (Angel and Landstreet, 1971).

The study of quadratic Zeeman effect in stellar spectra has been initiated by Preston (1970a), Hamada (1971), Trimble (1971). Hydrogen line profiles in DA-type white dwarfs have been calculated by Borra (1973a).

3.2 Calculation and determination of Lande factors

For most stars we cannot observe the Zeeman splitting directly and that is why correct calculation of the Lande factor z is important, z is the weighted mean parameter for groups of π and σ components (in the anomalous effect), which characterizes the magnetic sensitivity of a line.

Extensive calculations of the Lande factors have been performed, however Beckers' (1969) Tables have been the most popular. The Lande factors for the upper level q^u and the lower level q^l in the case of L-S coupling for multiplets of astrophysical interest have been calculated:

$$z = \bar{q} + \frac{\Delta J \cdot \Delta q (2\bar{J} + 1)}{4}; \; \bar{q} = \frac{q_u + q_l}{2}; \; \bar{J} = \frac{J_u + J_l}{2}; \; \Delta q = q_u - q_l, \; \Delta J = J_u - J_l. \tag{6}$$

Note that in VALD (Vienna Atomic Line Data Base) (Piskunov et al., 1995) the Lande factors have been calculated according to Beckers (1969).

The Lande factors for different types of coupling are discussed. For example, in the paper by Mathys (1990a) the Lande factor z is calculated for the case of J-l coupling

$$z = 2(qJ - 1)\frac{K(K+1) + J(J+1) - l(l+1)}{(2J+1)(2K+1)} + \frac{(2J+1)}{(2K+1)}, \tag{7}$$

where J, L and S are replaced by the J, L and S quantum numbers of the parent level. K is the quantum number of corresponding to the coupling of the total angular momentum l of the electron.

The Lande factor values can be determined in laboratory experiments, most of which can be found in extensive compilations of atomic data. The accuracy of these experimental values is generally rather good and quite sufficient for astrophysical applications (Mathys, 1990a). However, the Lande factors of many levels of astrophysically interesting ions have never been determined in laboratory.

In the magnetic tape of atomic data for lines of iron-period elements Kurucz (1969) has included the values of the Lande factors. These values are experimental ones, whenever available, or have been derived from detailed computation of the atomic eigenvectors.

Mathys (1990a) compared the Lande factors computed by Kurucz and those computed by simple formulae as in (3), (6) and (7). It is however likely that some of Kurucz's values are still rather inaccurate, and in particular, much less accurate than most experimental values. Nevertheless, in view of incompleteness of the laboratory data, Kurucz's new magnetic tape of atomic data for the lines of iron-period elements is a major contribution to improved studies of stellar magnetic fields, and its use in this context can be recommended.

More than 95% of well measured spectral lines in magnetic stars have the Lande factors z within a 0.5 — 2.0 range.

Of course, lines with $z > 2$ are preferable for magnetic measurements, but usually they are weak. We present lines with $z > 3$ (Romanyuk, 1984), practically useless for old photographic measurements, but can be usefull for modern CCD measurements (Table 1).

Table 1: Lines with the Lande factor $z > 3$

λ	Element,multiplet	z	lg gf
3119.3	Gd II (10)	3.00	-
3139.6	Fe I (161)	3.00	-4.63
3158.2	Fe I (160)	3.25	-3.55
3162.3	Fe I (159)	3.17	-
3175.9	Fe I (333)	3.00	-1.87
3221.9	Fe I (156)	3.00	-0.69
3228.9	Fe I (157)	3.00	-3.39
3270.5	Gd II (92)	3.67	-
3390.8	Gd II (73)	3.67	-0.42
3417.3	Gd II (91)	3.33	-0.10
3462.9	Mn II (12)	3.00	-1.25
3598.9	Fe I (322)	3.00	-1.83
3815.5	V I (28)	3.33	-1.46
3867.2	Gd II (50)	3.00	-1.20
3908.9	Fe I (153)	3.00	-4.58
3966.4	Fe II (3)	3.00	-6.87
4070.2	Mn I (5)	3.33	-1.09
4080.8	Fe I (557)	3.00	-
4116.6	V I (27)	3.33	-0.82
4210.3	Fe I (152)	3.00	-1.05
4327.1	Gd II (-)	3.00	+0.04
4558.0	Gd II (44)	3.20	-1.54
4654.7	Cr I (186)	3.00	-0.81
4878.2	Fe I (318)	3.00	-1.07
5175.8	Gd II (114)	4.00	-
5250.2	Fe I (1)	3.00	-4.84
5986.5	Fe II (24)	3.00	-6.23
6258.5	V I (19)	3.33	-

