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ORIGINAL ARTICLE

UVMag: stellar formation, evolution, structure and environment with space UV and visible spectropolarimetry

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Abstract Important insights into the formation, structure, evolution and environment of all types of stars can be obtained through the measurement of their winds and possible magnetospheres. However, this has hardly been done up to now mainly because of the lack of UV instrumentation available for long periods of time. To reach this aim, we have designed UVMag, an M-size space mission equipped with a high-resolution spectropolarimeter working in the UV and visible spectral range. The UV domain is crucial in stellar physics as it is very rich in atomic and molecular lines and contains most of the flux of hot stars. Moreover, covering the UV and visible spectral domains at the same time will allow us to study the star and its environment simultaneously. Adding polarimetric power to the spectrograph will multiply tenfold the capabilities of extracting information on stellar magnetospheres, winds, disks, and magnetic fields. Examples of science objectives that can be reached with UVMag are presented for pre-main sequence, main sequence and evolved stars. They will cast new light onto stellar physics by addressing many exciting and important questions. UVMag is currently undergoing a Research & Technology study and will be proposed at the forthcoming ESA call for M-size missions. This spectropolarimeter could also be installed on a large UV and visible observatory (e.g. NASA's LUVOIR project) within a suite of instruments.

Keywords Instrumentation: polarimeters · Instrumentation: spectrographs · Techniques: polarimetric · Ultraviolet: stars · Stars: magnetic fields · Stars: winds, outflows · Stars: activity · Stars: chromospheres

1 Introduction

During the formation and the entire life of stars, several physical processes influence their dynamics and thus im-

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pact their evolution. In particular magnetic fields and winds are key factors. They directly affect the internal structure of massive stars (Maeder 2009) and cool stars (Chabrier et al. 2007), the transport of angular momentum (Mathis 2013), the formation and mass accretion phases (Bouvier et al. 2007), and of course the direct circumstellar environment. They thus drive stellar evolution. Therefore the aim of the UVMag (UltraViolet and Magnetism) space project is to study the formation, structure, evolution and environment of all types of stars in particular through the measurement of their winds and possible magnetospheres, i.e. through the association of spectropolarimetry and spectroscopy in the UV and visible domains.

The UV domain is crucial in stellar physics because it is particularly rich in atomic and molecular transitions, especially resonance lines, and covers the region in which the intrinsic spectral energy distribution of hot stars peaks. Resonance lines are excellent diagnostics of the physical state and chemical composition of low-density plasmas. They are less likely to depopulate in low density environments such as chromospheres, circumstellar shells, stellar winds, nebulae and the interstellar medium, and so remain the only useful diagnostics in most of these environments. Another advantage of observing in the UV is the extreme sensitivity of the Planck function to the presence of small amounts of hot gas in dominantly cool environments. This allows the detection and monitoring of various phenomena that would otherwise be difficult to observe: accretion continua in young stars, magnetic activity, chromospheric heating, coronae, active regions on cool stars, and intrinsically faint, but hot, companions of cool stars. The UV domain is also exquisite for many other aspects. For example it is the domain in which Sun-like stars exhibit their hostility (or not) to Earth-like life, population III stars must have shone the brightest, accretion processes convert much kinetic energy into radiation which strongly impacts stellar formation and evolution, the "Fe curtain" features respond to changes in local irradiation, etc. Moreover, many light scattering and polarising processes are stronger at UV wavelengths.

In addition, most cool stars and some fraction of the hot stars are magnetic (Petit et al. 2014) and their magnetic field interacts with their wind and environment, modifies their structure and surface abundances, produces temperature variations, and contributes to the internal and external transport of angular momentum. Magnetic fields can be measured via the polarisation of the stellar light (see e.g. Landstreet 2009). With spectropolarimetry, one can thus address with unprecedented detail these important issues in stellar physics, from stellar magnetic fields to surface inhomogeneities, surface differential rotation to activity cycles and magnetic braking, from microscopic diffusion to turbulence, convection and circulation in stellar interiors, from abundances and pulsations in stellar atmospheres to stellar winds and accretion disks, from the early phases of stellar formation to the late stages of stellar evolution, from extended circumstellar environments to distant interstellar medium. Moreover, measuring polarisation directly in the UV wind-sensitive lines has never been done. The combination of UV polarisation and velocity information from line profiles, which can be used as a proxy to trace the wind density, would permit a 3 dimensional tomographic view of the magnetic field lines to be constructed. Finally, polarimetry is not restricted to magnetic fields only. The scope of stellar polarimetry is much broader, in particular with respect to linear polarisation and depolarisation processes in circumstellar environments, e.g. in accretion or decretion disks, or from exoplanets.

The UVMag project presented here has been designed to address all these exciting and important questions. For this, we need to obtain simultaneous UV and visible spectropolarimetry, continuously over at least one stellar rotation period. Of course, the UV domain requires a space mission. Therefore the UVMag consortium proposes to build a dedicated M-size space mission with a telescope of 1.3 m and UV and visible spectropolarimetric capabilities. The spectropolarimetric capability of UVMag, both in the UV and visible wavelength domains, will nicely complement its spectrograph to multiply tenfold the capabilities of extracting information on magnetospheres (i.e. circumstellar material retained within the magnetic field lines), winds, disks, and magnetic fields. Moreover, the better sampling afforded by a space-based instrument will allow us to obtain nearly continuous time-series of short-cadence measurements. Such time-series of data document phenomena on stars that can be impulsive (flares, infall), periodic (pulsations, migration of spots, corotating clouds), quasi-periodic (evolution of clumps and shock-induced inhomogeneities from hot winds), or gradual (evolution of spots).

2 Science objectives

A UV and visible spectropolarimeter will provide a very powerful tool to study most aspects of stellar physics in general and in particular for stellar formation, structure and evolution as well as for the stellar environment. The full science case is available at http://lesia.obspm.fr/UVMag. A non-exhaustive list of examples is provided below, assuming an M-size space mission dedicated to stellar physics. If the spectropolarimeter were to be installed on a larger telescope, its scientific scope would be extended to many more topics such as white dwarfs.

2.1 Pre-main sequence stars

2.1.1 T Tauri stars

T Tauri stars (TTS) are young, low to intermediate mass (0.5–2.5 $M_\odot$) pre-main-sequence (PMS) G to M stars, many of which are still surrounded by substantial disks. PMS models show that TTS interiors are either fully convective or have an outer convective envelope, depending on the stellar age and mass. They develop a radiative core as they approach the main sequence. TTS with masses greater than 1.2 $M_\odot$ then become fully radiative at the age of 20–30 Myr. The exact timescale on which this happens depends on the stellar mass and the PMS track used (e.g. Palla and Stahler 1993; Chabrier and Baraffe 1997; Siess et al. 2000; Behrend and Maeder 2001).

It is necessary to better understand the role of the convective phase that stars experience before reaching the birthline on the fossil field. A first observational result is that many intermediate-mass TTS (IMTTS) are indeed magnetic (Hussain et al. 2009). However, magnetic observations of this type of stars have only just started (Hussain and Alecian 2014).

TTS show variability at both short and long timescales, and over a range of wavelengths, from radio to X-ray. Many systems display excess UV continuum and Balmer emission lines, indicating that accretion from large circumstellar disks is ongoing. Stars that are accreting are called classical TTS (cTTS). As these systems evolve onto the main sequence, the gas and dust in their disks dissipate and can condense into planetary systems. "Naked" or weak-lined TTS (wTTS) represent a later evolutionary stage, have more evolved disks and do no longer accrete (Rebull et al. 2006; Cieza and Baliber 2007). Determining the timescales over which they stop accreting material from their surrounding disks is a key area in TTS research (e.g. Natta et al. 2007; Olofsson et al. 2009; Oliveira 2011).

Brown and Landstreet (1981) were the first to reveal that TTS host magnetic fields. These fields have later been shown to play a critical role in explaining key properties of TTS through magnetospheric accretion (Camenzind 1990; Koenigl 1991). For a comprehensive review, see Hussain (2012). In brief, the stellar magnetic field truncates the inner edge of the accretion disk either at or within the Keplerian corotation radius. Disk material is then channelled along these magnetic field lines onto the central star causing a shock above the stellar surface before the material can settle onto the star. Several analytical models of magnetospheric accretion have been developed, assuming a dipolar stellar field (Koenigl 1991; Shu et al. 1994; Choi and Herbst 1996). More recent simulations of accretion in TTS account for the complex field topologies that have been discovered by spectropolarimetric studies (e.g. Romanova et al. 2011).

A long-standing puzzle has been the reason for slow rotation in TTS ($P_{\rm rot} = 7$–10 days). As TTS contract and accrete material they would be expected to spin up and rotate at a few percent of their breakup speed. Instead the magnetic interaction between the star and the slowly rotating disk is responsible for slowing down the star (Ghosh and Lamb 1978; Shu et al. 1994). The efficiency of this braking process depends on the size and geometry of the magnetic field.

