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Magnetism of stars: the present and the future of ground and space spectropolarimetry

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For more than half a century, magnetic fields have been known to exist in stars. During this time, most efforts were focused on establishing the strength and geometry of fields in stars. The past two decades have seen remarkable advances in spectropolarimetric instrumentation. Enormous progress has been made on observing stellar magnetism in stars at all major stages of stellar evolution, from the pre-main sequence to the main sequence stage, the giant and AGB stages. Recent spectropolarimetric instruments have made it possible to routinely detect stellar magnetic fields as weak as 1 G and even less. As a result, interest is moving towards understanding the origin and evolution of stellar magnetic fields, understanding of the role of magnetic fields in the manifestations of stellar activity and star-planet magnetic interactions and so on. These new challenges require even more precise instruments and techniques. The era of stabilized spectropolarimetry comes. We review the present and the future of ground-based and space spectropolarimetry.

Keywords: Instrumentation: spectrographs, techniques: spectropolarimetric, telescopes, stars: magnetic field

1 Introduction

Babcock (1947) was the first astronomer who detected a magnetic field on a star other than the Sun, the star 78 Vir. He also discovered the most highly magnetic main sequence star, HD 215441, whose field strength is about 34 kG (Babcock 1960). Since those early years, major progress has been made on stellar magnetism thanks to high-quality data coming from surveys covering the full range of stellar masses and spanning all evolutionary phases, including pre-main sequence (e.g. Alecian et al. 2013a,b; Hubrig et al. 2013), main and post-main sequence (e.g. Auriére et al. 2015; Wade et al. 2016; Mathys 2017). The data accumulated by these surveys have allowed researchers to explore the incidence of magnetism among different type of stars, probe their magnetic field strength and structure, and study their field evolution and origin.

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In this paper, we will review some aspects of the present and the future of stellar magnetic field measurements using ground and space spectropolarimetry.

2 Stellar magnetic field measurement techniques

Stellar magnetic fields are detected and measured using the Zeeman effect. In the presence of an external magnetic field B, individual atomic energy levels (with energy E_0, Landé factor g, and total angular momentum J) split into $(2J+1)$ components. Each component is characterized by its quantum number M, where $-J \leq M \leq +J$. The energies of these states are given by the formula: $E(M) = E_0 gM\hbar\omega_{\rm L}$, where $\omega_{\rm L} = eB/(2m_{\rm e}c)$ is the Larmor frequency (here e is the charge of electron, $m_{\rm e}$ is the mass of electron, c is the speed of light).

As a result of this splitting, the transition of an electron between two stationary orbits (energy levels) in the presence of a magnetic field leads to a group of closely spaced spectral lines, Zeeman components, whereas in the absence of a field single lines are generated. Between sublevels, only such transitions are possible, under which M does not change ($\Delta M = 0$) or changes by ± 1 ($\Delta M = \pm 1$). Those lines resulting from transitions where $\Delta M = 0$ are concentrated symmetrically around the unshifted wavelength $\lambda_0 = hc/E_0$. These lines are called π-components, the π-components are linearly polarized. Those lines resulting from transitions where $\Delta M = \pm 1$ are called σ-components, the σ-components are also symmetrically shifted by $\Delta\lambda = \pm(e/4\pi m_{\rm e}c^2)z\lambda_0^2 B_{\rm e} = 4.67 \times 10^{-13} z\lambda_0^2 B_{\rm e}$ (here z is Landé factor) around the unshifted wavelength λ_0 and circularly polarized. Thus, by measuring the Zeeman shift $\Delta\lambda$ between circularly polarized σ-components, one can calculate the longitudinal component $B_{\rm e}$ of the magnetic field of a star.

Another way to measure stellar magnetic fields is to use the Stokes parameters, I, Q, U, and V, where I represents the intensity of the light and Q, U, and V are the different polarization states. Stokes Q is defined by subtracting two orthogonal linearly polarized beams. Stokes U also represent linear polarization but is shifted by 45° with respect to Q. Stokes V is determined by subtracting two beams circularly polarized in opposite directions. It should be noted, that linear polarization in stellar spectra (Stokes Q and U) are weaker than circular polarization by at least a factor of 10. So, the linear polarization signatures can be detected only in the presence of a strong magnetic field or with using intermediate or large telescopes ($D > 3$ m) equipped with high-resolution echelle spectrographs in other cases.

