UVMag: Stellar physics with UV and visible spectropolarimetry

1 Administrative details and management

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The UVMag consortium includes scientists willing to design and promote space UV spectroscopy and spectropolarimetry to study stellar magnetospheres (winds, magnetic fields, confinement of circumstellar material,...). The consortium currently consists of over 20 active scientists from 16 different institutes (see Table 1), but of course many more scientists from these institutes or elsewhere are also interested in the project.

A UVMag website is available at http://lesia.obspm.fr/UVMag. It includes a detailed document describing the science goals and technical requirements of the UVMag project. In addition, **we would gladly present our science objectives and investigations at a NASA workshop if invited.**

2 Science rationale

2.1 Science drivers: stellar physics

We propose to study the formation, structure, evolution and environment of all types of stars in particular through the measurement of their 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, and covers the region in which the intrinsic spectral distribution of hot stars peaks. The UV lines are the least influenced by non-LTE effects in stellar photospheres and are thus most useful e.g. for quantitative abundance determinations. The lower levels of these lines 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, corona, starspots on cool stars, and intrinsically faint, but hot, companions of cool stars. The UV domain is also the one where Sun-like stars exhibit their hostility (or not) to Earth-like life, population 0 stars must have shone the brightest, accretion processes convert much kinetic energy into radiation which strongly

Table 1: Active consortium members

Members	Institute	Email	Expertise
E. Alecian	LESIA, France	evelyne.alecian@obspm.fr	Herbig stars
T. Ayres	Univ. Colorado, USA	thomas.ayres@colorado.edu	Cool stars
D. Baade	ESO-HQ, Germany	dbaade@eso.org	Be stars
S. Bagnulo	Armagh Obs., UK	sba@arm.ac.uk	Ap/Bp stars
J.-C. Bouret	LAM, France	jean-claude.bouret@oamp.fr	O stars
D. Cohen	Swarthmore Coll., USA	cohen@astro.swarthmore.edu	X-rays
L. Drissen	Univ. Laval, Canada	ldrissen@phy.ulaval.ca	Wolf-Rayet stars
A. Fullerton	STScI, USA	fullerton@stsci.edu	O stars
C. Gry	LAM, France	cecile.gry@oamp.fr	ISM
G. Hussain	ESO-HQ, Germany	ghussain@eso.org	T Tauri stars
O. Kochukhov	Univ. Uppsala, Sweden	oleg@astro.uu.se	Surface imaging
J. Landstreet	Armagh Obs., UK	jlandstr@astro.uwo.ca	Ap/Bp stars
S. Mathis	CEA, France	stephane.mathis@cea.fr	Theory
G. Meynet	Univ. Geneva, Switzerland	georges.meynet@unige.ch	Structure/evolution
R. Monier	Univ. Nice, France	richard.monier@unice.fr	A stars
J. Morin	Univ. Göttingen	jmorin@gwdg.de	M stars
C. Neiner	LESIA, France	coralie.neiner@obspm.fr	Hot stars
N. Piskunov	Univ. Uppsala, Sweden	piskunov@astro.uu.se	Surface imaging
C. Robert	Univ. Laval, Canada	carobert@phy.ulaval.ca	Stellar formation
P. Petit	IRAP, France	petit@ast.obs-mip.fr	Cool stars
T. Rivinius	ESO, Chile	triviniu@eso.org	Be stars
M. Smith	STScI, USA	msmith@stsci.edu	γ Cas stars
R. Townsend	Wisconsin, USA	townsend@astro.wisc.edu	Magnetospheres
G. Wade	RMC, Canada	wade-g@rmc.ca	Hot stars
A. ud-Doula	Penn State Univ., USA	asif@psu.edu	MHD simulations

impacts stellar formation and evolution, the "Fe curtain" features respond to changes in local irradiation, etc.

In addition, most of cool stars and a fraction of hot stars are magnetic and their magnetic field interacts with their wind and environment, modifies their structure and surface abundances, and contributes to the transport of angular momentum. With spectropolarimetry, one can 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 polarization directly in the UV wind-sensitive lines has never been done, and would be extremely useful in order to trace the polarization along the field lines. Finally, polarimetry is not restricted to magnetic fields only. The scope of stellar polarimetry is much broader, in particular with respect to circumstellar processes.

The spectropolarimetric capability, both in the UV and visible wavelength domains, will therefore nicely complement the spectrograph to multiply tenfold the capabilities of extracting information on magnetospheres, winds, disks, and magnetic fields. The UV+visible spectropolarimeter will consequently provide a very powerful and unique tool to study most aspects of stellar physics in general and in particular for stellar formation, structure and evolution as well as for stellar environment. In particular, it will help to answer the following long-standing as well as new questions:

Stellar formation

- What are the statistical properties of the various populations of stars? What is the incidence of magnetic fields? What are the properties of wind and mass loss?
- What causes the segregation of tepid stars in two categories: those with sub-gauss magnetic fields (Vega-like stars) and those with fields above a few hundred of Gauss (Ap/Bp stars)? Why are there no tepid stars with intermediate strength field?
- What are the timescales over which magnetospheric accretion stops in pre-main sequence (PMS) stars?
- Why do T Tauri stars rotate slowly? How does the disk locking mechanism work?
- What happens during the magnetic stabilization phase at the start of the PMS? How does an abrupt change of magnetic obliquity affect the star and its environment?