Since they are accreting, cTTS should host very strong accretion-powered winds and can thus also lose angular momentum through their winds (e.g. Hartmann and MacGregor 1982; Matt and Pudritz 2005, 2008). The clumpy character of magnetospheric accretion can provide the required turbulent energy to the stars to drive their winds with mass-loss rates 10000 times weaker than the accretion rates (e.g. Cranmer 2008, 2009). However, the latest calculations suggest that winds alone may not be sufficient to explain the observed rotation rates, with a combination of both disk locking and accretion-powered winds required to explain the observed angular momentum properties of these systems (Matt et al. 2010; Zanni and Ferreira 2011; Brickhouse et al. 2012).

Magnetospheric models predict that the longer a star is coupled to its disk, the slower it should rotate, a prediction supported by Spitzer observations of young stellar clusters (Cieza and Baliber 2007). Once accretion stops the star is then presumably free to spin up. The timescales for disk locking are therefore very important for explaining the distribution of rotation periods on the zero age main sequence (Bouvier et al. 1997).

TTS magnetic fields are also important for the evolution of the entire system. Strong X-ray and UV heating from coronal heating, large energetic flares and coronal mass ejections can be responsible for driving the evolution of disks through irradiation and photo-evaporation (e.g. Gorti and Hollenbach 2009; Ercolano et al. 2009; Owen et al. 2011). Furthermore, the strength and geometry of the stellar magnetic field determines how far the inner disk can extend and therefore sets a limit to planet migration (Romanova and Lovelace 2006; Long et al. 2011).

To explain many of the above processes we need to understand TTS magnetic fields—the underlying driver of magnetospheric accretion. By probing the strength and geometry of magnetic fields in TTS, we can start to understand how these properties depend on stellar parameters (see Gregory et al. 2012) and to develop more realistic models of magnetospheric accretion and winds (e.g. Romanova et al. 2011). This is essential to develop a better understanding of stellar and planetary formation.

In weakly accreting TTS systems that are in the process of "switching off" accretion, accretion is best detected with UV diagnostics (e.g. Ingleby et al. 2011). Combined spectropolarimetric and UV studies of selected well studied systems would be important to evaluate the role of the stellar magnetic field on "switching off" accretion in systems transitioning into naked or weak TTS.

In particular, UV observations possess a variety of diagnostics that can be used to derive key insights into the accretion state of TTS: from Si IV, C IV, N V emission that points to hot gas from accretion shocks and absorption from outflows, to H_2 and CO emission originating in disks (at temperatures of 300–600 K and ∼2500 K respectively). Moderate resolution spectra are necessary to resolve the structure in the lines forming in the accretion shocks and outflows and test magnetospheric accretion theories. Contemporaneous spectropolarimetric visible and UV studies would enable more detailed, quantitative, tests of the magnetospheric accretion models than have been possible to date. At the same time the spectra would allow us to check if the studied TTS are binaries, which is an important aspect for the interpretation of many observations.

Recently Gómez de Castro and Marcos-Arenal (2012) determined UV- and X-ray-normalised fluxes to study the extent and properties of the TTS magnetospheres as a class. They found that the normalised fluxes are correlated in a different way than those of the main sequence cool stars. In particular there is a very significant excess emission in OI in the TTS caused by recombination radiation from the disk atmosphere after photoionization by extreme UV radiation, and the stronger the X-ray surface flux is, the weaker the observed UV flux. This last behaviour is counter-intuitive within the framework of stellar dynamo theory and suggests that UV emission can be produced in the extended and dense stellar magnetosphere directly driven by local collisional processes. The brown dwarf 2MASS J12073346-3332539 has been found to follow the same flux-flux relations as the TTS. Thus, TTS-normalised flux scaling laws seem to be extendable to the brown dwarf limit and can be used for identification/diagnosis purposes.

2.1.2 Herbig Ae/Be stars

Herbig Ae/Be (HAeBe) stars are the PMS progenitors of A/B stars with masses between 2.5 and 13 $M_\odot$. They are the higher-mass counterparts of TTS. HAeBe stars are contracting towards the main sequence and are surrounded by dust and gas left over from their original molecular cloud. To understand the formation of massive stars, as well as their magnetic and rotation properties, it is necessary to understand the structure of the matter around HAeBe stars and its interaction with the star.

While many pieces of evidence of magnetospheric accretion exist for TTS, it is not clear if accretion exists and how it operates onto HAeBe stars. Contrary to TTS, there is no clear indication of magnetospheric accretion, such as veiling, or the presence of blue-shifted forbidden emission lines (e.g. [OI] 6300 Å). However, HAeBe stars can show UV Balmer excess emission and Hα profiles, which appear analogous to those found in accreting TTS (Mendigutía et al. 2011). Inverse P-Cygni profiles and red-shifted circumstellar absorption features are also observed, mostly in Herbig Ae stars but also some Herbig Be stars (e.g. Boley et al. 2009). However, these features could be explained in terms of clumpy accretion rather than magnetospheric accretion (e.g. Mora et al. 2004). In addition, Finkenzeller and Mundt (1984) have detected P Cygni profiles in the Hα and MgII h & k lines in a large number of HAeBe stars, which indicate that they possess a stellar wind. The presence of forbidden emission lines, such as [OI] (6300 Å), also points toward the existence of a stellar wind (Boehm and Catala 1994). Moreover, radio emission detected in HAeBe stars (Skinner et al. 1993) is predominantly thermal, and in many cases wind-related. Finally, spectro-interferometric observations, around the Brγ line, of few HAeBe stars are better interpreted with the presence of an optically thick disk and a stellar wind whose apparent extent is much larger than the disk extension (e.g. Malbet et al. 2007).

However, the origin of the winds and jets associated with HAeBe stars is poorly understood. Corcoran and Ray (1997) propose the theory of accretion driven winds. They argue that the positive correlations observed between the forbidden emission lines [OI] and Hα, or the IR excess, imply a strong link between outflows and disk. However, in many HAeBe stars, the absence of high-mass disks (especially in HBe stars), as well as the evidence of low-mass accretion rates (e.g. Garcia Lopez et al. 2006), are rather an indication of passive disks. In HBe stars with their higher radiative flux, especially in the UV, theories like radiation driven winds might be more appropriate (e.g. Babel and Montmerle 1997).

According to the fossil field hypothesis, a small fraction of the HAeBe stars should host strong magnetic fields of simple configuration. In order to test this proposal, Alecian et al. (2012a, 2012b) performed a high-resolution spectropolarimetric survey of 70 HAeBe stars located in the field of the Galaxy. They found 9 magnetic stars (Alecian et al. 2012a), implying an incidence of about 10 %. Four of them have been studied in details, and they find that the fields are mainly dipolar, strong (from 300 G to 2.1 kG), and stable over more than 5 years (e.g. Folsom et al. 2008; Alecian et al. 2009). These results confirm that a fossil link exists between the pre-main sequence and main-sequence magnetic fields in the intermediate-mass stars, and that their magnetic fields must have been shaped during the star formation. However, magnetic studies of HAeBe stars, and in particular the role of fields in mediating accretion, are still in their infancy.

Using UV and visible spectropolarimetry would allow us to study the stellar magnetic field and wind of HAeBe stars to test, e.g., the origin of their wind, whether their disk is passive or linked to outflows, whether magnetospheric accretion exists, etc. In particular the variability of the wind and the disk in HBe stars would probably enable time series of UV spectra to assess the validity of the hypothesis of a disk origin of the winds.

2.2 Hot stars

Hot (OB) stars dominate the ecology of the universe as cosmic engines via their extreme output of radiation and matter, not only as supernovae but also during their entire lifetime with far-reaching consequences. They usually display strong variability on various time scales due to such phenomena as mass outflows, rapid rotation, pulsations, magnetism, binarity, radiative instabilities, and the influence of their circumstellar environment. In particular this applies to classical and Herbig Be, Bp, β Cep, Slowly Pulsating B (SPB), B[e] and O stars, as well as massive binaries such as the Be X-ray binaries and those that harbour O-type subdwarf companions, and virtually all evolved OB stars.

Research in the domain of OB stars has been progressing very rapidly in the last decade. However, UV spectrographs are missing to study the wind and magnetospheres of these objects and the current studies (e.g. Petit et al. 2013) rely mainly on the IUE archives which contain data for a rather limited number of stars. Archival IUE data rarely have contemporaneous observations at other wavelengths while the variability is often non-periodic, and the quality of data from contemporary facilities operating at non-UV wavelengths is also vastly improved. Efficient high-resolution ground-based spectropolarimeters (Narval, ESPaDOnS, HARPSpol) provide important clues about magnetic fields and the confinement of the circumstellar environment. These instruments, however, can only supply high signal-to-noise ratio (S/N) measurements in the visible domain of relatively bright stars and can hardly reach cluster stars.

Spectropolarimetry of fainter and numerous cluster stars could be reached with observations from space by adding signal from the UV domain, where OB stars emit most of their light. More importantly, simultaneous UV spectroscopy and visible spectropolarimetry would provide clear diagnostics for the study of magnetospheres and circumstellar environments.