With the advent of CCD detectors, which allow us to record a wide range of the spectrum simultaneously, the new era of spectropolarimetry began. Today the most effective tool set for measuring stellar magnetic fields is the high-resolution echelle spectrograph coupled with a spectropolarimeter. A typical spectropolarimeter includes an entrance retarding achromatic quarter-wave plate (or half-wave plate for linear polarization analysing), and a beam-splitter, which separates the fast and slow linearly polarized beams (see for more detail Donati & Semel 1990; Hubrig et al. 1994). When the telescope is operating in the spectropolarimetric mode, the light from a star is divided into two beams of opposite polarizations, which are fed into the spectrograph. So, these two beams are projected on the plane of the CCD as two spectra with opposite polarization.

Nowadays there is a large collection of portable or stationary spectropolarimeters installed at different telescopes. In Table 1 we summarize the large and intermediate class telescopes, where the regular spectropolarimetric observations are carried out.

Table 1 Main instruments for stellar magnetic field study.

Instrument	Observatory	D, m	λ, nm	$\lambda/\Delta\lambda$	Stokes
FORS2@VLT	Paranal, CL	8.2	330−1100	<5 000	IQUV
MSS@BTA	SAO, RU	6.0	445−500	15 000	V
ESPaDOnS@CFHT	Mauna Kea, US	3.6	370−1050	68 000	IQUV
HARPSpol@ESO	La Silla, CL	3.6	380−690	105 000	IQUV
ESPL@ZTSh	CrAO, RU	2.6	500−700	52 000	V
NARVAL@TBL	Pic-du-Midi, FR	2.0	370−1050	68 000	IQUV
BOES@BOAO	Bohyunsan, KR	1.8	350−1050	60 000	IQUV

To date, two major types of methods have been developed to measure the magnetic fields of stars using the above-mentioned spectropolarimetric tool sets. The methods of the first type (e.g. multiline methods) compute the magnetic field using large arrays of lines in the spectrum of the star simultaneously. The methods of second type (e.g. single-line methods) allow us to compute the magnetic field using any single lines or any set of single lines.

The most famous multiline method is the Least-Square Deconvolution method (LSD). For the first time, this method was proposed by Semel (1989), and then developed and implemented by Semel & Li (1996), and Donati et al. (1997). Least-Squares Deconvolution relies on combining intensity and polarization profiles of a large number of spectral lines into mean Stokes profiles that are characterized by a very high signal-to-noise ratio. This method is based on the assumption that all lines in spectrum have the same profile (and differ only in intensity) and that they can be added linearly. The field strength can be quantified by computing $B_{\rm e}$ and other field moments from the LSD profiles. LSD is sensitive to complex fields, and to magnetic field geometries with a negligible mean longitudinal field or equator-on oblique dipoles.

When using a single-line (SL) method (Hubrig et. al. 1994; Plachinda & Tarasova 1999; Plachinda 2005; Butkovskaya & Plachinda 2007), the Zeeman splitting is calculated relative to the centroids for each unblended spectral line. After this, the homogeneity of the statistical distribution of the obtained values is tested and the average magnetic field is calculated from homogeneous sampling. In contrast to LSD, SL method allows us to measure the magnetic field of any strength by any set of spectral lines having any shape and intensity.

3 Magnetic fields of non-generated stars across the H-R diagram

3.1 Pre-main-sequence stars

Two major classes of pre-main-sequence stars are T Tau stars and Herbig Ae/Be stars. Classical T Tau stars are believed to be almost fully convective and surrounded by gas-dust disks. T Tau stars are very young ($< 10^7$ y) and low mass ($<3M_{\odot}$) stars

(Appenzeller & Mundt 1989). It is widely accepted that their magnetic fields are dynamo-generated. Magnetic fields exceeding 1 kG were found on classical T Tau stars (see, for example, Johns-Krull 2007). The topology of the magnetic fields of these stars is still poorly understood. In particular, Donati et al. (2007, 2008) built ZDI (Zeeman Doppler imaging) maps of two T Tau stars, V2129 Oph and BP Tau, and concluded that their magnetic field geometry is a combination of a relatively weak dipole (0.35 kG and 1.2 kG) and octupole (1.2 kG and 1.6 kG), both slightly tilted with respect to the rotation axis. Magnetic fields of T Tau stars play an important role in their surface and flare activity, accretion and stellar winds (see, for example, Petrov 2003; Johns-Krull 2009).