3.3 Partial Paschen-Back effect

The above-said refers to the case of weak magnetic field where the quadratic Zeeman effect is negligible, and the magnetic splitting of the levels is small compared to the fine structure splitting of the term where they belong. These conditions are generally fulfilled for the field strength of a few tens of kG, but does not always hold true. In a magnetic field of 10 kG, the energy shift of the atomic levels must be studied using the theory of partial Paschen-Back effect (Mathys, 1990a; Mathys and Stenflo, 1987).

The shape of the Stokes line profiles formed in the presence of magnetic field depends not only on the magnetic field structure and effective Lande factor, but also on the type of anomalous Zeeman splitting pattern, which is determined by the atomic structure.

Mathys' conclusion has to be taken into account:

- while a line formed in the pure Zeeman effect has the same central wavelength as in the absence of magnetic field, lines formed in the partial Paschen-Back regime are globally shifted;
- lines formed in the partial Paschen-Back effect are not symmetric about their centre, contrary to lines formed in the pure Zeeman effect;
- in the partial Paschen-Back effect the total strength of a line differs from its strength in the absence of magnetic field.

4 Zeeman effect observations in stellar spectra

4.1 Instrumentation for magnetic measurements

4.1.1 Some general remarks

Observations show that the great majority of main sequence magnetic stars have fields less than 10 kG. Only 3-4 stars are in exception. As a result, the Zeeman splitting is no larger than 0.2 **A** in the visual spectral range. And that is why direct observations of splitting in stellar spectra are practically impossible because the line widths are usually larger than 0.1 **A,** mainly due to rotation of the star. There are only a few stars with the splitting measurable directly (Mathys, 1990b).

But the Zeeman effect consists not only in splitting but also in polarization of spectral lines. Using these properties astronomers have developed different methods of magnetic field measurements: magnetic shift measurements, narrow-band circular and linear polarization measurements across the spectral line profiles, magnetic broadening measurements and others.

Beginning in 1946 magnetic observations have been carried out on the largest telescopes of the world. Based on the observations, we know that magnetism is a wide-spread phenomenon in stars: different kinds of explosions, flares and other non-stationary processes are the result of magnetic field action. Magnetic fields have been discovered in different types of stars but the most reliable measurements have been made for the main sequence CP stars.

In connection with the 20th anniversary of magnetic measurements with the 6 m telescope, we consider it worthwhile to give sufficient attention to description of stellar magnetic field observations in Russia and especially with the 6 m telescope. Note that usually large coude spectrographs are used for magnetic measurements. Star light reaches a spectrograph, having been reflected from several inclined mirrors, which causes strong and variable instrumental linear and circular polarization, depending on the angle of inclination of the mirrors. The altazimuthal mounting of the 6 m telescope (Ioannisiani, 1977) permits large spectrographs at its Nasmyth foci to be installed. Star light is reflected from a single inclined (at a constant angle=45°) mirror, which permits the effect of instrumental polarization to be taken into account in a simplier manner. This makes the 6 m telescope especially attractive for magnetic observations.

Magnetic field investigation is one of the most important problems in modern astrophysics. That is why different kinds of apparatus for magnetic field measurements have been developed and made in our observatory for the 6 m telescope (Bychkov et al., 1988). Now we will consider different kinds of magnetic observations.

4.1.2 Magnetic shift measurements

Since the discovery of magnetic fields of solar spots by Hale (1908) all the attempts to find stellar magnetic fields have ended in failure.

The problem was first resolved successfully by Babcock in 1946, who constructed a special differential analyzer of circular polarization and found a dipole magnetic field in peculiar A stars. Double-polarized spectra, obtained by Babcock, permitted measuring the shift of lines in stellar spectra, in the presence of large-scale magnetic field.

