# ULTRAVIOLET ASTRONOMY IN THE XXI CENTURY


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# THE POLSTAR EXPLORER MISSION – SCIENCE DRIVERS AND SCOPE

*Paul Scowen (ASU, PI), Richard Ignace (ETSU), Coralie Neiner (Observatoire de Paris, Meudon), Gregg Wade (Royal Military College of Canada), Matt Beasley (SwRI), Jon Bjorkman (U. Toledo), Jean-Claude Bouret (LAM, France), Roberto Casini (HAO-NCAR), Tanausu del Pino Alemán (IAC, Spain), Samantha Edgington (LMCO), Ken Gayley (U. Iowa), Ed Guinan (Villanova), Jennifer Hoffman (U. Denver), Ian Howarth (University College London), Tony Hull (UNM), Rafael Manso Sainz (MPS, Germany), Yael Naze (U. Liege), Alison Nordt (LMCO), Stan Owocki (Bartol Inst., U. Delaware), Steve Petrinec (LMCO), Raman Prinja (University College London), Hugues Sana (U. Leuven), Matt Shultz (Bartol Inst., U. Delaware), Nicole St-Louis (U. Montreal), Clem Tillier (LMCO), Javier Trujillo Bueno (Instituto de Astrofisica de Canarias), Gopal Vasudevan (LMCO), Bob Woodruff (optical designer)*


## ABSTRACT:

PolStar is a FUV spectropolarimeter Explorer-class mission that is the first to combine the spectroscopic capabilities previously available in IUE and HST-COS with the polarimetric capabilities of a true successor to WUPPE. PolStar will provide access to the suite of resonance lines in the FUV to map the wind and magnetospheric structure of massive stars in 3D and gain insight into the effect these structures have on the mass loss and stellar evolution of the stars themselves. The mission will also address science related to how massive binary pairs interact with each other, and provide access to the interstellar reddening law at very short wavelengths for a variety of sight lines. The suite of science drivers is discussed in terms of requirements placed on the mission design and we outline the kinds of return we might expect from this mission, if selected.


## SPECTROPOLARIMETRIC DIAGNOSTICS

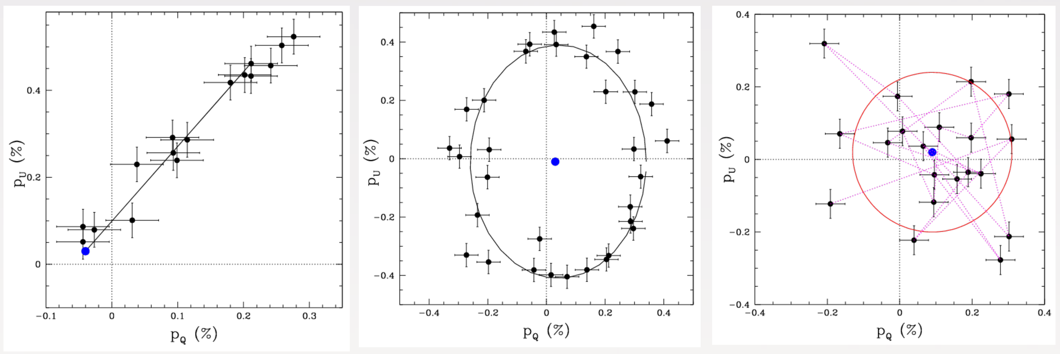
- Polarization data are referenced in terms of a Stokes vector with components I, Q, U, and V.
  - I is the total intensity and is the measurement standard for traditional spectroscopy
  - Q and U are measures of linear polarization, providing both amplitude and position angle (or orientation) information; metrics are relative intensities of pQ=Q/I and pU=U/I
  - V is circular polarization, which for astrophysics is typically associated with sensitivity to magnetism; metric is pV=V/I
- Crucial for Polstar will be the combination of polarization data with monitoring for time-variable measures.
- Continuum Polarization - Thomson scattering of free electrons produces linearly polarized scattered light and is the dominant polarigenic (and “gray”) opacity in the continuum of massive stars (see left)
- Line Polarization – one key effect is doppler shift – the rapid rotation of the star, disk rotation, fast winds, corotating magnetospheres all represent supersonic motions that lead to changes in the polarization – both amplitude and position angle – across a resolved spectral line (see left)
- A second key effect on line polarization is the polarigenic response of lines to magnetism. Key for Polstar is the well-known Zeeman effect that produces circular polarization for studying stellar magnetism (see left). Less known is the closely associated Hanle effect, a weak Zeeman effect leading to alteration of the linear polarization (as opposed to circular) across a resonance scattering line that has long been used in the Solar community