Herbig Ae/Be stars are pre-main-sequence stars of intermediate mass with outer radiation zones. By analogy to T Tau stars, Herbig Ae/Be stars are also surrounded by gas-dust matter, but their photospheres are hotter. Recent investigations show, that up to 10% of these stars can have simple dipole magnetic fields of a few hundred Gauss (Alecian et al. 2007, Wade et al. 2007). This topology seems to be stable for several years, however, the magnetic field can become very weak or completely disappear when they get to the main sequence (Hubrig et al. 2009).

3.2 Main-sequence stars

Intermediate mass stars. About 5% of intermediate-mass main sequence stars (1.5 to $6M_{\odot}$) between about B8 and F0 display strong magnetic fields with mean longitudinal fields between around 200 G and 30 kG. These are so-called chemically peculiar magnetic Ap and Bp stars. Their magnetic field geometry is stable over at least tens of years and is well described by dipoles whose axis is inclined with respect to the rotation axis (inclined rotator model). A small-scale structure, if present, is not dominant. The observed in Ap/Bp stars magnetic field is most likely fossil field, i.e. the relic of the initial field in the interstellar medium.

The rest of the A-stars population lack magnetic fields above a few Gauss. This phenomenon is called a bimodality in the population of intermediate-mass stars. In intermediate-mass stars such as Vega (A0) and Sirius (A1) a dynamo-generated field could float to the surface from a helium-ionization-driven convective layer beneath the surface (Cantiello & Braithwaite 2011). Long-term variability seems to be present in A-stars. In particular, the year-to-year variability of Vega was detected photometrically by Vasilev et al. (1989a,b) and confirmed by Butkovskaya et al. (2011) from spectral and spectropolarimetric observations. The last authors have determined the variability period of Vega to be equal to 21.28 year.

Massive stars. Magnetism is not a very common phenomenon among massive main sequence stars. It seems that only around 7% of the population host large-scale magnetic fields (Petit et al. 2013) of 300 G − 10 kG, and a variety of geometries. While some of the magnetic stars have an approximately dipolar field, others are found to have a more complicated geometry. It is accepted, that early-type stars have convective layers close to the surface which could generate fields, which then rise to the surface. The convection is driven by bumps in the opacity at certain temperatures, caused by the ionization of iron, helium and hydrogen. Massive stars have two or three such layers, the deepest of which is driven by iron ionization. The longitudinal component of the magnetic field of massive stars, as a rule, varies sinusoidally with

their axial rotation. As in the case of magnetic Ap stars, this "geometric" variability is explained within the oblique rotator model.

However, physical variability can also occur in massive stars. For example, Butkovskaya & Plachinda (2007) reported the modulation of the longitudinal magnetic field in β Cep type star γ Peg (B2 IV) with the amplitude of about 7 G over the 0.15-day pulsation period of the star. Ten years later, a similar variability with pulsation period was reported by Shultz et al. (2017) in another β Cep type star ξ^1 CMa. Butkovskaya et al. (2017b) also suspected the complex variability of the magnetic field of a large-amplitude β Cep type star BW Vul (B2 III) with the 0.2-day period of radial pulsations. Plachinda (2000), Butkovskaya et al. (2014) have registered the modulation of the longitudinal magnetic field of classical Cepheid η Aql with the radial pulsation period of about 7 days. They also noted the variability of the amplitude and phases of the extremes of the longitudinal field from year to year.

