The Polstar SMEX FUV Spectropolarimetry Mission

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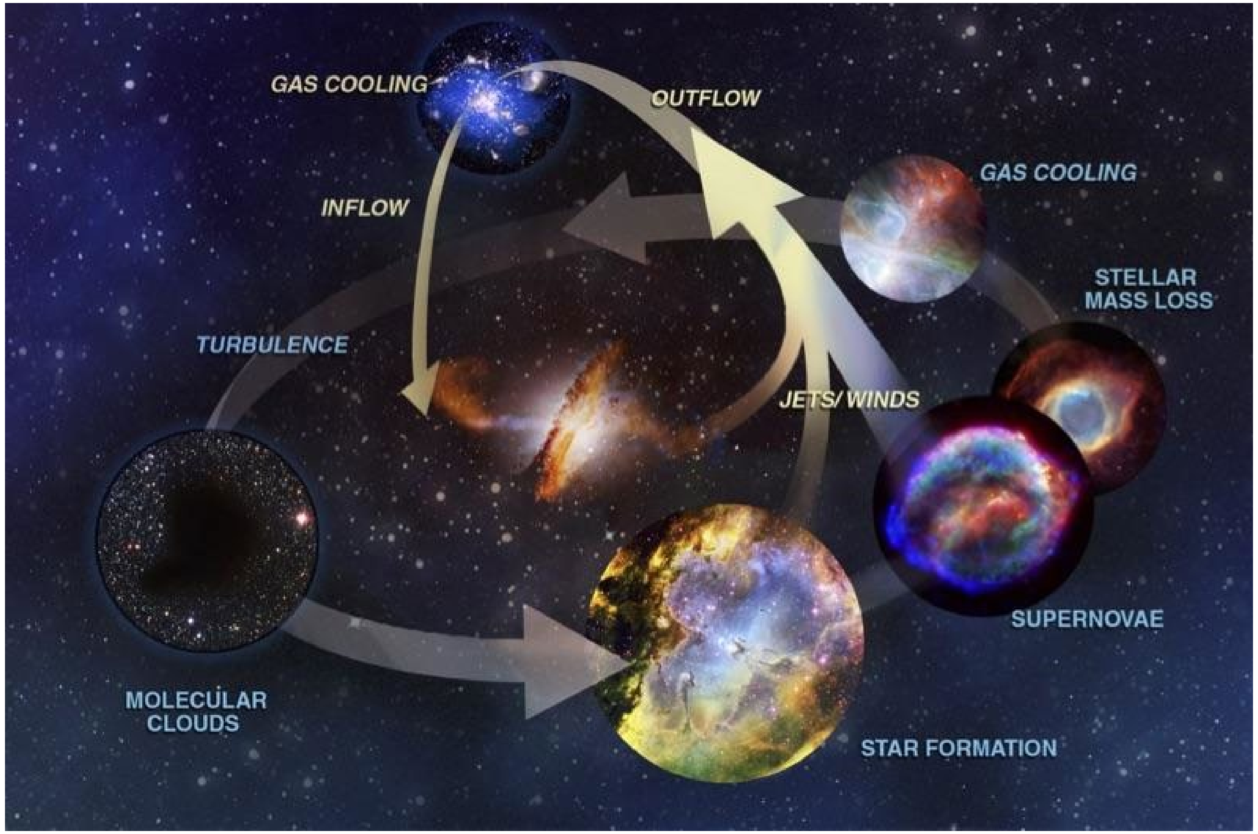
Science Scope

Polstar Science – The Role of Rapid Rotation in the Evolution of Massive Stars and the Galaxy

- Massive stars are the **most important contributors** to galactic cosmic evolution.
- They **live out their entire lives and go supernova** while low-mass stars are still forming.
- Massive stars **drive the ecology of star formation** through the Baryonic Cycle.
- A host of theories predict **profound**, yet different, **consequences** for rapid rotation in these stars, so **observational constraints** are now essential.
- Polstar will use **UV spectropolarimetry** to capitalize on telltale stellar and wind **asphericities** induced by **rapid rotation**, to constrain the internal physics that **dictates the evolution of the star** and its impact on the Galaxy.
- Massive stars are **very bright**, mostly **in the UV**, providing a sample size of about **a hundred suitable targets**, so we can spend **a lot of time** on each one, meaning **a large aperture is not required**.
- Polstar will provide a **new window, a new capability** to view the Universe with.