## MASSIVE BINARIES

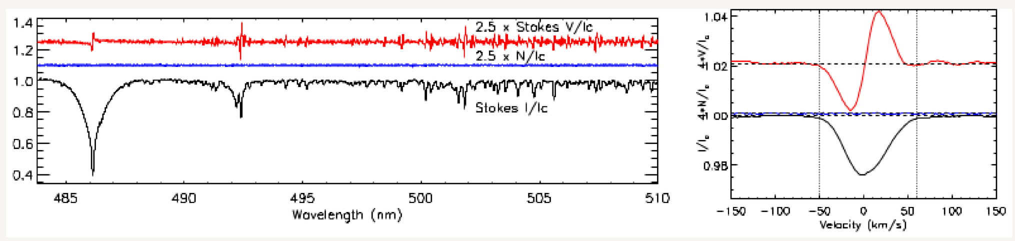
- Nearly all (i.e. >70%) massive OB / Wolf-Rayet stars are (or once were) members of binary or multiple star systems.
- Memberships of stars in binary systems, in particular eclipsing binaries, return crucial information that cannot be known for single stars. The analyses of their orbital radial velocities and light curves yield fundamental physical properties of the component stars - such as mass and radius (and with spectra/color giving: Teff and also luminosity) of the component stars.
- Polarization effects in close binaries arise from a number of sources and mechanisms. These include variable polarization arising from the scattering of stellar flux from the stars' tidally- and rotationally-distorted surfaces and the “reflection effect” in which the light of one star is scattered at the surface of the companion star.
- Polarization can also arise from magnetic surface structures as well as magnetic fields created (or embedded) in the outflowing and/or interacting plasmas.
- For the first time with FUV-spectropolarimetry from PolStar, it may be possible to study magnetic fields for some of the bright-FUV sources via circular polarization using high temperature FUV resonance emission lines that are only accessible with PolStar.
- Spectropolarimetry, especially in the FUV is a powerful tool for detailed investigation of their physical properties. The FUV spectral region is crucial in these studies because it is very rich in important spectral diagnostics including strong resonance lines and T~ 10,000-20,000 K “chromospheric” like emission lines that arise in plasmas with temperatures range from 10,000 K.

## MISSION MOTIVATION

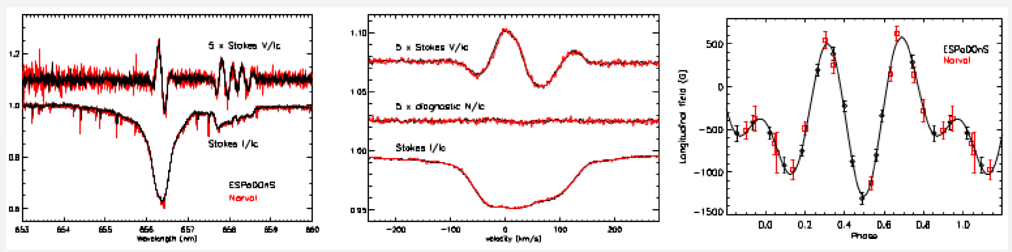
- Massive stars are the most important contributors to galactic cosmic evolution. They provide the raw materials and heavy elements for the interstellar medium, planets and all living matter, and the UV light to illuminate them and catalyze chemistry. Their rapid evolution, extreme luminosity, fundamental dynamical and chemical interactions with their environment will be revealed by PolStar.
- PolStar is a far ultraviolet (FUV) spectropolarimetry mission designed to target massive stars and their environments. PolStar will take advantage of resonance lines only available in the FUV to measure for the first time the magnetic and wind environment around massive stars to constrain models of rotation and mass loss that affect the star's evolution and end-of-life state. We will deliver the first 3D tomographic models of the stellar magnetospheres and tie them to known magnetic structures on the stellar surfaces to obtain the first complete picture of the stellar environment.
- PolStar is the first non-solar mission optimized for stellar high resolution UV spectral polarimetry, delivering a spectral resolving power of R ~ 30,000, while also measuring all 4 Stokes parameters. PolStar is well matched in scope for a timely and scientifically compelling mission. Recent advances in detector technology makes this mission possible now and delivers more than an order of magnitude improvement in sensitivity and spectral resolution over its predecessors.



Three illustrative Q-U diagrams for polarimetric variability patterns. Left is a variable source with fixed geometry; middle shows cyclic changes in geometry, such as a binary; right shows stochastic variations, such as wind clumping.