Solar-type stars. Main sequence stars with subsurface convection zones from later F to early K spectral classes demonstrate different levels of solar-type magnetic activity. Their global magnetic fields usually do not exceed 10 G, while local magnetic fields (in plages and starspots) are of the order of 1 kG. Fast rotating young stars of the solar type demonstrate high average levels of activity, while slower rotators as old as the Sun and older exhibit lower activity levels. Petit et al. (2008) suggested a change in the magnetic topology of stars rotating at different rate. They concluded, that slower rotators have mostly poloidal fields, large-scale toroidal component appears in the more rapidly rotating stars. Butkovskaya et al. (2017a) for the first time as a result of direct measurements recorded not only the global magnetic field, but also the possible manifestations of the local magnetic field in the yellow subgiant β Aql. From direct measurements of the magnetic field, the authors also have found the activity cycle of β Aql of about 2.7 years.

Low-mass dwarfs. Many of low-mass dwarfs show surface activity qualitatively similar to our Sun and generate flares, high X-ray fluxes, and large scale magnetic fields. Spectropolarimetric surveys of red dwarfs revealed numerous atomic and molecular Stokes V signatures formed in starspots and chromospheres (Berdyugina et al. 2006, 2008). The large fraction of these stars have strong magnetic fields up to 4 kG, with little or no dependence on the mass. Shulyak et al. (2018) have shown that large-scale magnetic fields tend to have simple axisymmetric geometry with dominant poloidal component in stars that are fully convective. In contrast, M dwarfs that are hotter and therefore only partly convective tend to have more complex fields with strong toroidal components. However the authors noted, that there is a number of exceptions when a rapidly-rotating fully convective star generates a large-scale magnetic field with a complex multipole geometry.

3.3 Post-main-sequence stars

Among evolved stars, very weak fields are found in some red giant branch (RGB) and asymptotic giant branch (AGB) stars. The decrease in magnetic activity is observed in RGB and AGB stars due to loss of angular momentum at the stage of the main sequence and after it. The range of magnetic field strength observed on RGB stars is from 1 to 10 G (Konstantinova-Antova et al. 2008, 2009), while AGB stars may show even weaker fields from 10 G near in the photospheres to 10^{-3}–10^{-1} G at the

outskirts of the circumstellar envelope.

RS CVn and FK Com type stars demonstrate the presence of a sub-kG magnetic field (Donati et al. 2003, Korhonen et al. 2009) and exhibit the activity phenomena such as strong chromospheric plages, strong flares in the optical, UV, radio and X-ray, coronal X-ray and microwave emissions.

4 Future ground-based and satellite spectropolarimetric projects

In recent years the explosive discovery of exoplanets around different types of stars became a new booster for evolution of spectropolarimetry. One of the most effective methods for exoplanet searching is radial velocity method, also known as Doppler spectroscopy. The Doppler technique measures the radial velocity variation that an orbiting planet induces on a star. Because the star-planet interaction is mediated by gravity, it is easier to detect close-in and more massive planets. To date the Doppler technique precision improved from about 10 m/s in 1995 to about 1 m/s when HARPS was launched (Mayor et al. 2003). But some intrinsic sources of stellar noise of various amplitudes can contribute to RV measurements at different time-scales. These so-called RV jitters modulate asymmetries in photospheric spectral line profiles by the rotational period of the star and can be confused with a planetary signal or potentially inhibit the detection of planetary signals of low amplitude. Moreover, all periodic RV jitters (i.e. stellar oscillations or temporal and spatial evolution of spots, plages, and convective inhomogeneities) can mimic the RV signature similar to a planet (Saar & Donahue; Saar et al. 1998).

Stellar RV jitters depend on effective temperature, stellar activity, and projected rotational velocity (e.g., Wright et al. 2004). Main sequence F, G and K stars typically exhibit moderate RV jitters about 5 m/s (Wright et al. 2005). Therefore, detection of exoplanets around the magnetically active lower and intermediate mass stars is strongly limited due to magnetic jitters associated with the active regions. The simultaneous determination of magnetic structures on the surface of the star, and the subsequent deduction of these magnetic jitter allow us to search for new exoplanet detections, despite a highly noised radial velocity signal. Thanks to the simultaneous measure of RV modulations and magnetic field measurement, a new field of exoplanet research will be opened. For this scientific goal a radial velocity long-term stability of better than some m/s is needed. Below we shortly review new instruments for stabilized spectropolarimetry.

