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UV spectropolarimetry: a new tool for breakthrough science

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Abstract. Several space mission projects for high-resolution spectropolarimeters covering a wide range of UV wavelengths are currently in preparation. From technological and scientific demonstration on the French CASSTOR nanosatellite to Pollux onboard the future large LUVOIR-like NASA flagship mission, through the NASA MIDEX Polstar and ESA M7 Arago mission proposals, a whole range of science cases become accessible. I will present these mission projects, their main science goals, and the timeline of the UV spectropolarimetry roadmap for astrophysics.

Key words. Instrumentation: polarimeters – Instrumentation: spectrographs – Stars: magnetic field – Ultraviolet: general – Ultraviolet: stars – Ultraviolet: planetary systems – Ultraviolet: ISM

1. Introduction

Since the mid 90's, visible high-resolution spectropolarimetry has revolutionised stellar physics with the detailed study of stellar magnetism in cool stars and the emergence of the field of stellar magnetism in massive stars. First Musicos (Donati et al. 1999) at the Télescope Bernard Lyot (TBL) in France pioneered this field, then ESPaDOnS (Donati et al. 2006) at the Canada France Hawaii Telescope (CFHT) in Hawaii, and Narval (Aurière 2003) at TBL recently upgraded to NeoNarval (Cabanac 2014), as well as HarpsPol (Piskunov et al. 2011) on the 3.6-m telescope at ESO in La Silla in Chile and PEPSI (Strassmeier et al. 2015) at the 11.8-m Large Binocular Telescope (LBT), have been used.

More recently the technique of high-resolution spectropolarimetry has been extended to the IR domain with the arrival of SPIRou (Donati et al. 2020) at CFHT, CRIRES+ (Lavail 2021) at the Very Large Telescope (VLT) of ESO in Paranal in Chile, and soon SPIP (Baratchart et al. 2022) at TBL.

All these instruments have brought major contributions to stellar physics, e.g. for the study of star-planet interactions (e.g. Folsom et al. 2020), stellar winds and magnetospheres (e.g. Shultz et al. 2019), PMS stars and accretion disks (e.g. Pouilly et al. 2020), solar analogs (Metcalfe et al. 2022), etc.

The next step in this field of research is to perform high-resolution spectropolarimetry in the UV domain (Neiner et al. 2014, 2019). However, this requires to go to space, i.e. to

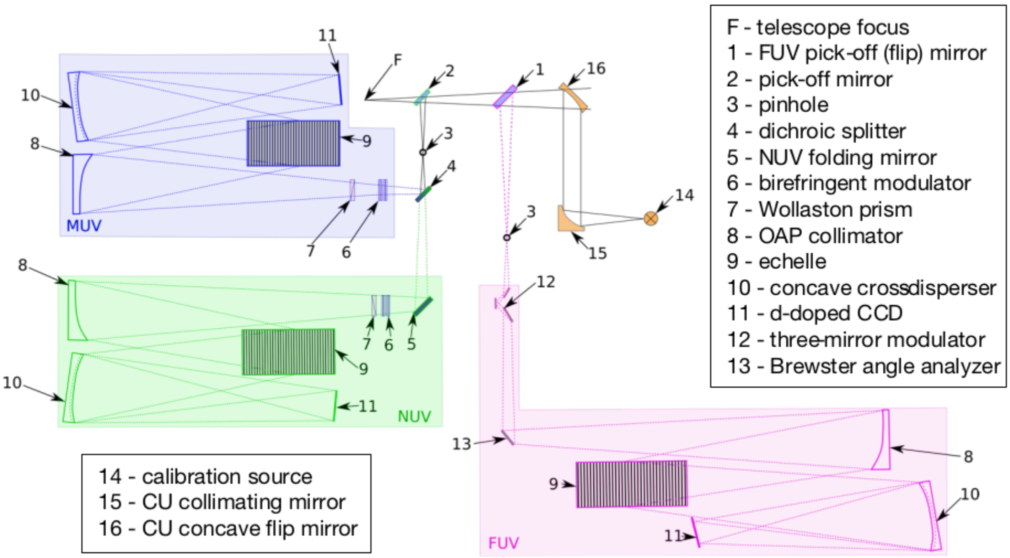

Fig. 1. Design of Pollux for LUVOIR-A, showing the 3 UV channels. Taken from The LUVOIR Team (2019).

put a UV spectropolarimeter onboard a space mission.