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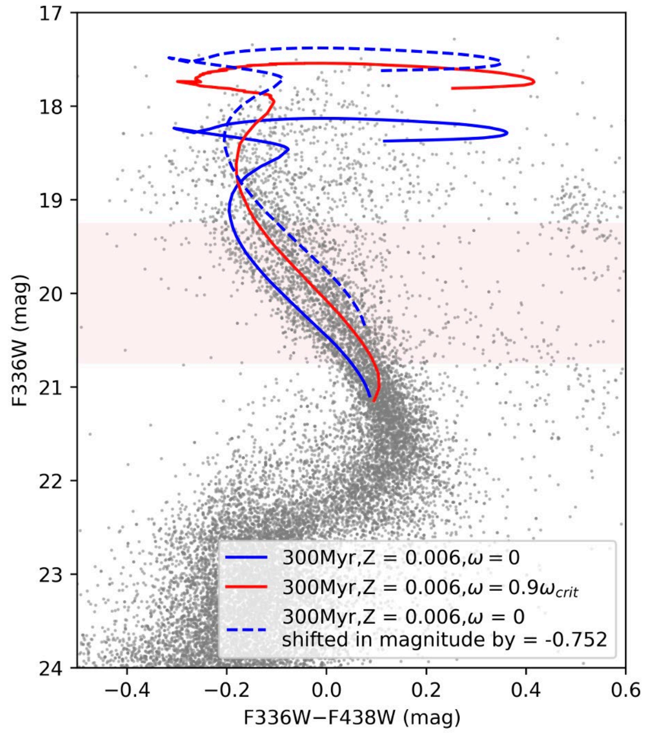
Why Do We Care About Rotation?

Rapid rotation of stars is crucial to understand because it:

- Is known to **create a bifurcated ZAMS** found by GAIA (previously and erroneously explained as multiple epochs of star formation since faster rotating stars look like older stars)
- Affects **stellar evolution by inducing mixing**, given that **chemical gradients** drive global stellar structure evolution, including envelope expansion

- Affects **how stars influence their surroundings**:
  - promotes co-rotating interaction regions (CIRs), producing shocks and enhancing ionizing radiation emission
  - alters overall wind geometry to induce latitudinal density differences, affecting the blast wave when the star goes supernova (many SNe are aspherical, affecting energy input to the interstellar medium)
  - angular momentum history linked to channeled gamma ray bursts
- Affects **how we understand stars**:
  - exposes the nature of the interior physics of the star that is capable of leading to rapid rotation in the first place (are there internal dynamos like Tayler-Spruit that promote rigid-body rotation? Can the core be made to contract enough to transport angular momentum outward, or does chemical mixing promote homologous evolution that would prevent core contraction?)
  - May signify angular momentum drawn from past binary interactions, common in massive stars, since orbits are large reservoirs of angular momentum
- Affects **observable diagnostics**:
  - can create disks that alter the line spectra and affect spectral typing and abundance estimates, as well as induce wavelength-dependent polarization via their extreme asphericity
  - induces breaks from spherical symmetry that perturb line spectra and allow for nonzero polarization



Wang et al. 2023

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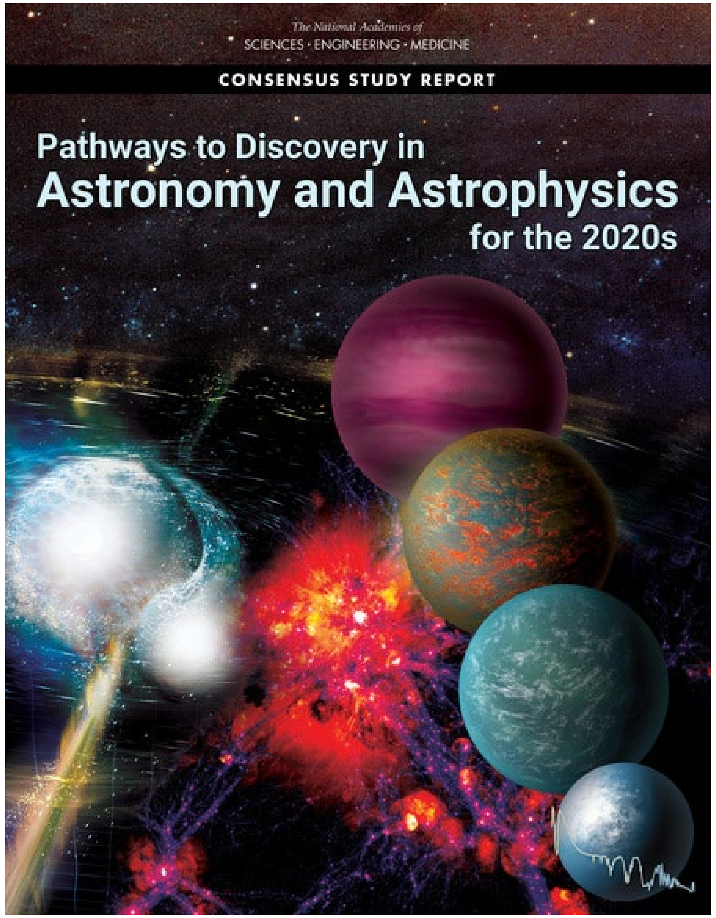
Polstar : Relevance to NASA Priorities