4.1 Ground-based optical spectropolarimetry

Neo-Narval[*] is an upgrade of Narval for high-precision velocimetry. Neo-Narval is designed to study the RV modulations down to 3 m/s in parallel to measuring the magnetic activity. This capability opens a large spectrum of studies from understanding the impact of stellar magnetism on RV jitters and confirmation of planets around magnetically active dwarf stars to the detection of giant planets around RGB stars

[*]http://www.tbl.omp.eu/en/INSTRUMENTATION2/neonarval

at different stages of evolution. The upgrade of Narval will allow to proceed with on-going Narval projects on stellar magnetism. Commissioning is scheduled for 2018.

HARPS3 is a fiber-fed, high resolution, high stability, robotic-operated echelle spectrograph. It is installed at the 2.5 m Isaac Newton Telescope in La Palma in the Canary Islands, and its design is a close-copy of HARPS (see Thompson et al. 2016 for more detail). Like its predecessor, HARPS3 will be high resolution ($R = 115\,000$), and via two optical fibers will provide simultaneous measurement of the stellar object and a spectral calibration source allowing accurate RV measurements to be made. The wavelength range is $380 - 690$ nm; the blue limit allows the measurement of Ca II lines that are used to monitor the stellar activity cycle. The ability to measure polarization will also provide an alternative and complementary way to monitor stellar activity. The HARPS3 polarimeter can be automatically deployed in the optical path in the Cassegrain adapter to provide dual-beam spectropolarimetry. The polarimetric unit will enable the measurement of both circular V and linear polarization Q, U. HARPS3 also should be able to make high-accuracy RV measurements in which a small (down to 10 cm/s RV amplitude), slowly varying ($100 - 300$ day period) signal can be detected. Commissioning is scheduled for 2018.

PEPSI is the bench-mounted, two-arm, fiber-fed and stabilized Potsdam Echelle Polarimetric and Spectroscopic Instrument for the 2×8.4 m Large Binocular Telescope (LBT), Arizona (Strassmeier et al. 2015). Each telescope simultaneously provides light from its optical axis as well as from an off-axis section to the spectrograph. On the CCDs, every single echelle order consists therefore of four independent spectra, two from the two optical axes of the telescopes and two from the respective off-axis positions. While the on-axis light is always reserved for a target star, the off-axis fibers simultaneously allow either sky light, wavelength-calibration light, or one of the two polarimetric beams. Each polarimeter provides simultaneous spectra of the ordinary and the extraordinary beam. Two polarimetric science modes are currently defaulted to circular Stokes V and linear Stokes Q, U. It takes two spectra for Stokes V and four spectra for Stokes Q and U. Three spectral resolutions of either 43 000, 120 000 or 270 000 can cover the entire optical/red wavelength range from 383 to 907 nm in three exposures. Spectropolarimetry is carried out at a fixed spectral resolution of $R = 120\,000$.

4.2 Ground-based infra-red spectropolarimetry

The Zeeman splitting of a spectral line is proportional to λ^2, so there is a huge leverage in going to the IR. For cool objects most of the flux is in the IR so there is also a gain due to the increased signal-to-noise ratio. Infra-red spectropolarimetry will make it possible to measure with greater accuracy magnetic fields in M-dwarfs and brown dwarfs.

CRIRES+ project (Follert et al. 2014) is the upgrade of the ESO instrument CRIRES (CRyogenic InfraRed Echelle Spectrograph) that was decommissioned in 2014. It was part of the VLT suite of instruments covering the near-infrared domain (Y to M bands) at high resolution ($R = 100\,000$). The original CRIRES was a single-order instrument with short wavelength coverage, poor stability and variable quality wavelength calibration. In 2012 consortium consisting of Uppsala University, Tautenburg Landessternwarte, Institute for Astrophysics of Göttingen University, and INAF

at Florence proposed to upgrade CRIRES optimizing it to study some science cases: (1) characterization of the atmospheres of planetary companions around cool stars, (2) search for exoplanets around cool stars, and (3) origin and evolution of stellar magnetic fields (including study of dynamo action in late M dwarfs and estimation of the stellar activity level experienced by exoplanets in habitable zones of such stars). To achieve these goals, the CRIRES was transformed into an echelle spectrograph and equipped with an infrared polarimeter unit (Lockhart et al. 2014) with high sensitivity and adaptive optics system. Today CRIRES+ upgrade is a unique combination of telescope collective area (installed at an 8 m class telescope), spectral resolution (R = 100 000), accessible wavelength range (0.95 - 5.2 μm) and a high simultaneous wavelength coverage (only 2 − 4 settings to cover the entire J band without any gaps). The polarimetric unit should be able to measure Stokes I, Q, U, V. CRIRES+ also should be able to make high-accuracy RV measurements (down to 3 m/s). Commissioning is scheduled for 2018.