The magnetic fields of high-mass stars are different from those of low-mass stars (e.g. Neiner 2007). They are detected in only 7 % of high-mass stars (Wade et al. 2013) and they are structurally much simpler, and internally much stronger, than the fields of cool stars. In addition, their characteristics show no clear correlation with basic stellar properties such as age, mass or rotation (e.g. Mathys et al. 1997; Kochukhov and Bagnulo 2006; Landstreet et al. 2007). These characteristics reflect a different field origin: they are fossil fields, i.e. remnants of field accumulated or generated during star formation, rather than fields generated by dynamos (e.g. Mestel 2001; Moss 2001; Ferrario and Wickramasinghe 2006). This fossil origin allows us to study how magnetic fields are modified as well as how they influence the evolution of stellar properties. For example, recent spectropolarimetric observations show that magnetic fields are less often present in massive binaries than in single massive stars (Neiner and Alecian 2013). However, the physical details of fossil magnetic fields are only just beginning to be addressed (e.g. Braithwaite and Nordlund 2006; Aurière et al. 2007; Duez and Mathis 2010; Alecian et al. 2012a, 2012b). In addition, the study of fossil fields in massive stars provides clues on the fossil field probably also present inside cooler stars but not visible at their surface. Therefore massive stars are a tool for the study of momentum transport in the whole Hertzsprung-Russell diagram.

Hot stars also represent unique targets for the study of stellar magnetospheres. Their strong, radiatively-driven winds couple to magnetic fields and generate magnetospheric clouds and disks (e.g. Babel and Montmerle 1997; Sundqvist et al. 2012). Models and simulations (e.g. ud-Doula et al. 2006, 2013; Townsend et al. 2005, 2007) show that magnetic confinement of stellar winds can explain UV and X-ray variability in magnetic OB stars (e.g. Favata et al. 2009; Petit et al. 2013). The interaction of the wind with the magnetic field modifies mass loss, and may lead to rapid stellar spindown via magnetic braking (e.g. Weber and Davis 1967; ud-Doula et al. 2009; Townsend et al. 2010; Meynet et al. 2011). Since the evolution of massive stars is particularly sensitive to rotation and mass loss (e.g. Chiosi and Maeder 1986; Maeder and Meynet 2000), the presence of a magnetic field can drastically influence the evolution of massive stars and thus also their supernova explosions and feedback to the interstellar medium (ISM, see e.g. Ekström et al. 2008).

In addition to being structured on large scales by processes like rotation or magnetism, the powerful winds of hot stars can be structured on small-scales by the intrinsic "line-driven instability" (LDI, see e.g. Owocki 2011). The presence and interactions between density structures on both these scales is poorly understood, and may compromise the reliability of measurements of the properties of the outflows. Moreover, most models of such line-driven winds still assume a smooth and steady-state outflow. Spectral diagnostics such as UV resonance and visible recombination lines have different dependencies on density, and will provide crucial constraints for the further development of dynamical hot star wind models, as well as for how the resulting wind structures affect derived quantities such as mass loss and rotation, which are essential inputs for corresponding models of stellar evolution and feedback. Although clumping appears to be a universal feature of line-driven winds, it is not known how the LDI interacts with other processes that structure the wind. Some key questions concern possible inhibition of the lateral fragmentation of clumps, the effects on the structure within the closed field loops, and how these different behaviours alter the interpretation of spectral diagnostics, in particular the determination of mass-loss rates.

UVMag can address all these issues by providing extended time-series and polarimetric information at higher spectroscopic resolution for OB stars, including those already known to be magnetic.

2.3 Solar-type stars

According to dynamo models, the variable magnetic field of the Sun is the consequence of the interplay between two main ingredients. First the radial and latitudinal differential rotation generate a large-scale toroidal magnetic field from an initial poloidal field. Then the poloidal magnetic component is regenerated. How this second process occurs is still debated, with models invoking either the cyclonic convection in the convection zone or the transport of decaying active regions by meridional circulation. These two steps produce a dynamo and succeed at building continuously a large-scale magnetic field that oscillates with time, giving rise to the 22-year solar cycle. Despite considerable progress since the very first solar dynamo models (Brun et al. 2004; Charbonneau 2005; Brun 2011), there are still many aspects of solar magnetism that the current models cannot reproduce or did not fully explore.

Our understanding of the solar dynamo can benefit from the observation of other cool stars, where different dynamo types can be observed, either because they are analogues of the Sun observed in a rare activity state (similar, e.g., to the solar Maunder minimum) or because their physical properties (e.g. their mass and rotation rate) differ significantly from the Sun and lead to a different dynamo. Using spectropolarimetric observations, the magnetic fields of cool stars can be directly characterised from the polarised signatures they produce in spectral lines, and the associated field geometries can be reconstructed using tomographic imaging techniques, like Zeeman-Doppler Imaging. This has already been done from the ground for a small number of cool stars and provided important results in the last decade. However, statistics are needed to obtain a global view of the problem, i.e. we need to reach fainter stars and compare stars in clusters with various parameters (metallicity, age…). A space-based spectropolarimeter would allow to reach this goal thanks to a much better S/N ratio. Associated to UV spectropolarimetry these observations would allow to fully characterise magnetospheres around Sun-like stars, young Suns, and cool stars in general.

The solar cycle of 22 years can be probed in other stars by observing the changes in activity in solar-type stars. For example the star τ Boo has a cycle of $\sim$2 years while the cycles detected in X-rays in HD 81809 and 61 Cyg A seem to be of the order of $\sim$8 years. An increasing number of observational evidences for short cycles has been accumulated recently for cool stars (e.g. Morgenthaler et al. 2011; Metcalfe et al. 2013). Therefore a mission of 5 years or more would be sufficient to measure magnetic cycles in such stars. In the same way as X-ray observations provided new insights on stellar cycles, UV observations of such cycles will cast new light, in particular by allowing to observe changes in the wind and chromosphere along the cycle. Irregularities in the 22-year solar cycle correlate with dramatic changes in the Earth's climate (e.g., the Maunder solar minimum probably led to the Little Ice Age on Earth), so it could be vital to understand such long-term variations.

As the winds of cool main sequence stars are relatively weak (e.g. the solar wind has a mass loss of $\dot{M} = 10^{-14}\ M_\odot$) direct detections are not possible. Indirect detections of stellar winds in the UV can be made through their interaction with the surrounding interstellar medium, such as the presence of extra H I Lyα absorption (Wood et al. 2005). In the solar system the heliosphere is populated by hot hydrogen atoms through charge exchange between the ionised gas in the solar wind and the cold ISM hydrogen. Hot hydrogen builds up particularly in the region between the bow shock and the heliopause. In cool stars this is detected as blueshifted Lyα absorption; column density and velocity measurements of this extra absorption are fitted using hydrodynamic models of the interaction between the stellar wind and the ISM and enable mass loss rates to be computed. Stronger winds result in a larger astrosphere and increased absorption. Only ten systems have been studied in this way, with new HST observations of more systems underway. With coordinated spectropolarimetric studies it is possible to learn how the activity levels of young solar-type stars affect the sizes of astrospheres and therefore the strength of the winds in young planetary systems. Following the astrospheres and magnetic fields of the stars over timescales of years will reveal how winds and conditions inside astrospheres (i.e., in interplanetary environments) can change over the timeframe of stellar activity cycles.

Finally, mapping (Doppler imaging) the sizes and structures of sub-coronal plasma in active stars requires to obtain enough signal in a few minutes so that there is no significant smearing over the rotation period. It is also particularly crucial to obtain observations covering at least two rotation periods in order to discriminate between rotational modulation of stable coronal structures and intrinsic variability (e.g., due to flares). This requires very good phase coverage and can be done thanks to UVMag.

2.4 M dwarfs

Main-sequence stars below approximately 0.35 $M_\odot$ are fully convective and therefore do not possess a tachocline, the thin shear layer at the base of the solar convection zone thought to play an important role in generating the solar magnetic field (e.g. Charbonneau and MacGregor 1997; Browning et al. 2006). Dynamo processes in these fully-convective M dwarfs are therefore believed to differ significantly from those in the Sun; in particular, they may operate throughout the whole stellar interior (e.g. Chabrier and Küker 2006;

Browning 2008). M dwarfs are thus of prime interest to study stellar dynamos operating in physical conditions quite remote from the solar case as well as to understand the role of the tachocline in the dynamos of solar-type stars.

Therefore with very cool stars, one can study both sides of the full-convection threshold (at spectral type M4). Recent spectropolarimetric studies have shown that partly-convective M dwarfs as well as a few fully-convective ones feature complex magnetic geometries with a significant non-axisymmetric component (Donati et al. 2008; Morin et al. 2010), while most fully-convective stars host a strong and long-lived axial dipole component (Morin et al. 2008). Explaining such a diversity in the magnetic field geometries of M dwarfs constitutes an important challenge for stellar dynamo theories.