Over the last 10 years, development of UV polarimeters working over a wide wavelength range at the Paris Observatory, funded by the French space agency CNES, led to several space mission projects. The main ones are described hereafter.

2. Pollux on the flagship LUVOIR/LUVEx mission

LUVOIR (Large UV, Optical, IR surveyor Roberge et al. 2021; The LUVOIR Team 2019) is a flagship mission proposed to the US Astronomical 2020 Decadal Survey. Two versions were proposed: LUVOIR-A with a 15-m on-axis telescope and LUVOIR-B with a 8-m off-axis telescope. The Decadal Survey recommended such a space mission with an inscribed diameter of at least 6 m, which corresponds to LUVOIR-B's 8-m external diameter. This mission is now sometimes referred to as LUVEx. The launch of this mission to the L2 Lagrangian point is planned for the first half of the 2040's.

Onboard LUVOIR, four instruments are foreseen. Three instruments are led by the USA: ECLIPS (Extreme Coronagraph for Living Planetary Systems) is a coronagraphic imager and low-resolution (~100) spectrograph with a contrast ratio of 10^{-10}, covering the wavelength domain from 200 nm to 2 μm (Pueyo et al. 2019); HDI (High Definition Imager) is a wide-field imager with a field-of-view of 2x3 arcmin, covering the domain from 200 nm to 2.5 μm with 6.45 mas per pixel in the UV and Visible domain and 12.89 mas per pixel in the near IR (Corsetti et al. 2019); LUMOS (LUVOIR UV Multi-object Spectrograph) is a multi-object UV low and mid resolution (500 to 30000) spectrograph and far UV imager (2x2 arcmin) covering the domain from 100 nm to 1 μm (France et al. 2019). The fourth instrument, Pollux, is a European contribution to LUVOIR led by France (Ferrari et al. 2019). It is a high-resolution UV spectropolarimeter.

LUVOIR is a general purpose multi-wavelength observatory for a wide-range of astrophysics: star forming regions, first starlight, early galaxies, planet formation, surface and clouds on solar-system planets and Kuiper belt

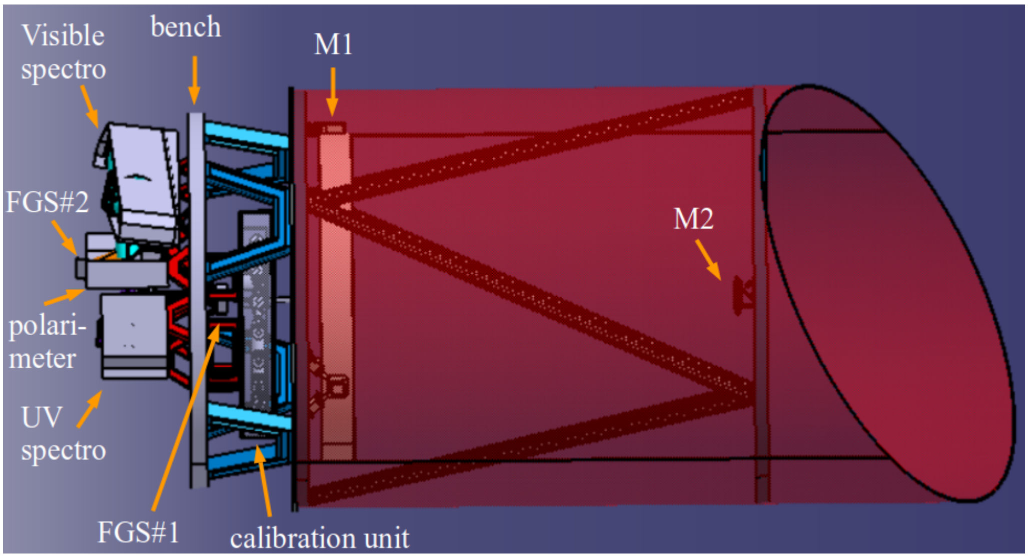

Fig. 2. View of the Arago payload. Taken from the Arago M7 proposal (Neiner et al. 2022).

objects, etc. However, its design is driven by its first and most challenging goal: probe habitability of Earth-like planets around solar-type stars and signs for life on these planets through atmospheric biosignatures.