SPIRou (SPectropolarimétre InfraRouge) is a near-infrared high-resolution echelle spectropolarimeter (R = 70 000) that is under design for the CFHT 3.6 m telescope. The main science drivers of SPIRou are the study of magnetic topology of young stars and protostars via spectropolarimetry observations and the search for habitable Earth-mass planets around M dwarfs through very precise (1 m/s) radial-velocity monitoring. SPIRou builds largely on the radial velocity monitoring experience from HARPS and SOPHIE (Perruchot et al. 2008) as well as the spectropolarimetry of ESPaDOnS. SPIRou will operate in wavelength range 1.0 − 2.4 μm and will be able to measure Stokes I, Q, U, V. Commissioning is scheduled for 2018.

SPIP[†] is a copy of SPIRou for TBL. Being simultaneously a high-resolution spectropolarimeter (R = 70 000) and a high-precision velocimeter ($<$ 1 m/s), SPIP will gather a large community of users from various research fields and especially all those working on exoplanets and stellar magnetic fields. Commissioning is scheduled after 2019.

4.3 Spectropolarimetry on space missions

The major advantages of space-based observations are access to wavelength ranges invisible from surface of the Earth and the possibility to collect long data sets that allow us to study long-term stellar cycles and to detect irregular events. Several space missions are in preparation for the coming decades (Weiss et al. 2018). It is expected that these space projects will significantly expand our knowledge of stellar magnetism. In particular high-resolution spectropolarimetry is being developed for the projects Arago and LUVOIR.

Arago will be a 1.3-m space telescope that will perform high-resolution (R = 25 000–35 000) Stokes I, Q, U, V spectropolarimetry simultaneously in the UV and visible domains from 119 to 888 nm. The major goal of Arago is to study the life cycle of matter, including the entire life cycle of stars and planets, impact of hosting stars on the formation of planets and the emergence of life, star-planet interactions (including magnetic interaction), irradiation of the planet by the star (space weather), and others. The project of equipment of Arago with the high resolution spectropo-

[†]http://www.tbl.omp.eu/en/INSTRUMENTATION2/spip

larimeter is studied by CNES & European consortium for M6 (launch in 2032). The project was proposed for M5 but rejected based on cost.

LUVOIR is a concept for a multi-wavelength 15 m observatory, one of four Decadal Survey Mission Concept Studies initiated by NASA in 2016. LUVOIR is planned to be equipped with four instruments: a multi-object low and medium resolution UV spectrograph and imager, a multiresolution visible and IR spectrograph, a coronagraph, and a high-resolution ($R = 120\,000$) Stokes I, Q, U, V spectropolarimeter Pollux. The Pollux will operate in three bands: FUV (90–123 nm) or MUV + NUV (119–220 & 210–390 nm). The major goals of LUVOIR are the study of evolution of galaxy, stars and solar system, star and planet formation, stellar winds and magnetism, exoplanets, white dwarfs, supernovae, and so on. The spectropolarimeter Pollux is studied by CNES & Europian consortium. It will be evaluated with LUVOIR and its other tools at the 2020 NASA Decadal survey.

Summary

Today stellar magnetic fields are in the center of interest because of their influence on stellar structure, magnetic dynamos, stellar activity, habitability of planets, and many other topics. In the recent years the explosive discovery of exoplanets around different types of stars became a new booster for evolution of spectropolarimetry. Together with observations of RV modulations, direct magnetic fields measurements and reconstruction of field geometries allow us to search for new exoplanet detections, despite a highly noised radial velocity signal. For this scientific task, long series of high-precision measurements of magnetic fields are required and new tools for stabilized spectropolarimetry are being developed.

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