Despite many differences between planetary and stellar interiors, several recent studies have strengthened the idea that the dipole-dominated large-scale magnetic fields observed on a number of fully-convective stars are much more akin to planetary dynamos than to dynamos of Sun-like stars (Goudard and Dormy 2008; Christensen et al. 2009). The discovery of the co-existence of two distinct types of magnetism among stars having similar masses and rotation rates among very-low-mass stars (Morin et al. 2010) is now interpreted in the framework of dynamo bi-stability originally developed in the planetary dynamo context (Morin et al. 2011; Gastine et al. 2013).

In addition, important evolutions of the surface magnetic fields of early M dwarfs as well as late M dwarfs exhibiting complex fields have been observed on timescales ranging from weeks (due to differential rotation) to years (Donati et al. 2008; Morin et al. 2010). However, up to now no magnetic cycle could be identified on these objects.

Finally, the evolution of angular momentum in M dwarfs is an issue that triggers a number of questions. For example, Reiners and Mohanty (2012) studied the influence of radius change across the fully-convective limit on angular momentum loss and Vidotto et al. (2011b, 2013) produced MHD simulations of the winds of a few M dwarfs. Measuring wind properties of M dwarfs, e.g., astrospheric absorption measurements in the UV (see Sect. 2.3), will provide crucial observational constraints for these studies.

By adding spectropolarimetric capabilities to the UV spectroscopy, it will also be possible to study flares on M dwarfs, probing the short-term variability of the activity level of their chromospheres and the relation with the magnetic topology. On the most active M dwarf stars (UV Ceti type variables), flux increases of several magnitudes in the blue/near-UV are observed on timescales ranging from minutes to hours, and ∼0.1 % of their bolometric luminosity is emitted in the form of flares. These frequent, powerful events, are caused by magnetic reconnection. They exhibit an equivalent black-body temperature of some 10000 K and result in a number of emission lines. In particular the hydrogen Balmer series and CaII H and K as well as lines of HeI and HeII, and atomic species such as CaI, FeI and FeII are observed at visible wavelengths. The UV domain reveals a rich spectrum of highly ionised emission lines such as CIV, SiIV and NV. The most powerful M dwarf flares can also release important amounts of high energy radiations up to the hard X-ray spectral domain (Osten et al. 2010). The radiation and particle fluxes from flares may exert a significant influence on the atmospheres of orbiting planets, and affect their habitability. Understanding these effects is of prime interest for the surveys dedicated to the search for Earth-like planets orbiting M dwarfs.

2.5 Evolved stars

2.5.1 Cool supergiants

Since both global and small-scale dynamos may be simultaneously active in the Sun, it is not easy to disentangle the respective magnetic outcome of these two different processes. A promising way to reach this goal consists in observing a star with no rotation at all, or at least a star rotating so slowly that the onset of a global dynamo in its internal layers is unlikely. If stellar spectropolarimetry is our best asset to detect a magnetic field, the polarimetric detection of Zeeman signatures is mostly insensitive to small-scale magnetic elements as those expected to be generated by a local dynamo. This issue is inescapable for solar-type dwarfs, on which millions of photospheric convective cells are visible at any time, resulting in a highly tangled intra-network field pattern. Cool supergiant stars may offer a rare opportunity to circumvent this problem, since their convective cells are expected to be much larger than on the Sun, with only a few of them covering the stellar surface (Schwarzschild 1975; Chiavassa et al. 2010), so that the spatial scale of convection may be sufficiently large to limit the mutual cancellation of Zeeman signatures of close-by magnetic elements with opposite polarities.

The feasibility of magnetic field detection in cool supergiant stars has been successfully tested from the ground on Betelgeuse (Aurière et al. 2010). Using spatially-resolved, high-resolution UV spectroscopy with the HST, Uitenbroek et al. (1998) were able to propose a rotation period of about 17 years and a low inclination of the rotation axis, of about 20°. Thanks to the brightness of Betelgeuse, it was indeed possible to reveal the presence of a weak ∼1 G surface magnetic field. This is an important observational result, in the sense that the physical interpretations proposed for other objects to account for their magnetic nature cannot be applied here. First, the magnetic field of Betelgeuse has to be generated without the help of a fast, or even moderate stellar rotation, and this specificity should exclude any global dynamo.

Second, the very large radius implies that any magnetic remnant of a strong magnetic field on the main sequence would be too diluted to be detectable at photospheric level. In this situation, a more natural interpretation would involve the convection alone as the engine of a dynamo, bringing the first strong observational evidence that such a process (initially proposed by Durney et al. 1993 and then by Dorch and Freytag 2003 for supergiants) can be efficient in cool stars.

This exciting result, confirmed for a larger sample of cool very bright supergiants (Grunhut et al. 2010), comes together with a number of additional tracers of magnetic activity and convection (chromospheric emission, radial velocities, line bisectors, Stokes V asymmetries). This wealth of information is a motivation to pursue the spectropolarimetric monitoring of cool supergiants, in order to investigate longer-term trends that may affect the various measurements at our disposal and study the possible role of the surface magnetic field in the onset of the mass-loss of Betelgeuse and other supergiant stars. However, to study more (fainter) cool supergiants, a space-based instrument such as UVMag is needed.

2.5.2 AGB and post-AGB stars

The stars located along the Asymptotic Giant Branch (AGB) are the evolutionary descendants of low or intermediate mass stars before their transition towards the post-AGB and the Planetary Nebulae (PN) stages. Evolved stars located at the tip of the AGB or present in the post-AGB domain undergo an important mass loss which is driven mainly by radiation pressure on dust, with the supposed combined action of other factors (e.g., condensation and opacity of dust grains, and—for the pulsating AGB stars, namely Mira stars—stellar pulsations and propagation of shock wave throughout the atmosphere). Hence AGB and post-AGB objects are surrounded by rich circumstellar envelopes (CSE) exhibiting peculiar morphologies gaining an even more and more important degree of complexity along the rapid transition from AGB to PN symmetries (e.g. Sahai and Trauger 1998). Magnetic fields have been invoked in order to rule the mass loss geometry and to help to shape PN's morphology (Blackman 2009) according to theoretical predictions (Soker and Zoabi 2002). Throughout the last decade, several works, mainly based on radio-astronomy facilities, have brought observational evidences for magnetic fields around PN and in the CSE of their AGB and post-AGB progenitors (see Vlemmings 2011, for a global overview).

Moreover, with spectropolarimetric instruments, very weak magnetic fields (i.e., at the gauss level) have been detected at the surface of non pulsating M-type AGB stars (Konstantinova-Antova et al. 2010) and even at the surface of a pulsating Mira star (Lèbre et al. 2014). The origin of the surface magnetism in all these cool and evolved stars (AGB/Miras, post-AGB and in red supergiants, their massive counterparts) still has to be identified. It may rely, at least partly, within a connection with the photospheric or the atmospheric dynamics: either by generating a magnetic field from a local dynamo (or from the shock wave structure itself), or by amplifying (under the action of the shock wave) an extremely weak surface field. Within these objects, atmospheric dynamics is indeed very complex as shown especially by high resolution spectroscopic and interferometric observations performed for pulsating objects at very specific dates along their light curves. Hence, while ground-based observations are highly conditioned and limited by the weather, space facilities bring a very good opportunity to tackle the origin of the magnetism in these evolved stars, from AGB to PN stages.

In addition, concerning more specifically post-AGB stars, a UV facility appears to be a powerful tool. Indeed, in globular clusters, the so-called UVbright objects are the analogues of the field B-type post-AGB stars (Moehler 2001). As they result from low-mass star evolution on their way to the PN stage (van Winckel 2003), these objects can be confused with post-Main Sequence hot and massive B stars. For field or cluster stars, only detailed chemical studies (based on diagnostics from the UV and blue parts of the spectrum) can help to identify genuine post-AGB objects, and thus to address the problem of their magnetism.

2.6 Additional science: ISM, novae, exoplanets

Below we present a selection of science topics, outside of stellar physics, that would benefit from an M-size mission such as UVMag. Would the UV and visible spectropolarimeter of UVMag be installed on a larger telescope, other science domains could also be considered such as Active Galactic Nuclei (AGN).

2.6.1 ISM

The structure and physical properties of the diffuse interstellar medium (ISM) are best studied with high-resolution UV spectra because the resonance lines of a wide variety of atoms and ions are located in the UV. In addition, absorption lines formed in cold and warm ISM gas are narrow, and the velocity separation in individual clouds along a given line of sight is often only a few $\mathrm{km\,s^{-1}}$. Therefore, many of the observations obtained in the frame of the UVMag core program could also be used to study the ISM. Additional observations could be obtained in specific directions as required. Reciprocally, the study of the ISM in the direction of UVMag's targets would allow us to better take the correction for foreground polarization into account.

UVMag targets are best suited to study the local ISM (LISM), in the immediate vicinity of the Sun. The LISM is composed principally of one main diffuse warm cloud, about 10 parsecs in size, embedded in a cavity called the Local Bubble, which may contain very tenuous, very hot gas and extends 50–150 pc around the Sun in all directions. The Sun moves at a velocity of about 25 km s^{-1} relative to the local cloud, which is responsible for the formation of the heliosphere by interaction with the solar wind.