Pollux in particular will concentrate on massive stars (Neiner et al. 2018), solar system planets, the interstellar and circumgalactic medium (Lebouteiller & Gry 2018), active galactic nuclei (Marin et al. 2018), the nucleosynthesis of the Big Bang via the relative abundance of light primordial elements, the evolution of the temperature of the cosmic background,... (Bouret et al. 2019). Since Pollux will point at one star at a time and the pressure on LUVOIR time will make it unlikely that observations can last for several weeks on a single target (at least in the first years of the mission), the observational program of LUVOIR rather concentrates on statistical studies of large samples or snapshot observations.

In the version proposed to the 2020 Decadal Survey (The LUVOIR Team 2019), Pollux has a resolution of 120000. It can record circular and linear polarisation at the same time (i.e. Stokes IQUV) or can be used in a purely spectrocopic mode. It observes either the far UV domain (90-124.5 nm) or the mid and near-UV domains simultaneously (118.5-200 nm and 200-400 nm) (see Fig. 1). However, this version had been designed for LUVOIR-A. Since the mission selected by the Decadal Survey is very similar to LUVOIR-B, a new study of Pollux-B will start in January 2023 to adapt to the smaller telescope size and off-axis design. This may result in a narrower wavelength coverage and/or lower resolution for Pollux, as well as a less precise polarization accuracy. Indeed, an off-axis telescope will introduce instrumental polarization, which can be modeled and corrected but will introduce some small polarization uncertainties.

3. The M-size Arago candidate for ESA

Arago (Muslimov & Neiner 2022) is a space mission proposed to ESA in response to its M7 call. It is a 1-m on-axis telescope equipped with a UV and Visible polarimeter feeding two spectrographs (one for the UV, one for the Visible), with a resolution of 25000 in the UV and 35000 in the Visible (see Fig. 2). It measures circular and linear polarization (Stokes IQUV) simultaneously over the 119-320 nm and 350-888 nm wavelength domains. Placed at the L2 Lagrangian point, Arago can point in any direction and observe the same target for several weeks consecutively. This allows Arago to reconstruct the 3D map of the surface and environment of the observed star.

Arago has 2 main science objectives. Its first goal is to understand the cycle of matter in the Milky way. To this aim it will characterize the ISM by measuring the magnetic field, size, and nature of interstellar grains and the interaction between various ISM phases. It will also study young accreting stars on the pre-main sequence, in particular magnetospheric accretion, the initial angular momentum, coronal activity, irradiation of the protoplanetary disk, migration of planets,... On the main sequence it will study, for example, fossil magnetic fields in massive stars, their powerful stellar winds, and strong UV radiation. For all types of stars it will determine the structure, geometry, and dynamics of stellar environments along stellar evolution by linking activity, magnetism, and wind, by measuring mass loss and momentum loss, and studying disks, magnetospheres, chromospheres, and binary systems. Finally from the study of late stages of evolution, which are often poorly understood, such as Wolf-Rayet stars, luminous blue variables, supergiants, white dwarfs, and supernovae, Arago will allow us to understand and quantify the radiation, angular momentum, and chemical elements that are injected back in the ISM.

The second scientific goal of Arago is to understand how stars affect their planets and the emergence of life on these planets. Arago will therefore study the interactions between stars and their planets. For example the stellar wind particles can erode the atmosphere of the planet, or the planet may be protected by its own magnetosphere. When the stellar and planetary magnetospheres collide, a bow shock is created. The position of this bow shock and the measurement of the stellar magnetic field by Arago will allow us to derive the magnetic field of the planet. Arago will also observe the ejection of coronal mass and magnetospheric reconnections. In addition, it will be able to observe tidal effects such as an increase of stellar activity or the heating of the chromosphere and corona. The UV irradiation by the star of the upper atmosphere of close planets will cause heating and evaporation of the planetary atmosphere but will also cause photochemistry. It is very important to understand these phenomena and thus to fully characterize the host star and space weather, to be able to interpret the spectra of exoplanets (observed by other facilities such as JWST or soon Ariel). Indeed, features in the exoplanet spectra could be interpreted as biomarkers while they are simply due to photochemistry produced by the host star irradiation. Finally comparing stellar systems similar to the solar system but at various ages, and observing solar system planets with Arago, will allow us to better understand the history of the Sun and solar system.