The value $\Delta\lambda$ of the shift is defined by the formula (Babcock, 1958)

$$\Delta\lambda = \pm 4.67 \cdot 10^{-13} \cdot z \cdot H \cdot \lambda^2 \quad [\text{Å}], \tag{8}$$

where:
H is the longitudinal magnetic field strength,
z — the Lande factor of a line.
A more detailed explanation you can find in (Babcock, 1958).

Note that Babcock made observations of a few hundred stars. Up to now magnetic observers have used the same, slightly modernized Babcock's analyzer with the largest telescopes of the world: 5 m Palomar and 2.5 m Mt.Wilson (Babcock, 1947, 1958), 3 m Lick (Preston and Pyper, 1965), 2.2 m Hawaii (Wolff and Bonsack, 1972), 2.7 m Mc Donald (Vogt et al., 1980), 3.6 m ESO (Mathys and Stenflo, 1986), 2 m Tautenburg (Scholz and Gerth, 1981) and others.

A specific achromatic circular polarization analyzer for the 6 m telescope was made by Najdenov and Chuntonov (1976). Because we cannot observe a clear Zeeman splitting in stellar spectra, observations of magnetic displacements of oppositely circularly polarized spectra or measurements of circular polarization inside spectral lines are used (both for longitudinal field determination). Transversal field observations need linear polarimetric measurements and the difference in sharpness of lines in two opposite linear polarizations to be found. The accuracy of transversal field determination is over one tenth as high as for longitudinal field.

It should be borne in mind that relatively low accuracy photographic measurements had been used up to the late 80s. Modern observations with precision CCD equipment have a short history. The accuracy of shift measurements depends strongly on the line width. In particular, it is impossible to measure magnetic field on photographic plates if the line width is larger than 1 Å. The use of CCD moved this limit to 2-3 Å. For such lines an accuracy of 500 G is possible to achieve.

The magnetic measurements of the first 10 years were collected in the well-known Babcock catalogue (1958), containing 89 magnetic stars. During the 50 years of measurements astronomers have obtained about 20000 Zeeman spectra. About 1000 stars have been measured and 150 of them have been found to have magnetic fields. The accuracy of measurements is generally 100 - 200 G, depending on the type of stars.

Most of the measurements have been made in USA by G. Preston, S. Wolff, W. Bonsack, K. Stepien, D. Pyper. A great activity is demonstrated by G. Mathys (ESO) and J. Landstreet (Canada).

Measurements with the 6 m telescope were started 20 years ago, in 1976 (Glagolevskij et al., 1977). More than 2000 Zeeman spectra have been obtained. The greatest activity in magnetic observations with the 6 m telescope is exercised by the astrophysicists in SAO (Yu.V. Glagolevskij, V.D. Bychkov, V.G. Elkin, I.I. Romanyuk, and occasionally I.M. Kopylov, V.G. Klochkova, S.N. Fabrika and others); institutes in Russia (Moscow group: V.L. Khokhlova, T.A. Ryabchikova, N.E. Piskunov; St.Petersburg group: Yu.N. Gnedin, T.N. Natsvlishvili); Ukraine (Crimean observatory: A.B. Severny, V.M. Kuvshinov, S.I. Plachinda, N.S. Polosukhina, V.P. Malanushenko); Germany (E. Gerth, G. Scholz, S. Hubrig, E. Zelwanova, W. Schoneich and others), Czech and Slovak Republics (Z. Mikulashek, J. Ziznovsky, Yu. Zverko, J. Budaj); Bulgaria (I. Iliev), Switzerland (P. North); Canada (W. Wehlau, J. Matthews, G. Wade).

The first attempt of linearly polarized spectrum observations have been made by Kodaira and Unno (1969) and they showed no evidence of transverse field in the known bright star HD 112413.

SAO and Moscow groups made attempts to take linear Zeeman spectra for the same star with measurable Q and U Stokes parameters (Glagolevskij et al., 1984).

4.1.3 Circular polarization measurements

Circular polarimetry inside spectral lines was proposed independently by A.B. Severny (1970) and J. Landstreet (1970). New devices, photoelectric magnetometers with electrooptical modulators, were created for this purpose. Devices of this kind measure circular polarization with a very high accuracy (better than 0.01%). It is possible to discover and measure very weak (tens of Gauss) magnetic fields in different type bright stars provided that the distribution of the V Stokes parameter across the line profile is known with that accuracy.