The study of the local ISM is interesting to understand the structure, physical conditions and evolution of the direct environment of our Solar System, in interaction with it. It is also an excellent laboratory for studying the basic physics at work in general diffuse gas. Indeed, the simplicity of the short sight-lines in the solar vicinity provides a unique opportunity to study individual regions, individual clouds, individual interfaces, that are usually blended in longer sight-lines. In particular the dynamics of a cloud propagating in a hot bubble, the interaction of hot gas and cooler material, and the mechanisms producing OVI, can be studied thanks to the position of the Sun in the Local Bubble.

Another aspect of the ISM that would be ideally served by UVMag observations is the study of molecular hydrogen in diffuse gas. The far UV domain covered by UVMag gives rise to many H2 absorption lines in the Lyman and Werner bands. Studies of the high rotational states ($J > 2$) are particularly interesting since there is evidence that in diffuse molecular gas these states could be collisionally excited (Gry et al. 2002) and would imply the existence of a warm phase, also related to the formation of the CH+ molecule. UVMag also gives access to CO electronic bands present in the UV domain, and permits their observation together with H2, for the first time at high resolution for both species, giving the opportunity to measure the abundance ratio of these two molecules in individual clouds and study its evolution with cloud properties.

2.6.2 Novae

Novae are stars that expand, and thus brighten, suddenly and for a short period of time, due to their interaction with a close companion. They represent unique objects to understand physical conditions of accreting matter from a companion, outburst, and interaction of ejecta in the ISM.

In spite of recent observational progress, two fundamental questions remain about novae: what drives the mass loss during the outburst, and what are the masses and structures of the ejecta? Radiative processes depend on the chemical abundances (i.e. on evolution) and on the luminosity. These processes might also produce a stellar wind during the ejection (e.g. Hauschildt et al. 1994). Explosions are powered by the decay of radioactive elements generated after the envelope expansion during the thermonuclear runaway, but subsequent mass loss arises from flux distribution versus envelope opacities (Shore 2002).

The UV domain is the most important spectral region for the analysis of novae. In particular in the UV it is possible to directly probe the properties (abundances, structure, mass) of the ejecta and determine the energetics of the thermonuclear runaway. Indeed, in the visible or IR the photometric behaviour is driven by flux redistribution from the central remnant white dwarf, while in the UV we can measure the resonance lines during the first months of outburst. Measuring polarisation in these UV lines would certainly provide new insight into the novae phenomenon.

2.6.3 Exoplanetary magnetic fields

From HST near-UV light-curves of transits, Fossati et al. (2010) observed that the near-UV transit light-curve of WASP-12b shows an early ingress when compared to its transit in the visible domain. While the time of the transit egress occurs almost simultaneously at the near-UV and visible wavelengths, the ingress of the transit is first seen in the near-UV wavelength range. This asymmetric behaviour has been explained by the presence of asymmetries in the planetary atmosphere.

Close-in giant gas planets are rather inflated and most have developed an exosphere that can fill or even overflow the planet's Roche lobe (Gu et al. 2003; Li et al. 2010; Ibgui et al. 2010). This may result in mass transfer through a Lagrangian point to the star that could cause an asymmetry in the appearance of the transiting planet-star system as seen from the Earth (Lai et al. 2010). Asymmetries could also be produced by cometary tails. However, Ehrenreich et al. (2008) demonstrated for HD 209458b that a radiation-driven cometary tail would produce a late egress of the planetary transit light curve, instead of an early ingress. In the case of the near-UV transit asymmetry of WASP-12b, Vidotto et al. (2010) suggested that this asymmetry can be explained by the presence of a shock surrounding the planet's magnetosphere.

The interaction of a planet with the corona of its host star can give rise to the formation of shocks that surround the planet's magnetosphere. Similar to what occurs around the Earth and other planets in the solar system, bow-shocks may develop around exoplanets. This idea has recently been applied to explain the light-curve asymmetry observed in the near-UV transit of the close-in giant planet WASP-12b (Vidotto et al. 2010). Monte Carlo radiation transfer simulations of the near-UV transit of WASP-12b support this hypothesis, as it explains both the observed level of absorption and the time of the (early) ingress observed in the near-UV light-curve of the planet (Llama et al. 2011).

Vidotto et al. (2011a) applied the shock model initially developed for WASP-12b to other known transiting systems, determining which planets are prone to develop shocks, which could lead to an observable early near-UV ingress.

They predicted that a significant number of transiting systems (36 out of 92 planets) might have a detectable shock, implying that bow shocks might indeed be a common feature surrounding transiting planets. Furthermore, once the stand-off distance of the shock (determined through the time difference of transit observations in the near-UV and visible) and the stellar magnetic field strength are known, the planetary magnetic field intensity can be derived.

In addition, the planetary magnetic field is believed to be responsible for shielding the planet against the erosion of the planetary atmosphere by the host star's wind or the impact of energetic cosmic particles. Such effects could harm creation and development of life on the planet. Furthermore, the presence of a planetary magnetic field may induce other sorts of interactions, such as through reconnection between stellar and planetary magnetic field lines. Such an interaction is believed to generate planetary radio emission (Zarka 2007; Ignace et al. 2010; Vidotto et al. 2012). Unfortunately, despite many attempts, radio emission from exoplanets has not been detected so far.

Near-UV observations during planetary transits may provide an alternative to probe planetary magnetic fields over observations at radio wavelengths. However, the observations of these sorts of systems requires regular observations to monitor the activity level. Coordinated observations of systems in the UV and visible domains would be important to study the environment and fate of hot Jupiters. Therefore, clear synergies exist between UVMag and targets observed with space missions dedicated to exoplanets such as CHEOPS, TESS or Plato.

3 The UVMag space project

3.1 UV and visible spectropolarimetry

To fulfill the requirements of the scientific objectives presented above, we propose to develop a UV and visible spectropolarimeter on an M-size space mission, with a telescope diameter of about 1.3 meters. Since many of the targeted phenomena are known, or at least suspected, to be sensitive to metallicity, it is essential that stars in the LMC and SMC can be reached. This objective is just fulfilled with the proposed baseline aperture of 1.3 m, which should, therefore, not be reduced.

The spectropolarimeter should ideally cover the full wavelength range from 90 to 1000 nm and at least the most important lines in the domains 117–320 nm and 390–870 nm. Polarisation should be measured at least in Stokes V (circular polarisation) in spectral lines, but the aim is to measure all Stokes QUV parameters (circular and linear polarisation) in the lines and continuum. A high spectral resolution is required, at least 25000 in the UV domain and at least 35000 in the visible, with a goal of 80000 to 100000 especially in the far-UV (90–117 nm) to increase the spatial resolution and improve the ISM studies. The peak signal-to-noise ratio should typically be above 100.

Spectroscopy with these specifications in the UV and visible domains is relatively easy to achieve with today's technology and detectors. A preliminary design of the UVMag echelle spectrograph for the wavelength range 117 to 870 nm has already been done, using a grism for the UV domain and a prism for the visible domain. In the visible domain, the detector will be a thinned back-illuminated double-depletion CCD passively cooled to below −60 degrees. In the UV domain, two different types of detectors will probably have to be used: a back-illuminated CCD for the longer UV wavelength range and multi-channel plates (MCP) with a multianode readout device for the shorter UV wavelength range.

However, spectropolarimetry (rather than just spectroscopy) in the UV and visible domains is more challenging. Indeed, (1) high-resolution spectropolarimetry of stars has never been obtained from space, except for the Sun; (2) visible spectropolarimeters available on the ground are large; and (3) it is very important to keep the instrumental polarisation at a low level (below a few percent). In addition, several technical issues need to be addressed, such as the lack of birefringent material over the full UV domain, the wish to avoid moving parts in space, and the difficulty to assemble optical components while keeping them transparent to UV light (i.e. without using glue). Therefore we have started a Research & Technology (R&T) program to study a space UV+visible spectropolarimeter. Our study is based on existing ground-based spectropolarimeters, such as ESPaDOnS or Narval, and new spectropolarimetric techniques proposed in the literature. In particular, we are studying two possible designs for the polarimeter, one combining spatial and spectral modulation following Sparks et al. (2012) and the other one using polychromatic temporal modulation adapted from Snik et al. (2012). See Pertenaïs et al. (2014) for more details on the polarimeter study and its challenges.

Information about the UVMag design can be found at http://lesia.obspm.fr/UVMag as the project progresses.

3.2 Observing program

UVMag will observe all types of stars in the magnitude range at least $V = 3$–10. The observing program includes two parts: (1) 50 to 100 stars will be observed over at least one full rotational cycle with high cadence in order to study them in great details and reconstruct 3D maps of their surface and environment. In addition, the solar-like stars among those will be re-observed every year to study their variability over activity cycle timescales. We propose that the stars will be selected following a proposal process, the data will be distributed to the corresponding teams and become public after a 1-year proprietary period; and (2) one or two spectropolarimetric measurements of several thousands stars will be obtained to provide information on their magnetic field, wind and environment. This will include an unbiased statistical survey as well as targets selected following a proposal process. The unbiased survey data (intensity and Stokes spectra) will be made publicly available upon acquisition. These snapshot data will provide input for stellar modelling.