Left - portion of a spectrum (top Stokes V, middle N, bottom I). Right - LSD profiles for full source optical spectrum illustrating S/N gains in field detection using the LSD technique. The derived surface field is well-modeled as an oblique dipole rotator.



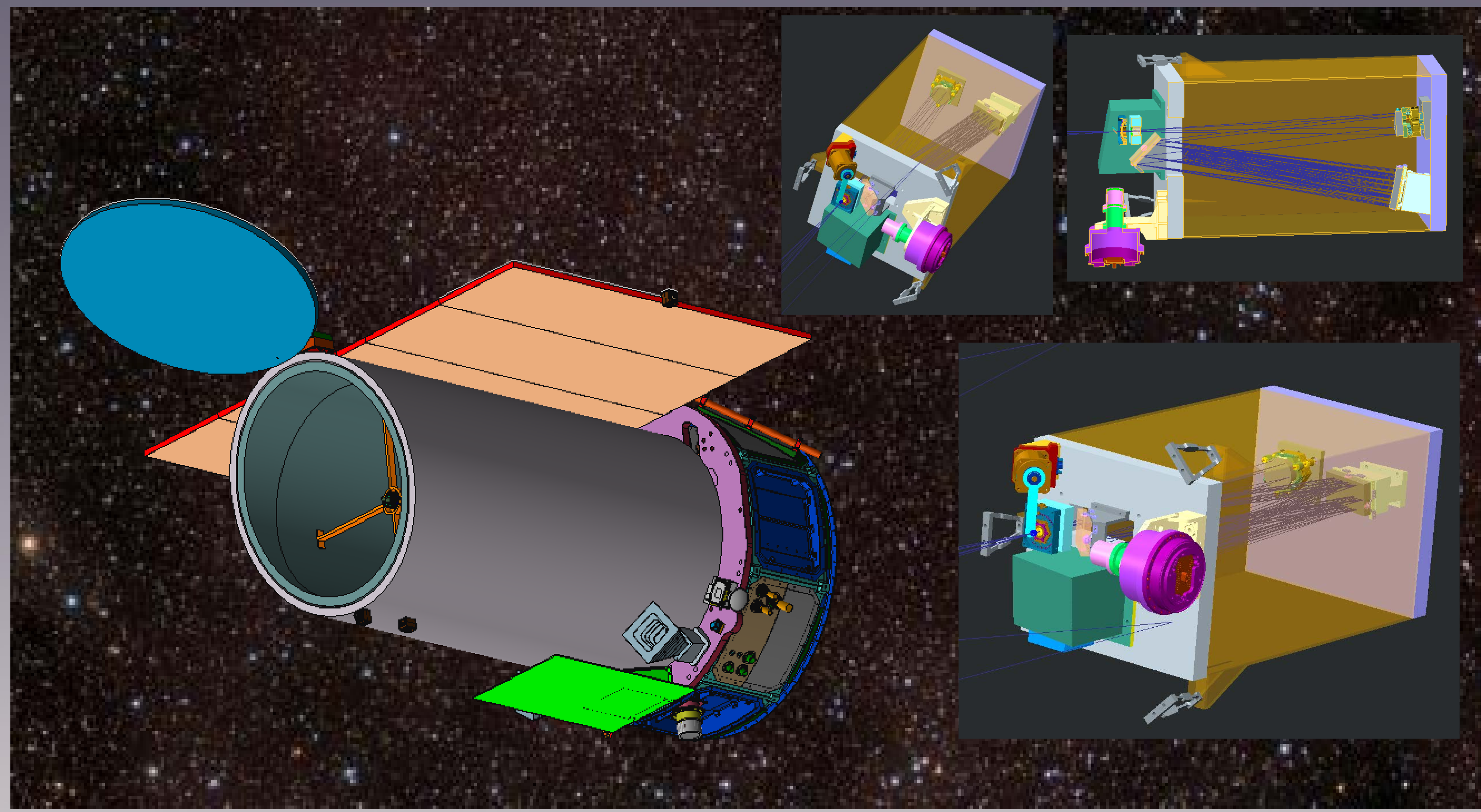
Left - portion of spectrum (top Stokes V, bottom I); Middle - LSD profiles for full spectrum; Right - derived longitudinal field with rotational phase. Illustrates capability for ascertaining a multiple surface field.

## ORIGIN AND EVOLUTION OF BE STAR DISKS

Be stars are a common class of variable, rapidly rotating, near-main-sequence B stars. About 30% of Galactic B stars are Be stars. In addition to their Balmer emission, Be stars have an infrared excess from free-free emission, and they are intrinsically polarized. We know from optical and IR interferometry that the hydrogen emission lines, IR excess, and polarization are produced by a geometrically thin circumstellar disk that is in Keplerian rotation. Stellar material injected into orbit around the star will spread outward forming a so-called viscous decretion disk. What is unknown is how the material is transferred from the star into the disk, and, in particular, how is enough angular momentum added so that this material attains orbital velocity.