Crimean astrophysicists started their observations with a modernized solar magnetometer mounted at the coude focus of the 2.6 m telescope (Kuvshinov et al., 1974), later on at the Cassegrain focus (Bukach et al., 1977). Kuvshinov (1974) has done much work for instrumental polarization investigation's. It has been shown in practice that high resolution V Stokes parameter measurements with a one-channel photoelectric magnetometer can be made for the brightest stars only and require too much observing time. The result is the small number of measurements obtained at CrAO.

J.D. Landstreet and his colleagues made a few different magnetometers: high resolution magnetometer (Borra and Landstreet, 1973), Balmer-line magnetometer (Borra and Landstreet, 1980) and others. There is no need to use high spectral resolution in the Balmer-line magnetometer and then narrow-band (~ 5 Å) filters are used for selection of a required spectral range. The Balmer-line magnetometer of Landstreet is known to magnetic people as a very good and long-lived device. Most photoelectric magnetic measurements were made by Landstreet and his collaborators. The total number of such measurements cannot be overestimated, it amounts to a few thousand (Landstreet et al., 1975; Borra and Landstreet, 1977; Borra and Landstreet, 1980; Landstreet, 1982 and others). Observations with this magnetometer were carried out at various telescopes: from the 5 m Palomar giant telescope to the 1.2 m telescope of the University of Western Ontario.

The magnetic field H from the measured V Stokes parameter is determined by the formula below (Borra and Landstreet, 1977). V_R and V_L polarizations are measured in the right and the left wing of the line. Average polarization $< V >= (V_R - V_L)/2$. $< V >$ depends on the field strength H in the following manner:

$$< V >= 4.67 \cdot 10^{-13} z H (dI/d\lambda)/I_\lambda, \tag{9}$$

where

I is the observed profile,

z — the Lande factor, approximately equal to 1.0 for hydrogen lines.

For most A stars in the case of H_β observation

$$H(\text{Gauss}) = 13000 < V > \%. \tag{10}$$

The shape $(dI/d\lambda)$ of hydrogen line profiles is more or less constant for various stars, thus for the magnetic fields measured from hydrogen lines the following correlation is true: 1% of $< V >$ corresponds to a 10-20 kG magnetic field. The shape of narrow metallic lines is essentially higher and in this case: 1% of $< V >$ equals to a 500 G magnetic field.

High accuracy (better than 0.01%) measurements of $< V >$ are very difficult to achieve as a result of variable instrumental polarization. Bright stars with weak fields are more preferable for high resolution measurements of metallic lines, while extended measurements of 6-8 magnitude stars (especially fast rotating) with the Balmer-line magnetometer are more effective.

Both types of magnetometers for the 6m telescope were made.

1. The high-resolution (~0.08 Å) magnetometer with a Fabry-Perot interferometer permits observations without loosing light on the slit of the spectrograph (which is typical) (Glagolevskij et al., 1979; 1988). The use of the Fabry-Perot interferometer increases the efficiency of the magnetometer, but even so it can be effectively used only for magnetic measurements of bright stars.

2. The hydrogen-line magnetometer of the 6 m telescope is based on the spectrograph. For spectral band selection special movable mask-slits are used (in contrast to the narrow band filters in Landstreet's magnetometer) (Shtol', 1984; Shtol' et al., 1985). Masks of various sizes were made and spectral band from 3 Å to 300 Å is possible to select. This makes it possible to measure the circular polarization, both inside the spectral lines and in the continuum in a wide spectral range, 4000 — 6000 Å. A few hundred measurements of magnetic field and broad-band circular polarization were made with this magnetometer-spectropolarimeter.

A detailed description of both magnetometers can be found in the paper of Bychkov et al. (1988).

4.1.4 Linear polarimetric measurements

The linear polarization of spectral lines in the Zeeman effect is very small, 0.1% - 0.01%. The theory is well developed (for example, the book of Dolginov et al., 1979, and the new edition of Dolginov et al., 1995, and references therein).

J-L. Leroy (1962) developed a theory of broad-band linear polarization measurements. The results of 55 magnetic star measurements were published in the series of papers (Landolfi et al., 1993; Leroy et al., 1993; 1995; Bagnulo et al., 1995; Leroy, 1995), and in the present issue. Leroy (1993) published a catalogue of linear polarization measurements of 1000 nearest stars.