The acquisition of the data for these programs will take 5 years. A longer mission would of course allow us to observe more targets, in particular to propose interesting targets detected in the survey sample for detailed follow-up, and to expand the coverage of activity cycles.

4 Conclusions

We plan to study how fossil magnetic fields confine the wind of massive stars and influence wind clumping, how magnetic interactions impact binary stars, how a solar dynamo impacts the planets and how it evolves, how magnetic fields, winds and mass-loss influence the late stages of stellar evolution, in which conditions a magnetic dynamo develops, how the angular momentum of stars evolves, how small-scale and large-scale stellar dynamos work and how their cycles influence their environment, what explains the diversity of magnetic properties in M dwarfs, what causes the segregation of tepid stars in two categories (those with sub-gauss magnetic fields and those with fields above a few hundreds gauss), what are the timescales over which magnetospheric accretion stops in PMS stars, etc. These questions will be answered by observing all types of stars: massive stars, giants and supergiants, chemically peculiar stars, pre-main sequence stars, cool stars, solar twins, M dwarfs, AGB and post-AGB stars, binaries, etc. Additional possible science includes the study of the ISM, white dwarfs, novae, exoplanets, atomic physics, … .

The UVMag consortium has set the basic requirements for an M-size space mission to study the magnetospheres and winds of all types of stars. This is the next step to progress on the characterisation and modelling of stellar environments, as well as on important questions regarding stellar formation, structure and evolution. Simultaneous UV and visible spectropolarimetry over long periods of time is indeed the only way to comprehend the full interaction between various physical processes such as the stellar magnetic field and stellar wind. An R&T study is ongoing for the instrument. The M-size mission will be proposed at ESA. We also consider the option of installing the spectropolarimeter of UVMag as part of a series of instruments on a large UV and visible observatory, such as NASA's LUVOIR project (see NASA's astrophysics roadmap).[1]

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References

Alecian, E., Wade, G.A., Catala, C., Bagnulo, S., Böhm, T., Bouret, J.-C., Donati, J.-F., Folsom, C.P., Grunhut, J., Landstreet, J.D.: Mon. Not. R. Astron. Soc. **400**, 354 (2009)
Alecian, E., Wade, G.A., Catala, C., Grunhut, J.H., Landstreet, J.D., Bagnulo, S., Böhm, T., Folsom, C.P., Marsden, S., Waite, I.: Mon. Not. R. Astron. Soc. 394 (2012a)
Alecian, E., Wade, G.A., Catala, C., Grunhut, J.H., Landstreet, J.D., Böhm, T., Folsom, C.P., Marsden, S.: Mon. Not. R. Astron. Soc. 395 (2012b)
Aurière, M., Wade, G.A., Silvester, J., Lignières, F., Bagnulo, S., Bale, K., Dintrans, B., Donati, J.F., Folsom, C.P., Gruberbauer, M., Hui Bon Hoa, A., Jeffers, S., Johnson, N., Landstreet, J.D., Lèbre, A., Lueftinger, T., Marsden, S., Mouillet, D., Naseri, S., Paletou, F., Petit, P., Power, J., Rincon, F., Strasser, S., Toqué, N.: Astron. Astrophys. **475**, 1053 (2007)
Aurière, M., Wade, G.A., Lignières, F., Hui-Bon-Hoa, A., Landstreet, J.D., Iliev, I.K., Donati, J.-F., Petit, P., Roudier, T., Théado, S.: Astron. Astrophys. **523**, 40 (2010)
Babel, J., Montmerle, T.: Astron. Astrophys. **323**, 121 (1997)
Behrend, R., Maeder, A.: Astron. Astrophys. **373**, 190 (2001)
Blackman, E.G.: In: Strassmeier, K.G., Kosovichev, A.G., Beckman, J.E. (eds.) Cosmic Magnetic Fields: From Planets, to Stars and Galaxies. IAU Symposium, vol. 259, p. 35 (2009)
Boehm, T., Catala, C.: Astron. Astrophys. **290**, 167 (1994)
Boley, P.A., Sobolev, A.M., Krushinsky, V.V., van Boekel, R., Henning, T., Moiseev, A.V., Yushkin, M.V.: Mon. Not. R. Astron. Soc. **399**, 778 (2009)
Bouvier, J., Forestini, M., Allain, S.: Astron. Astrophys. **326**, 1023 (1997)
Bouvier, J., Alencar, S.H.P., Harries, T.J., Johns-Krull, C.M., Romanova, M.M.: Protostars and Planets V 479 (2007)
Braithwaite, J., Nordlund, Å.: Astron. Astrophys. **450**, 1077 (2006)
Brickhouse, N.S., Cranmer, S.R., Dupree, A.K., Günther, H.M., Luna, G.J.M., Wolk, S.J.: Astrophys. J. Lett. **760**, 21 (2012)
Brown, D.N., Landstreet, J.D.: Astrophys. J. **246**, 899 (1981)
Browning, M.K.: Astrophys. J. **676**, 1262 (2008)
Browning, M.K., Miesch, M.S., Brun, A.S., Toomre, J.: Astrophys. J. Lett. **648**, 157 (2006)
Brun, A.S.: In: Wozniak, H., Hensler, G. (eds.) EAS Publications Series. EAS Publications Series, vol. 44, p. 81 (2011)
Brun, A.S., Miesch, M.S., Toomre, J.: Astrophys. J. **614**, 1073 (2004)
Camenzind, M.: In: Klare, G. (ed.) Reviews in Modern Astronomy. Reviews in Modern Astronomy, vol. 3, p. 234 (1990)
Chabrier, G., Baraffe, I.: Astron. Astrophys. **327**, 1039 (1997)
Chabrier, G., Küker, M.: Astron. Astrophys. **446**, 1027 (2006)
Chabrier, G., Gallardo, J., Baraffe, I.: Astron. Astrophys. **472**, 17 (2007)
Charbonneau, P.: Living Rev. Sol. Phys. **2**, 2 (2005)
Charbonneau, P., MacGregor, K.B.: Astrophys. J. **486**, 502 (1997)
Chiavassa, A., Haubois, X., Young, J.S., Plez, B., Josselin, E., Perrin, G., Freytag, B.: Astron. Astrophys. **515**, 12 (2010)
Chiosi, C., Maeder, A.: Annu. Rev. Astron. Astrophys. **24**, 329 (1986)

[1] http://science.nasa.gov/media/medialibrary/2013/12/20/secure-Astrophysics_Roadmap_2013.pdf.