Stellar structure

- In which conditions does a dynamo magnetic field develop?
- What is the interplay between magnetic fields, rotation and wind in the activity of stars, e.g. how does the angular momentum loss due to the magnetically-driven wind affect the dynamo of cool stars which in turn affects the wind?
- Under what conditions do OB stars become Be stars? What causes Luminous Blue Variable outbursts? What happens when a star reaches critical rotational velocity? What is the origin of γ Cas stars behavior?
- How does the solar cycle work? How is it influenced by the solar environment? What are the respective impacts of the global and small-scale solar dynamos?
- What explains the diversity of magnetic properties of M dwarfs? How is their magnetism related to that of planets, brown dwarfs and of solar-type stars?

Stellar evolution

- What is the role of magnetic field, rotation, metallicity and mass loss in the evolution of stars? In particular, how does it influence their late stages (white dwarfs, supernovae, neutron stars, black holes, γ-ray bursts)?
- What allows a fossil magnetic field to survive the various phases of stellar evolution?
- How strong was the solar magnetic field when the Sun was young? How will it evolve?

Stellar environment

- How does a stellar magnetic field influence mass loss, in particular what is responsible for wind clumping and the formation of a circumstellar disk or clouds?
- How do magnetospheric interactions impact binary stars? What are the tidal effects?
- How does the solar dynamo impacts our Earth, and how does it evolve with time?
- What are the star-planet magnetospheric interactions?

These questions will be answered by studying various types of stars: O stars which exhibit very strong clumpy winds, Of?p stars which have very specific spectral characteristic probably related to their magnetic field, active B stars which associate various extreme physical processes, Be stars which are very rapidly rotating and undergo outbursts producing a circumstellar disk, γ Cas stars which emit unexplained variable X-ray flux, Ap/Bp stars which host very strong fossil magnetic fields, A stars that are very weakly magnetized, δ Scu and γ Dor stars which pulsate, roAp stars in which magnetic field and pulsations interact strongly, Herbig Ae/Be stars which are the precursor of main sequence Ap/Bp stars, intermediate-mass T Tauri stars which cover the transition from a fully convective star to a radiative star, classical T Tauri stars which are still accreting mass, weak-lined T Tauri stars which have stopped accreting but have not yet reach the main sequence, solar-type stars with dynamo magnetic fields, young and old Suns to be compared with our Sun, cool supergiants which offer the possibility to study small-scale dynamos, M dwarfs which exist on both side of the full-convection threshold, red giants, planetary nebulae and post-AGB stars which represent later stages of stellar evolution, stars in the Magellanic Clouds which are in a different environment in terms of metallicity, and binaries which probe additional ingredients in stellar evolution and undergo tidal effects.

In addition to stellar physics, several additional science topics could be investigated with no or little changes in the proposed project. This includes for example studies of the ISM, white dwarfs, or novae. These examples are described in the more detailed document available on the UVMag website. Moreover, with some additional requirements, our project could be enhanced to also study other topics, e.g. exoplanetary magnetospheres. In this example, polarization signals of the order of 10^{-4} (for hot Jupiters) or less (down to 10^{-11} for Earth-like planets around solar-like stars) would be required, i.e. a very high signal-to-noise and very low instrumental polarization.

2.2 COR science objectives

Our science goals are well within the COR science objectives. In particular they would help understand how the first stars formed, evolved and influenced their environment, enriching it in various elements and leading to new generations of stars. They will therefore also allow us to pinpoint the mechanisms by which stars and their planetary systems form today. Finally, they will provide clues about how a stellar environment influences its planets and thus life on the planets.

3 Space mission

3.1 Concept

To observe in the UV domain, as well as to reach faint stars and weak magnetic fields, it is necessary to collect the requested observations from space. In addition, we wish to obtain long continuous spectropolarimetric time series of a number of targets, which is hampered from the ground when the variability period is close to 1 day or a fraction/multiple of 1 day. Finally, simultaneous spectropolarimetric observations in the UV and visible domains would provide information on the wind and polarization properties at the same time, providing new insights into certain phenomena such as magnetospheric confinement or chromospheric activity. We therefore propose to study a concept of a space spectropolarimeter working in the UV and visible domains. It could be installed either on a small space mission (small mirror, lower cost) dedicated to solving a limited number of stellar physics issues exposed above and available for long-term monitoring of stars, or on a large UV space observatory (LUVO) with which better statistics could be reached and where the spectropolarimeter could benefit other science topics besides stellar physics. However, more instrumental flexibility and complexity might then be needed, e.g. a MOS/IFU mode or an imaging mode.