The transverse Zeeman effect in the CP star 53 Cam was investigated by Borra (1973) and Kemp and Wolstencroft (1974). Borra and Vaughan (1976) carried out a high resolution linear polarimetry of β CrB across the Fe I 4520 line. They found the Stokes U and Q parameters to rotate with the rotational period of the star and thus confirmed the oblique rotator model for the magnetic field of β CrB.

The small number of high resolution linear polarimetric measurements is explained as follows: the signal of Q and U Stokes parameters in the transverse Zeeman effect is over 10 times smaller than the V Stokes parameter signal in the same intensity longitudinal effect (in a field of a few thousand Gauss).

4.1.5 Four Stokes parameters

Full information on the Zeeman effect can be derived from measuring the 4 Stokes parameters with a high spectral resolution. But this is a very involved observing problem because too much light from a star is needed and it can be resolved well only for the Sun.

We measured the 4 Stokes parameters in a broad band centered on the 5200 Å depression known in many CP stars, using the Balmer-line magnetometer (Shtol' et al., 1988). No real polarization was measured with the 6 m telescope for some stars. The main problems in our measurements are 1) too much observing time is needed to measure each Stokes parameter separately; 2) calibration and standardization of measurements.

4.1.6 Magnetic broadening measurements

Magnetic fields exist not only in CP stars. Fields can be of complex structure, of very large or very small intensity and cannot be found by Zeeman effect measurements. Various methods of magnetic field investigation are given in the review of Gnedin and Natsvlishvili (1996, this issue).

We present in this section a variety of methods of magnetic field measurements, based on investigations of spectral line magnetic broadening (i.e. Zeeman effect investigations).

It is not possible to observe a clear picture of Zeeman splitting in the case of complex stellar magnetic field structure even in very strong fields. Fine polarization profile analysis permits us to investigate the magnetic field structure of different stars.

Of course, it is possible to measure the magnetic broadening of a line in a dipole magnetic field (for example, Glagolevskij et al., 1988), but the sensitivity of this method is low in comparison to the magnetic shift measurement method. Practice shows that magnetic shift measurements are essentially easier and more sensitive in measuring the longitudinal component of the magnetic field. But the magnetic broadening is possible to be measured using ordinary (not Zeeman) spectra. The number of non-Zeeman spectra is many times over the number of Zeeman spectra since there is no need to use additional specialized polarimetric equipment in observations, and it is possible to use library spectra for analysis. Modeling of measurements needs full information of line profiles to be used.

It should be borne in mind that for magnetic broadening measurements very high-resolution (0.1 **A)** and high S/N ratio (>200) spectra are required. Using such spectra for sharp line stars it is possible to detect a 1 kG magnetic field or larger even using very high S/N spectra, that is about one order larger uncertainties than the accuracy of Zeeman spectra measurements.

Starting from the paper of Boyarchuk et al. (1960) a series of papers describing the magnetic intensification investigations have been published (for example, Ryabchikova and Piskunov, 1984; Ryabchikova et al., 1988). Mathys (1994; 1995) developed moments method, which was successfully used for analyses of a lot of magnetic stars.

4.2 Some results of magnetic measurements

A number of excellent reviews of magnetic stars have been published in last few decades (Babcock, 1958; Ledoux and Renson, 1966; Preston, 1971a; Landstreet, 1980; Khokhlova, 1983, and others). The purpose of the present review is to clear up some important points in the history of stellar magnetic investigations.

15-20 astronomers who demonstrate the highest activity in magnetic field mesurements can be named (references to their papers are present in my review). But the most important contribution to Zeeman effect investigations has been made by H.Babcock, G. Preston and J.Landstreet.

- H.Babcock designed and built the first Zeeman analyzer, discovered stellar magnetic fields. For 10 years he was one, who observed magnetic fields using the 5 m and 2.5 m telescopes. The results of these observations were published in his well-known list (Babcock, 1958), 89 magnetic stars were discovered in this catalogue. Babcock continued his observations in the 60s and discovered, in particular, the largest magnetic field in the AO star HD 215441 (Babcock, 1960). As a result, after Babcock's investigations it became clear that stellar magnetic fields are present, that these are measurable and that Ap stars have strong (few kG) fields of dipole structure.