Choi, P.I., Herbst, W.: Astron. J. **111**, 283 (1996)
Christensen, U.R., Holzwarth, V., Reiners, A.: Nature **457**, 167 (2009)
Cieza, L., Baliber, N.: Astrophys. J. **671**, 605 (2007)
Corcoran, M., Ray, T.P.: Astron. Astrophys. **321**, 189 (1997)
Cranmer, S.R.: Astrophys. J. **689**, 316 (2008)
Cranmer, S.R.: Astrophys. J. **706**, 824 (2009)
Donati, J.-F., Morin, J., Petit, P., Delfosse, X., Forveille, T., Aurière, M., Cabanac, R., Dintrans, B., Fares, R., Gastine, T., Jardine, M.M., Lignières, F., Paletou, F., Ramirez Velez, J.C., Théado, S.: Mon. Not. R. Astron. Soc. **390**, 545 (2008)
Dorch, S.B.F., Freytag, B.: In: Piskunov, N., Weiss, W.W., Gray, D.F. (eds.) Modelling of Stellar Atmospheres. IAU Symposium, vol. 210, p. 12 (2003)
Duez, V., Mathis, S.: Astron. Astrophys. **517**, 58 (2010)
Durney, B.R., De Young, D.S., Roxburgh, I.W.: Sol. Phys. **145**, 207 (1993)
Ehrenreich, D., Lecavelier Des Etangs, A., Hébrard, G., Désert, J.-M., Vidal-Madjar, A., McConnell, J.C., Parkinson, C.D., Ballester, G.E., Ferlet, R.: Astron. Astrophys. **483**, 933 (2008)
Ekström, S., Meynet, G., Maeder, A.: In: Bresolin, F., Crowther, P.A., Puls, J. (eds.) Massive Stars as Cosmic Engines. IAU Symposium, vol. 250, p. 209 (2008)
Ercolano, B., Clarke, C.J., Drake, J.J.: Astrophys. J. **699**, 1639 (2009)
Favata, F., Neiner, C., Testa, P., Hussain, G., Sanz-Forcada, J.: Astron. Astrophys. **495**, 217 (2009)
Ferrario, L., Wickramasinghe, D.: Mon. Not. R. Astron. Soc. **367**, 1323 (2006)
Finkenzeller, U., Mundt, R.: Astron. Astrophys. Suppl. Ser. **55**, 109 (1984)
Folsom, C.P., Wade, G.A., Kochukhov, O., Alecian, E., Catala, C., Bagnulo, S., Böhm, T., Bouret, J.-C., Donati, J.-F., Grunhut, J., Hanes, D.A., Landstreet, J.D.: Mon. Not. R. Astron. Soc. **391**, 901 (2008)
Fossati, L., Haswell, C.A., Froning, C.S., Hebb, L., Holmes, S., Kolb, U., Helling, C., Carter, A., Wheatley, P., Collier Cameron, A., Loeillet, B., Pollacco, D., Street, R., Stempels, H.C., Simpson, E., Udry, S., Joshi, Y.C., West, R.G., Skillen, I., Wilson, D.: Astrophys. J. Lett. **714**, 222 (2010)
Garcia Lopez, R., Natta, A., Testi, L., Habart, E.: Astron. Astrophys. **459**, 837 (2006)
Gastine, T., Morin, J., Duarte, L., Reiners, A., Christensen, U.R., Wicht, J.: Astron. Astrophys. **549**, 5 (2013)
Ghosh, P., Lamb, F.K.: Astrophys. J. Lett. **223**, 83 (1978)
Gómez de Castro, A.I., Marcos-Arenal, P.: Astrophys. J. **749**, 190 (2012)
Gorti, U., Hollenbach, D.: Astrophys. J. **690**, 1539 (2009)
Goudard, L., Dormy, E.: Europhys. Lett. **83**, 59001 (2008)
Gregory, S.G., Donati, J.-F., Morin, J., Hussain, G.A.J., Mayne, N.J., Hillenbrand, L.A., Jardine, M.: Astrophys. J. **755**, 97 (2012)
Grunhut, J.H., Wade, G.A., Hanes, D.A., Alecian, E.: Mon. Not. R. Astron. Soc. **408**, 2290 (2010)
Gry, C., Boulanger, F., Nehmé, C., Pineau des Forêts, G., Habart, E., Falgarone, E.: Astron. Astrophys. **391**, 675 (2002)
Gu, P.-G., Lin, D.N.C., Bodenheimer, P.H.: Astrophys. J. **588**, 509 (2003)
Hartmann, L., MacGregor, K.B.: Astrophys. J. **259**, 180 (1982)
Hauschildt, P.H., Starrfield, S., Shore, S.N., Gonzalez-Riestra, R., Sonneborn, G., Allard, F.: Astron. J. **108**, 1008 (1994)
Hussain, G.A.J.: Astron. Nachr. **333**, 4 (2012)
Hussain, G.A.J., Collier Cameron, A., Jardine, M.M., Dunstone, N., Ramirez Velez, J., Stempels, H.C., Donati, J.-F., Semel, M., Aulanier, G., Harries, T., Bouvier, J., Dougados, C., Ferreira, J., Carter, B.D., Lawson, W.A.: Mon. Not. R. Astron. Soc. **398**, 189 (2009)
Hussain, G.A.J., Alecian, E.: In: Jardine, M., Petit, P., Spruit, H. (eds.) Magnetic Fields Throughout Stellar Evolution. IAU Symposium, vol. 302 (2014)
Ibgui, L., Burrows, A., Spiegel, D.S.: Astrophys. J. **713**, 751 (2010)
Ignace, R., Giroux, M.L., Luttermoser, D.G.: Mon. Not. R. Astron. Soc. **402**, 2609 (2010)
Ingleby, L., Calvet, N., Hernández, J., Briceño, C., Espaillat, C., Miller, J., Bergin, E., Hartmann, L.: Astron. J. **141**, 127 (2011)
Kochukhov, O., Bagnulo, S.: Astron. Astrophys. **450**, 763 (2006)
Koenigl, A.: Astrophys. J. Lett. **370**, 39 (1991)
Konstantinova-Antova, R., Aurière, M., Charbonnel, C., Drake, N.A., Schröder, K.-P., Stateva, I., Alecian, E., Petit, P., Cabanac, R.: Astron. Astrophys. **524**, 57 (2010)
Lai, D., Helling, C., van den Heuvel, E.P.J.: Astrophys. J. **721**, 923 (2010)
Landstreet, J.D.: In: Neiner, C., Zahn, J.-P. (eds.) EAS Publications Series. EAS Publications Series, vol. 39, p. 1 (2009)
Landstreet, J.D., Bagnulo, S., Andretta, V., Fossati, L., Mason, E., Silaj, J., Wade, G.A.: Astron. Astrophys. **470**, 685 (2007)
Lèbre, A., Aurière, M., Fabas, N., Gillet, D., Herpin, F., Konstantinova-Antova, R., Petit, P.: Astron. Astrophys. **561**, 85 (2014)
Li, S.-L., Miller, N., Lin, D.N.C., Fortney, J.J.: Nature **463**, 1054 (2010)
Llama, J., Wood, K., Jardine, M., Vidotto, A.A., Helling, C., Fossati, L., Haswell, C.A.: Mon. Not. R. Astron. Soc. **416**, 41 (2011)
Long, M., Romanova, M.M., Kulkarni, A.K., Donati, J.-F.: Mon. Not. R. Astron. Soc. **413**, 1061 (2011)
Maeder, A.: Physics, Formation and Evolution of Rotating Stars, (2009)
Maeder, A., Meynet, G.: Annu. Rev. Astron. Astrophys. **38**, 143 (2000)
Malbet, F., Benisty, M., de Wit, W.-J., Kraus, S., Meilland, A., Millour, F., Tatulli, E., Berger, J.-P., Chesneau, O., Hofmann, K.-H., Isella, A., Natta, A., Petrov, R.G., Preibisch, T., Stee, P., Testi, L., Weigelt, G., Antonelli, P., Beckmann, U., Bresson, Y., Chelli, A., Dugué, M., Duvert, G., Gennari, S., Glück, L., Kern, P., Lagarde, S., Le Coarer, E., Lisi, F., Perraut, K., Puget, P., Rantakyrö, F., Robbe-Dubois, S., Roussel, A., Zins, G., Accardo, M., Acke, B., Agabi, K., Altariba, E., Arezki, B., Aristidi, E., Baffa, C., Behrend, J., Blöcker, T., Bonhomme, S., Busoni, S., Cassaing, F., Clausse, J.-M., Colin, J., Connot, C., Delboulbé, A., Domiciano de Souza, A., Driebe, T., Feautrier, P., Ferruzzi, D., Forveille, T., Fossat, E., Foy, R., Fraix-Burnet, D., Gallardo, A., Giani, E., Gil, C., Glentzlin, A., Heiden, M., Heininger, M., Hernandez Utrera, O., Kamm, D., Kiekebusch, M., Le Contel, D., Le Contel, J.-M., Lesourd, T., Lopez, B., Lopez, M., Magnard, Y., Marconi, A., Mars, G., Martinot-Lagarde, G., Mathias, P., Mège, P., Monin, J.-L., Mouillet, D., Mourard, D., Nussbaum, E., Ohnaka, K., Pacheco, J., Perrier, C., Rabbia, Y., Rebattu, S., Reynaud, F., Richichi, A., Robini, A., Sacchettini, M., Schertl, D., Schöller, M., Solscheid, W., Spang, A., Stefanini, P., Tallon, M., Tallon-Bosc, I., Tasso, D., Vakili, F., von der Lühe, O., Valtier, J.-C., Vannier, M., Ventura, N.: Astron. Astrophys. **464**, 43 (2007)
Mathis, S.: In: Goupil, M.-J., Belkacem, K., Neiner, C., Lignières, F., Green, J.J. (eds.) Studying Stellar Rotation and Convection. Lecture Notes in Physics, vol. 865, p. 23. Springer, Berlin (2013)
Mathys, G., Hubrig, S., Landstreet, J.D., Lanz, T., Manfroid, J.: Astron. Astrophys. Suppl. Ser. **123**, 353 (1997)
Matt, S., Pudritz, R.E.: Astrophys. J. Lett. **632**, 135 (2005)
Matt, S., Pudritz, R.E.: Astrophys. J. **678**, 1109 (2008)
Matt, S.P., Pinzón, G., de la Reza, R., Greene, T.P.: Astrophys. J. **714**, 989 (2010)
Mendigutía, I., Calvet, N., Montesinos, B., Mora, A., Muzerolle, J., Eiroa, C., Oudmaijer, R.D., Merín, B.: Astron. Astrophys. **535**, 99 (2011)
Mestel, L.: In: Mathys, G., Solanki, S.K., Wickramasinghe, D.T. (eds.) Magnetic Fields Across the Hertzsprung-Russell Diagram. Astronomical Society of the Pacific Conference Series, vol. 248, p. 3 (2001)