Arago's observing program includes a Legacy survey of the ~3000 brightest UV targets, 3D mapping of ~60 well-chosen stars for a complete cartography of their surface and environment, statistical surveys and snapshot observations, as well as a target of opportunity mode to observe potential bright supernovae, Be outbursts, novae, etc.

Unfortunately, it was very recently announced that Arago has not been selected as ESA's M7 mission.

4. The Polstar MIDEX/SMEX candidate

Polstar (Scowen et al. 2022) is a space mission project proposed to NASA as a MIDEX mission (see Fig. 3). It consists of a 60-cm telescope placed in a high elliptical orbit around the Earth. The telescope feeds one of the 2 channels of a UV spectropolarimeter: a high-resolution (R=30000) channel covers the 121 to 200 nm wavelength domain, and a low resolution (R=20) channel covers the 121-320 nm range. Polstar records all Stokes (IQUV) parameters simultaneously.

The science goals of Polstar concentrate on the study of the wind, rotation, binarity, and magnetic fields of hot stars (Scowen et al. 2019), the ISM and in particular the alignment of its grains (Andersson et al. 2021), and the formation and habitability of exoplanets.

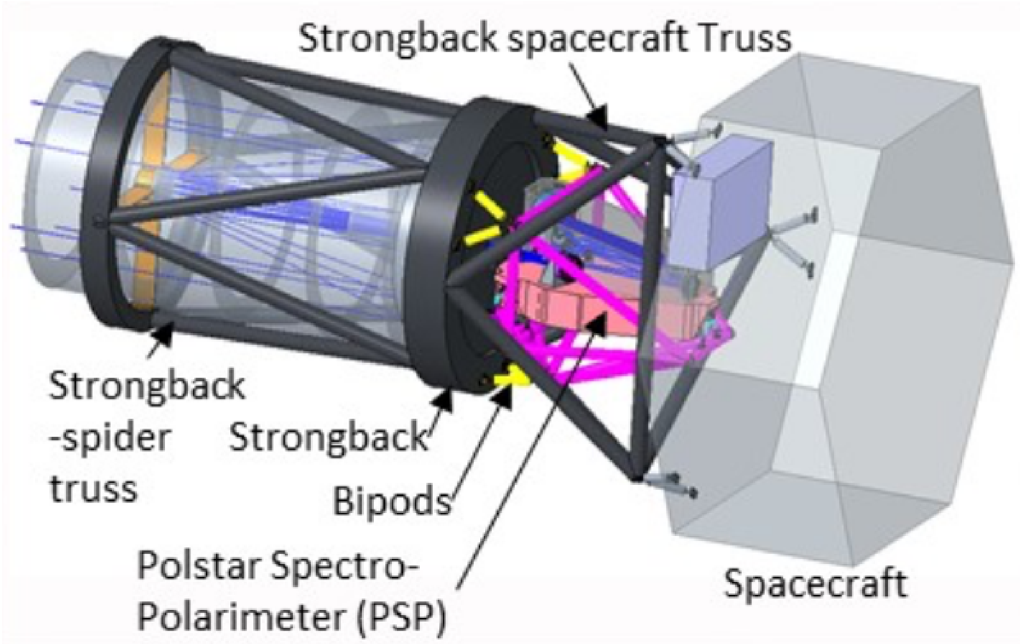

Fig. 3. View of the Polstar MIDEX mission. Taken from Scowen et al. (2022).

Unfortunately, Polstar has not been selected by NASA in 2022 for its next MIDEX mission. Polstar is however likely to be resubmitted, either as a MIDEX or as a SMEX version concentrating on hot stars, in the coming years.

5. The CASSTOR nanosatellite

CASSTOR is a nanosatellite developed in France with CNES, that will be launched to a sun-synchronous orbit around the Earth (Konaka et al. 2023). It is equipped with a 12-cm telescope and a spectropolarimeter with a resolution of 12500 covering the 135-291 nm wavelength range.