Details about the instrumental concept can be found on the UVMag website and will be submitted to the forthcoming RFI #2.

3.2 Scientific requirements for the instrument

To measure the line profiles, we should obtain spectropolarimetric data with a high resolution. In addition, to fulfill our goals we need to reach a high signal-to-noise ratio and therefore to observe bright stars. We also wish to reach fainter stars to be able to observe certain rare classes of stars (such as M dwarfs or Herbig Ae/Be stars) and to probe other environments, e.g. the Magellanic Clouds. Thus our dynamical range needs to be very large.

Moreover, we would like to point in any direction in the sky, to reach any interesting target. We wish to observe once several thousands of stars of all types forming a statistical survey. We also require to be able to remain stably pointed on a shorter list of stars (targeted objects) continuously for 2 rotation cycles. Such time series document phenomena on stars that can be impulsive (flares, infall), periodic (pulsations, rotational migration of spots, corotating clouds), quasi-periodic (evolution of blobs from hot winds), and gradual (evolution of spots). While some hot stars rotate very fast (of the order of 1 day), other targets have rotation periods of several weeks. In Table 2 we considered that on average the rotation period is 2 weeks. The mission duration derives from this mean rotation period and the number of targets, at least 4 years. A mission of 12 years would not only allow to study 2 times more targeted and survey objects but to probe stellar magnetic cycles (similar to the 22-year solar cycle).

Table 2: Basic scientific specifications considered for the instrument. The minimal requirement is given, as well as the objective.

Specification	Requirement	Goal
Spectral range	117-320 + 390-870 nm	90-1000 nm
UV resolution	25000	100000 and 2000
Optical resolution	35000	80000
UV S/N	100	200
Optical S/N	100	300
Polarization	V in lines	QUV in lines + continuum
Instrumental polarization	3%	1%
Accuracy in radial velocity	1 km s^{-1}	0.3 km s^{-1}
Target magnitude	V=3-10	V=2-15
Targeted stars	50	100
Time per targeted star	4 weeks	6 weeks (4+1+1)
Survey stars	4000	8000
Time per survey star	20 min	30 min
Mission duration	4 years	12 years

Table 3: Number of available targets per spectral type, according to Simbad. An estimate of the number of magnetic stars is also given, according to the statistical occurrence of magnetic fields in each type of targets. Numbers are also given for some examples of rare types of objects. The numbers are given for the minimal requirement and goal for the magnitude.

Spectral type	V=3-10	V=2-15	Magnetic rate	Magnetic V=3-10	Magnetic V=2-15
O	428	1823	6%	26	109
B	19940	42891	6%	1196	2573
A	53143	102442	20%	10629	20488
F	61867	105487	50%	30934	52744
G	55780	97365	50%	27890	48683
K	88358	121052	50%	44179	60526
M	10276	18367	50%	5138	9184
Be stars	1225	1705	1%	12	17
Herbig Ae/Be	44	60	10%	4	6
M dwarfs	94	693	50%	47	347

Precise radial velocity is requested for example for Doppler Imaging of active binary systems or probing the redshifts of high temperature emission lines in the subcoronal atmospheres of cool stars.

Polarization in Stokes V in spectral lines is the minimum requirement to be able to infer magnetic properties. However, polarization in QUV would allow full 3D mapping of the magnetospheres and linear polarization (QU) would also allow to measure other physical processes such as depolarization from a circumstellar disk, probing scales well beyond what is feasible with interferometry. In addition, polarization of the continuum would be very useful to study dusty environments, providing important information about e.g. star forming regions or protostars.

3.3 Ongoing activities

Previous UV instruments (e.g. IUE, STIS or FUSE), have provided valuable data for the first studies of stellar magnetospheres. HIRDES on the future WSO would also provide the instrumental capabilities needed to address the scientific rationale exposed here. However, these instruments are either unavailable anymore or available for too short periods of time to perform a time series over a full stellar rotation cycle. This is why we need a new UV spectrograph.

In addition, ground-based optical spectropolarimeters provide important datasets for all types of bright stars. However, there are no space stellar spectropolarimeters, to reach fainter targets and to obtain continuous timeseries. Moreover, UV spectropolarimetry cannot be achieved from the ground. There are already several ongoing projects in this field in the optical (e.g. for SST, Solar Orbiter or SPEX), but not in the UV. However, in the frame of UVMag, a Research & Technology (R&T) study funded by the French space agency CNES has just started at IRAP and LESIA, to develop a prototype of a space-based spectropolarimeter. Space-based spectropolarimetry is very novel, especially in the UV, but we expect that the required technology will be available by the time a mission would be launched.