- G.Preston and his colleagues have found that the longitudinal component of the magnetic field of Ap stars (B_e) varies periodically. The correlations between periodical magnetic field variations and periodical variations of light and equivalent widths of spectral lines convinced astronomers of validity of the oblique rotator model for Ap stars. G.Preston has detected 8 stars with resolved Zeeman components and, as a result, has found the surface magnetic field in those stars (Preston, 1971). The correlation between the surface and longitudinal magnetic field variations also confirmed the oblique rotator model of Ap star (Preston, 1967; 1969 a,b; 1970 a,b; 1971 a,b; Preston and Pyper,, 1965; Preston and Stepien, 1968 a,b,c; Preston et al., 1969, and others).

- H.Babcock and G.Preston ceased their activity in magnetic field measurements. And J. Landstreet, the last of the three "magnetic Mohikans", continues magnetic investigations. J. Landstreet and his colleagues have designed and built a very effective Balmer-line photoelectric magnetometer. They measured rapidly rotating peculiar A stars and some of them were found to be magnetic. Practically all measurements for a new class of magnetic stars (He-rich and He-weak peculiar stars) were made by Landstreet and collaborators. Some unusual stars with a complex magnetic field structure were discovered among those stars (Landstreet, 1990; Borra and Landstreet, 1979; Thompson and Landstreet, 1985; Bohlender and Landstreet, 1990). Landstreet and his co-authors found magnetic white dwarfs (Angel and Landstreet, 1971) with a megagauss field and made measurements for a few dozen objects of this kind. His contribution to the problem of correlation of magnetic field and abundance distribution geometry is known too. Magnetic field and abundance modeling was done first for 2 stars, 53 Cam and HD 215441, and showed an important role of the multipolar components of their magnetic fields (Landstreet, 1988; Landstreet et al., 1989). The list of the most important supplementary papers of J.Landstreet and his collaborators are: Angel and Landstreet, 1971, 1972, 1974; Kemp et al, 1970; Borra et al., 1973, 1983; Borra and Landstreet 1973, 1977, 1978, 1979, 1980; Landstreet, 1978; Bohlender et al., 1987 and many others.

A large number of observations have been made for Ap stars. But other stars have been studied too. A good review paper on magnetic white dwarf investigations was presented by Angel (1978).

Long series measurements of circular polarization in the continuum of 100 white dwarfs and Zeeman effect measurements of 12 white dwarfs were presented by Angel et al. (1981).

Cool stars with local magnetic fields of complex structure are being investigated at the present time. It is not possible to observe a clear Zeeman effect in this case as in a dipole field. Accurate modeling is needed for such field determination. Various methods for such field investigation have been developed (Donati et al., 1989; Semel, 1989; Chugajnov, 1991; Gnedin and Natsvlishvili, 1996, and others).

4.3 Main results of stellar magnetic investigations in Russia

Stellar magnetic measurement is one of the most important observational programs on the 6 m telescope. Today is the 20th anniversary of the first measurement and a short summary of the principal results of magnetic investigations in the former USSR (and Russia), and of observations with the 6 m telescope, in particular, has to be given.

A large contribution to the theory of polarization and line formation in a magnetic field was made by Leningrad (St.Petersburg now) astrophysicists Yu.N. Gnedin, A.Z. Dolginov, N.A. Silant'ev (Dolginov et al., 1979, 1995; Silant'ev, 1988; Gnedin et al., 1972; Pavlov et al., 1975; Gnedin and Silant'ev, 1976, 1984; Gnedin and Pogodin, 1985) and others. The theorists of St.Petersburg school proposed many observation tests for checking the theory and explained many fine polarization effects inside spectral lines and in the continuum. For example, Gnedin and Red'kina (1984) proposed a theory of magnetic field of Herbig Ae/Be stars and possible way of its estimation by polarimetric measurements.

Astrophysicists from the Crimea (Ukraine now) were the first to measure magnetic fields of bright stars using a modernized solar magnetograph (Kuvshinov et al., 1974; Bukach et al., 1977). Now CCD measurements with the 2.6 m telescope are continued.