We will use PolStar to address:

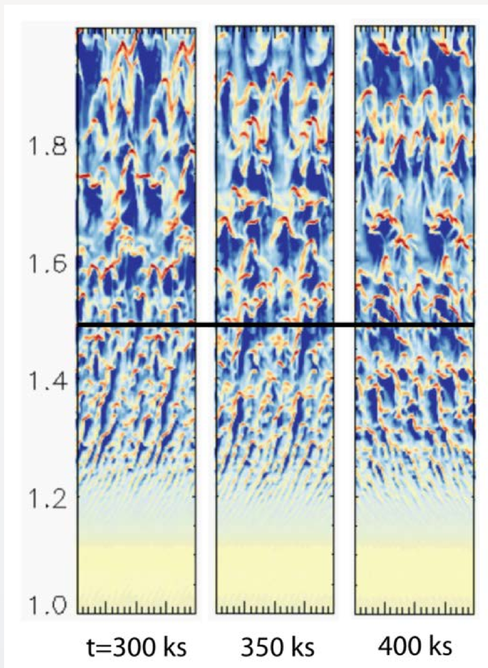
- Where is the material injected into the disk? Spectropolarimetry is sensitive to radial location via the correlation of Keplerian disk velocity with distance.
- How does the material merge into and spread within the disk? Q-U loops can be used to map the location of orbiting blobs and watch how they spread and merge into the disk.
- How is this injection correlated with the stellar pulsations? We will have high S/N PolStar flux measurements of the UV photospheric line profiles, providing detailed simultaneous observations of the stellar pulsations.
- How does the disk dissipate? Does it flow back onto the star or is the material carried away via disk ablation and a disk wind?



## PHYSICS, STRUCTURE, AND VARIABILITY OF RADIATIVELY-DRIVEN WINDS

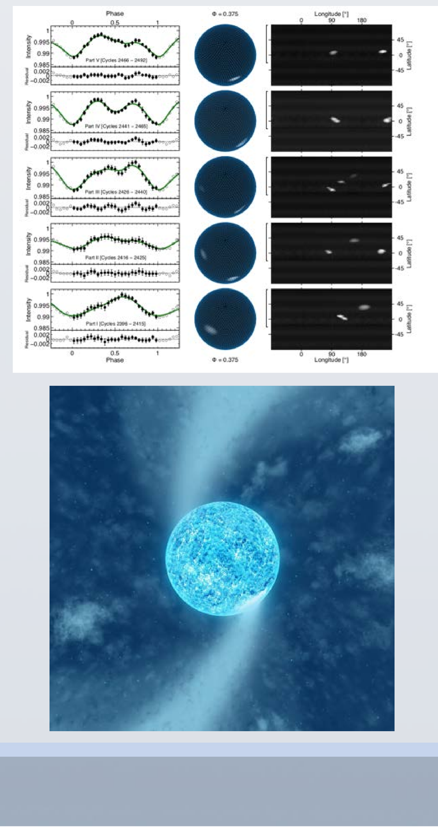
A key defining characteristic of massive stars is their strong winds. Because of their high luminosities, a large number of photons can be absorbed or scattered through spectral lines in the outer layers of massive stars, leading to a radiative acceleration that is strong enough to generate an outflow: the radiatively driven stellar wind. Since (UV) spectral lines are sensitive to both velocity and density structures in the stellar wind, they permit the study of two key effects:

- Small-scale structures: Clumps and Blobs - to understand the spatio-temporal structure of clumping and its evolutionary dependence, high-cadence (hours), high signal-to-noise ratio (>100) spectroscopic time series of O stars are required, focused on wind-sensitive resonance lines that are only present in the far UV




Instability-generated spatial and temporal variation of logarithmic density, relative to the an intial steady-state in a line-driven stellar wind. Color scales range from log(0.1) = −1 for lowest density (blue) to log(10) = +1 for highest density (red), with yellow (log(1) = 0) representing densities equal to the initial, steady-state. The vertical variation extends from the stable, subsonic wind base at the stellar surface, to a height of one stellar radius R∗. The 3 panels show time snapshots at t =300, 350, and 400 ks, long after the initial condition has developed into a statistically steady turbulent state. From Owocki & Sundqvist (2018).