Metcalfe, T.S., Buccino, A.P., Brown, B.P., Mathur, S., Soderblom, D.R., Henry, T.J., Mauas, P.J.D., Petrucci, R., Hall, J.C., Basu, S.: Astrophys. J. Lett. **763**, 26 (2013)
Meynet, G., Eggenberger, P., Maeder, A.: Astron. Astrophys. **525**, 11 (2011)
Moehler, S.: Publ. Astron. Soc. Pac. **113**, 1162 (2001)
Mora, A., Eiroa, C., Natta, A., Grady, C.A., de Winter, D., Davies, J.K., Ferlet, R., Harris, A.W., Miranda, L.F., Montesinos, B., Oudmaijer, R.D., Palacios, J., Quirrenbach, A., Rauer, H., Alberdi, A., Collier Cameron, A., Deeg, H.J., Garzón, F., Horne, K., Merín, B., Penny, A., Schneider, J., Solano, E., Tsapras, Y., Wesselius, P.R.: Astron. Astrophys. **419**, 225 (2004)
Morgenthaler, A., Petit, P., Morin, J., Aurière, M., Dintrans, B., Konstantinova-Antova, R., Marsden, S.: Astron. Nachr. **332**, 866 (2011)
Morin, J., Donati, J.-F., Forveille, T., Delfosse, X., Dobler, W., Petit, P., Jardine, M.M., Collier Cameron, A., Albert, L., Manset, N., Dintrans, B., Chabrier, G., Valenti, J.A.: Mon. Not. R. Astron. Soc. **384**, 77 (2008)
Morin, J., Donati, J.-F., Petit, P., Delfosse, X., Forveille, T., Jardine, M.M.: Mon. Not. R. Astron. Soc. **407**, 2269 (2010)
Morin, J., Dormy, E., Schrinner, M., Donati, J.-F.: Mon. Not. R. Astron. Soc. **418**, 133 (2011)
Moss, D.: In: Mathys, G., Solanki, S.K., Wickramasinghe, D.T. (eds.) Magnetic Fields Across the Hertzsprung-Russell Diagram. Astronomical Society of the Pacific Conference Series, vol. 248, p. 305 (2001)
Natta, A., Testi, L., Calvet, N., Henning, T., Waters, R., Wilner, D.: Protostars and Planets V 767 (2007)
Neiner, C.: In: Okazaki, A.T., Owocki, S.P., Stefl, S. (eds.) Active OB-Stars: Laboratories for Stellare and Circumstellar Physics. Astronomical Society of the Pacific Conference Series, vol. 361, p. 91 (2007)
Neiner, C., Alecian, E.: In: EAS Publications Series, vol. 64, p. 75 (2013)
Oliveira, I.: Observational Constraints on The Evolution of Dust in Protoplanetary Disks. Ph.D. Thesis, University of Leiden (2011)
Olofsson, J., Augereau, J.-C., van Dishoeck, E.F., Merín, B., Lahuis, F., Kessler-Silacci, J., Dullemond, C.P., Oliveira, I., Blake, G.A., Boogert, A.C.A., Brown, J.M., Evans, N.J. II, Geers, V., Knez, C., Monin, J.-L., Pontoppidan, K.: Astron. Astrophys. **507**, 327 (2009)
Osten, R.A., Godet, O., Drake, S., Tueller, J., Cummings, J., Krimm, H., Pye, J., Pal'shin, V., Golenetskii, S., Reale, F., Oates, S.R., Page, M.J., Melandri, A.: Astrophys. J. **721**, 785 (2010)
Owen, J.E., Ercolano, B., Clarke, C.J.: Mon. Not. R. Astron. Soc. **412**, 13 (2011)
Owocki, S.: Bull. Soc. R. Sci. Liège **80**, 16 (2011)
Palla, F., Stahler, S.W.: Astrophys. J. **418**, 414 (1993)
Pertenaïs, M., Neiner, C., Parès, L., Petit, P., Snik, F., van Harten, G.: In: Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series (2014). ArXiv e-prints 1406.4378
Petit, P., Louge, T., Théado, S., Paletou, F., Manset, N., Morin, J., Marsden, S.C., Jeffers, S.V.: ArXiv e-prints 1401.1082 (2014)
Petit, V., Owocki, S.P., Wade, G.A., Cohen, D.H., Sundqvist, J.O., Gagné, M., Maíz Apellániz, J., Oksala, M.E., Bohlender, D.A., Rivinius, T., Henrichs, H.F., Alecian, E., Townsend, R.H.D., ud-Doula, A. MiMeS Collaboration: Mon. Not. R. Astron. Soc. **429**, 398 (2013)
Rebull, L.M., Stauffer, J.R., Megeath, S.T., Hora, J.L., Hartmann, L.: Astrophys. J. **646**, 297 (2006)
Reiners, A., Mohanty, S.: Astrophys. J. **746**, 43 (2012)
Romanova, M.M., Lovelace, R.V.E.: Astrophys. J. Lett. **645**, 73 (2006)
Romanova, M.M., Long, M., Lamb, F.K., Kulkarni, A.K., Donati, J.-F.: Mon. Not. R. Astron. Soc. **411**, 915 (2011)
Sahai, R., Trauger, J.T.: Astron. J. **116**, 1357 (1998)
Schwarzschild, M.: Astrophys. J. **195**, 137 (1975)
Shore, S.N.: In: Hernanz, M., José, J. (eds.) Classical Nova Explosions. American Institute of Physics Conference Series, vol. 637, p. 175 (2002)
Shu, F., Najita, J., Ostriker, E., Wilkin, F., Ruden, S., Lizano, S.: Astrophys. J. **429**, 781 (1994)
Siess, L., Dufour, E., Forestini, M.: Astron. Astrophys. **358**, 593 (2000)
Skinner, S.L., Brown, A., Stewart, R.T.: Astrophys. J. Suppl. Ser. **87**, 217 (1993)
Snik, F., van Harten, G., Navarro, R., Groot, P., Kaper, L., de Wijn, A.: In: Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series, vol. 8446 (2012). arXiv:1207.2965
Soker, N., Zoabi, E.: Mon. Not. R. Astron. Soc. **329**, 204 (2002)
Sparks, W., Germer, T.A., MacKenty, J.W., Snik, F.: Appl. Opt. **51**, 5495 (2012)
Sundqvist, J.O., ud-Doula, A., Owocki, S.P., Townsend, R.H.D., Howarth, I.D., Wade, G.A.: Mon. Not. R. Astron. Soc. **423**, 21 (2012)
Townsend, R.H.D., Owocki, S.P., Groote, D.: Astrophys. J. Lett. **630**, 81 (2005)
Townsend, R.H.D., Owocki, S.P., ud-Doula, A.: Mon. Not. R. Astron. Soc. **382**, 139 (2007)
Townsend, R.H.D., Oksala, M.E., Cohen, D.H., Owocki, S.P., ud-Doula, A.: Astrophys. J. Lett. **714**, 318 (2010)
ud-Doula, A., Townsend, R.H.D., Owocki, S.P.: Astrophys. J. Lett. **640**, 191 (2006)
ud-Doula, A., Owocki, S.P., Townsend, R.H.D.: Mon. Not. R. Astron. Soc. **392**, 1022 (2009)
ud-Doula, A., Sundqvist, J.O., Owocki, S.P., Petit, V., Townsend, R.H.D.: Mon. Not. R. Astron. Soc. **428**, 2723 (2013)
Uitenbroek, H., Dupree, A.K., Gilliland, R.L.: Astron. J. **116**, 2501 (1998)
van Winckel, H.: Annu. Rev. Astron. Astrophys. **41**, 391 (2003)
Vidotto, A.A., Jardine, M., Helling, C.: Astrophys. J. Lett. **722**, 168 (2010)
Vidotto, A.A., Jardine, M., Helling, C.: Mon. Not. R. Astron. Soc. **411**, 46 (2011a)
Vidotto, A.A., Jardine, M., Opher, M., Donati, J.F., Gombosi, T.I.: Mon. Not. R. Astron. Soc. **412**, 351 (2011b)
Vidotto, A.A., Fares, R., Jardine, M., Donati, J.-F., Opher, M., Moutou, C., Catala, C., Gombosi, T.I.: Mon. Not. R. Astron. Soc. **423**, 3285 (2012)
Vidotto, A.A., Jardine, M., Morin, J., Donati, J.F., Opher, M., Gombosi, T.I.: Mon. Not. R. Astron. Soc., ArXiv e-prints 1311.5063 (2013)
Vlemmings, W.H.T.: In: Zijlstra, A.A., Lykou, F., McDonald, I., Lagadec, E. (eds.) Asymmetric Planetary Nebulae 5 Conference, (2011)
Wade, G.A., Grunhut, J., Alecian, E., Neiner, C., Auriere, M., Bohlender, D.A., David-Uraz, A., Folsom, C., Henrichs, H.F., Kochukhov, O., Mathis, S., Owocki, S., Petit, V., the MiMeS Collaboration: ArXiv e-prints 1310.3965 (2013)
Weber, E.J., Davis, L. Jr.: Astrophys. J. **148**, 217 (1967)
Wood, B.E., Redfield, S., Linsky, J.L., Müller, H.-R., Zank, G.P.: Astrophys. J. Suppl. Ser. **159**, 118 (2005)
Zanni, C., Ferreira, J.: Astrophys. J. Lett. **727**, 22 (2011)
Zarka, P.: Planet. Space Sci. **55**, 598 (2007)