CASSTOR will be the first high-resolution UV spectropolarimeter covering a wide wavelength range to fly and would therefore be a scientific demonstrator for the larger missions mentioned above. It will concentrate on ~30 very bright hot stars (magnetic hot stars, pulsating hot stars, classical Be stars, Wolf-Rayet stars, hot supergiants,...) and produce the very first UV spectropolarimetric results.

Moreover, the three missions mentioned above use a UV polarimeter based on rotating birefringent plates in MgF_2 followed by a Wollaston prism (Le Gal et al. 2018), which is also the technology used in CASSTOR. Only the far UV channel of Pollux uses a different polarimetric technique based on reflections (Le Gal et al. 2020a). CASSTOR will therefore also be a technological demonstrator for the UV polarimeters of Arago, Polstar, and the mid and near UV channels of Pollux. This will allow to increase the technological readiness level of the UV polarimeters.

CASSTOR has already undergone a Phase 0 study and could be ready for launch within a few years.

6. Conclusions

Several high-resolution UV spectropolarimetric mission projects of various sizes are ongoing, such as Pollux on LUVOIR, Arago, Polstar, and CASSTOR. They are summarized in Table 1. The CASSTOR nanosatellite is likely to be launched first around 2026 while

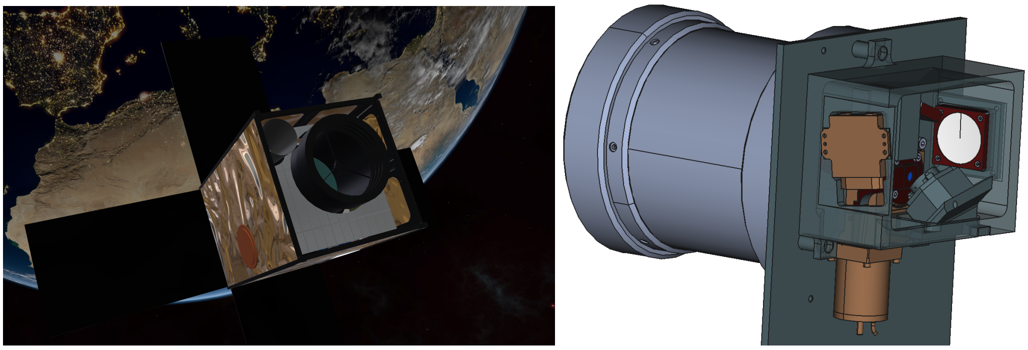

Fig. 4. Left: the CASSTOR nanosatellite. Right: view of its 12-cm telescope and payload.

Table 1. Current high-resolution UV spectropolarimetric mission projects.

Mission	Type	Telescope diam. (m)	Wavelength range (nm)	Resolution	Launch
Pollux@LUVOIR-A	NASA Flagship	≥6	90-124.5 or 118.5-400	120000	~ 2042
Arago	ESA M	1	119-320+350-888	25000+35000	
Polstar	NASA MIDEX	0.6	121-200 or 121-320	30000 or 20	
CASSTOR	Nanosatellite	0.12	135-291	12500	~ 2026

the large flagship mission LUVOIR will be launched in the first half of the mid 2040's. Arago and Polstar have not been selected by ESA and NASA so far but will be resubmitted and, if selected at the next round, would then be launched between CASSTOR and LUVOIR.

These missions will address a very broad range of science objectives with a new technique and thus provide a brand new view on the targets. Moreover, since we will perform UV spectropolarimetry for the first time, the discovery space is also very large and will bring science results that we cannot even imagine today.

During the study and development phases of these space projects, new science is also being performed to predict and prepare observations, and to model expected results (e.g. Folsom et al. 2022; Shultz et al. 2022; Jones et al. 2021; ud-Doula et al. 2022). In addition, many technological developments have already been executed, e.g. on UV polarimeters and dichroics (e.g. Pertenais et al. 2015; Le Gal et al. 2020b), but more developments are required, e.g. to optimize diffraction gratings, cross-dispersers, and detectors for the UV domain. The development of UV spectropolarimeters will thus also bring valuable new technology for other UV applications.

Finally, consortia have been formed for the various projects but are still open for contribution. In particular the European Pollux consortium will start a new Pollux-B study early 2023.

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