The Moscow group (V.L. Khokhlova, T.A. Ryabchikova, N.E. Piskunov and others) have been the leader in the investigation of non-uniform distribution of elements on the stellar surfaces. They have developed a mapping technique. As a result of their work it is shown that the non-uniform chemical composition is an ordinary phenomenon in the atmospheres of peculiar stars. It is shown that the most peculiar rare elements are concentrated in small strong spots around the magnetic poles of a star. This is evidence of the corellation between the distribution of elements on the surface and the field configuration (Khokhlova, 1983; Goncharskij et al., 1983; Piskunov and Khokhlova, 1983, 1984; Piskunov et al, 1990, 1994; Wehlau et al., 1991; Piskunov and Rice, 1993, and others).

Now about the main observing programs with the 6 m telescope. Extensive observations of magnetic stars in open clusters of different age were conducted in 1980-1987. It was shown that peculiarities and magnetic fields appear at a very early stage of stellar evolution, before the main sequence (Glagolevskij et al., 1987). Magnetic fields were found in very young stars (see, for example, Straizys et al., 1991).

Many tens of stars with predicted Geneva fields (Cramer and Maeder, 1980) were measured for discovery of new magnetic stars. We have found more than 10 new magnetic stars, the largest magnetic field has been detected in HD 147010, a member of the Sco-Cen association (Glagolevskij et al., 1981, 1986).

Detailed magnetic measurements with rotational period have been made for a few CP stars. The most interesting results have been obtained for 3 of them: 1) CQ UMa shows sinusoidal magnetic field variations, while spectral variations are complex (Mikulashek et al., 1984; Glagolevskij et al., 1985); 2) the information on the magnetic field presence in 21 Per is inconsistent. We have found a very weak (100 G) field and thus verified the hypothesis that all peculiar stars are magnetic stars (Glagolevskij et al., 1995; Elkin et al., 1987); 3) for HD 192678 we have found a magnetic field (Glagolevskij et al., 1981) and performed a cooperative complex investigation and proposed a magnetic model for this star (Wade et al., 1996).

We have searched for magnetic fields in Hg-Mn stars and showed that 10-15 G fields are possible in their atmospheres (Glagolevskij et al., 1985). There are no measurable magnetic fields in some λ Boo stars (Iliev et al., 1988) and in F-Sr λ 4077 stars (North et al., 1992). We have investigated the Zeeman effect in supergiants (Scholz et al., 1984), Ap stars with weak peculiarities (Ziznovsky and Romanyuk, 1990). We have found direct evidence of a very strong and complex magnetic field of the He-r star HD 37776 (Kopylova and Romanyuk, 1992; Romanyuk et al., 1996, and this issue).

Taking advantage of the good violet transparency of the telescope and the spectrograph optics we have taken a series of Zeeman spectra in the 3300-4000 Å band for 3 CP stars (HD 112413, HD 137909 and HD 152107). Thus the Balmer jump is located in the middle of the plate. Spectra were used for search for radial gradient of magnetic field. It is shown that for HD 112413 the magnetic field increases with depth, for HD 137909 we have found a phase shift of 0.15 P between the longitudinal magnetic field curves observed on both sides of the Balmer jump (Romanyuk, 1984; 1986; 1991).

New CCD detectors enable investigation of polarization and magnetic field properties of Herbig Ae/Be stars (Glagolevskij, 1990; 1996). Principal difficulties in the investigation of these objects are the small number of lines and their complex structure.

At last, magnetic observations of white dwarfs with the 6 m telescope have been conducted for the last 10 years (Bychkov et al, 1991 and a series of papers in the present book). The magnetic field of sub dwarfs has been studied by Elkin (1996).

5 Conclusions

The fate of Zeeman effect measurements in astrophysics differs strongly from that of Doppler effect measurements. Although a 1 kG field causes approximately the same magnetic shift (0.02 Å) as the Doppler shift of moving objects at a speed of 1 km/s (in the generally used spectral range around 500(Å), the number of radial velocity measurements are by 3-4 orders larger than magnetic measurements.

The main reasons for this situation are the technical difficulties of Zeeman effect measurements, instrumental effects, which can have influence on measurement results, difficulties in getting observing time at the largest telescopes, and finally, there is no polarimetric equipment at large telescopes.

Nevertheless the introduction of new detectors, a better accuracy of observations and modeling inspires one with optimism for the future and we believe that magnetic investigations of stars are at the initial stage.

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