- Large-scale structures: Co-rotating Interaction Regions (CIRs) - to test the relationship between photospheric and wind variability, high-cadence (hours), long-duration (weeks), high signal-to-noise ratio (>100) UV spectroscopic time series of O stars are required. As many photospheric and wind lines as possible would be monitored simultaneously in order to sample the transition region between the stellar surface and the wind- dominated atmosphere.



Mapping the photosphere of ζ Pup as observed by BRITE in 2014-2015 using light curve inversion. Time increases upwards. The left (upper) segment illustrates the observed light curve (filled circles) during successive parts of the BRITE observing run, along with the reconstructed light curve (green line), with the residuals plotted below the light curves. Then follows a view of the star at rotational phase 0.375 (Middle segment) and the pseudo-Mercator projection of the stellar surface (Right segment). The vertical open brackets on the left of the pseudo-Mercator projections indicate the range of latitudes visible by the observer. The lower panel is an artist's conception of the CIRs proposed to be driven by the bright spots inferred from the photometry. From Ramiaramanantsoa et al. (2018).

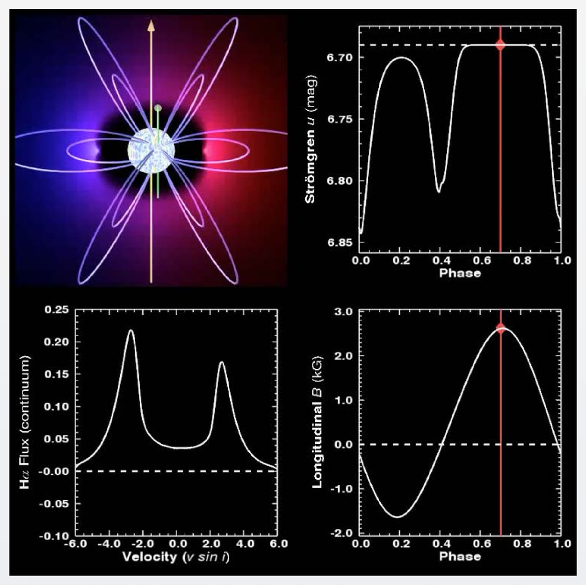
## WIND/MAGNETIC FIELD INTERACTION AND MAGNETOSPHERIC PHYSICS

In hot stars, fossil magnetic fields with surface strength from 100 G to a few tens of kG, usually dominated by oblique dipoles, have formed and frozen into their radiative envelopes long before the PMS stage (e.g., Alecian et al. 2013).

Such fields may contain the imprint of magneto-hydrodynamic processes occurring during early phases of star formation, before the star is visible. Moreover, they have important consequences for later formation phases, especially in their role as intermediaries in accretion and mass-loss processes. During main sequence (MS) and post-main sequence (post-MS) evolution, fossil magnetic fields have been shown to couple strongly to stellar winds, enhancing the shedding of rotational angular momentum through magnetic braking (Townsend et al. 2010).

Simultaneously, the presence of the field impedes mass loss, redirecting outflowing wind back toward the stellar surface. As rotation and mass loss are key determinants of the evolution of hot stars, magnetic fields potentially have an enormous impact (e.g. Petit et al. 2017, Georgy et al. 2018, Kesztheyi et al. 2019).

An illustration of the approach of building 3D tomographs of magnetic and wind structures around a star based on the time evolution of emission line profiles, and their polarimetric properties as a function of time – as the source rotates under our line of sight. PolStar will use this approach to map the winds and magnetospheres of massive stars using resonance lines in the FUV that map the larger environment.




Sophisticated tomographic mapping of stellar surface structures and magnetic fields is now possible. However, due to the current reliance on visible wavelength observations, such mapping is effectively confined to the stellar photosphere. The range of stellar and circumstellar diagnostics provided by PolStar thanks to its UV wavelength coverage, when coupled with the high-cadence, long-term continuous monitoring from space, will allow the extension of indirect mapping methods into the discs and winds of hot stars, providing the first truly 3D views of their magnetospheres and immediate environments.

Therefore the unique capabilities of PolStar, namely space-borne UV high-resolution spectropolarimetry, will allow us, for the first time, to fully characterise the direct relation of stellar magnetic fields with circumstellar activity. The Sun is currently the only star for which a reliable map of its 3D environment exists. PolStar will provide such maps for a set of well-chosen, key hot stars.

The key diagnostics required for this science case are simultaneous, multi-epoch spectroscopy of photospheric lines, wind-sensitive resonance lines, and the (polarized) continuum at high spectral resolving power and high signal-to-noise ratio (100-1000+).