The Polstar Science Program addresses NASA Strategic Objective 1.1 by answering critical questions for understanding massive star evolution identified by both the 2020 and 2010 Decadal Surveys, and the NASA Astrophysics Roadmap under Stellar Feedback, by employing NASA Strategy 1.3 to use techniques across stellar astrophysics and heliophysics:

- Addressing the *inclusion of more realistic geometries beyond assuming stars are spherical [2020, pg. 2-5]*
- Providing *more sensitive space-based UV spectroscopy […] necessary to better characterize the spectra and winds of massive stars [2020, pg. 2-36]*
- Gaining insight into an *understanding [of] binary stellar evolution […] critical for understanding the global energetics of stellar feedback in galaxies [2020, pgs. 2-36, B-3]*
- Taking advantage of UV spectropolarimetry for *stellar surface feature mapping* and *magnetic field mapping [2020, G-Q3]*
- Addressing *how […] rotation and magnetic fields affect stars? [2010, SSE1]*
- Addressing how the stellar end-of-life state affected by rotation rate and the strength and distribution of magnetic field structure [2020, pgs. G-3, G-9, G-13, J-23]
- Providing an understanding of how stellar lives and their impact on cosmic evolution is based on knowledge of mass loss, rotation and stellar evolution. [2020, pg. G-3; 2010 pgs. 61,64]



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Scientific Question

- **Objective**: **How does rapid rotation affect the physics of massive stars?**

- **Data set required**: for a suite of 100-200 late O to late B stars, including binaries, and Be stars, determine the following physical properties: stellar oblateness; latitudinal temperature gradient; abundance anomalies from mixing; pole-to-equator mass flux contrast; wind clumping properties; wind velocity inhomogeneities; magnetospheric velocities and densities; circumstellar density, temperature, & kinematics; binary orbital parameters.

- **Observations required**: spectral and polarimetric measurements at R=10k (30 km/s) to a polarimetric precision of 0.01% for diagnostic lines from 122 to 320nm, to be obtained over several days and across several epochs to extract dynamical evolution.

- **Observables include**: variable polarization angle with wavelength and orbital phase; polarization variation across photospheric and wind lines; degree of polarization from the photosphere and orbiting disk; spectroscopy: FUV line profile variations monitored continuously for days; rotational phase monitoring; variations in polarization angle as function of binary phase; photospheric and wind lines from 115 to 320 nm

Initial Goals and Objectives

- Goal A) Understand the connection between rapid rotation in massive stars, internal structure, and evolution.
    - A1) Correlate stellar oblateness and gravity darkening with rotational criticality to test theoretical predictions.
    - A2) Test solid body vs. differential rotation.
    - A3) Test surface abundance for rotation-induced mixing.
- Goal B) Understand the connection of rapid rotation to circumstellar asphericity: disks, jets, wind, and binarity
    - B1) Test how rotation affects prolate/oblate winds, CIRs, clumping, and mass and angular momentum loss.
    - B2) Test how strong magnetism inhibits mass loss while increasing angular momentum loss.
    - B3) Test the role of binary mass transfer in systems with a history of it, and probe its nature in systems doing it.
    - B4) Apply binary searchlight effects to diagnose rotational effects on the circumstellar environment.

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Why Spectropolarimetry?

Intrinsic polarization from a point source comes from departure from spherical symmetry, which in the 93 percent of massive stars that are not strongly magnetized is due primarily to rapid ***rotation*** and/or ***binarity***.

- Doppler shifts in spectra map phenomena only to their line of sight motion, so **do not resolve ambiguities in the global geometry** (rotation, inclination, disks, etc.).
- Stokes Q and U are fundamentally contrasts between the geometry along two perpendicular axes, so are **well suited to detect perpendicular azimuthal contrasts** like rotational axis vs. equator, or polar jets vs. equatorial disk.
- This includes the Ohman effect in photospheric absorption lines even without gravity darkening, and continuum polarization in the presence of gravity darkening. Hence **the combination of line and continuum polarization independently constrains both the rotation rate and the gravity darkening** induced by that rotation rate
- Ambiguities between rotation speed and inclination (the infamous v sin i problem), and in global geometry, require additional independent constraints provided by polarization.
- **The combination of line diagnostics, line polarization, and continuum polarization provide powerful constraints on the multiple simultaneous unknowns**

Why The UV?

- The key physics favors the UV:
  - Polarization and spectral diagnostics require high S/N, so high photon counts, and **hot stars are UV targets with high UV photon fluxes**.
  - Polarization requires anisotropy in the local radiation field, and this anisotropy is most extreme when the stellar continuum is most sensitive to the T gradient, which is **near the Planck peak in the UV**.
  - Wavelength dependence across the full observing band provides crucial information, as this is not only essential for removing ISM contamination (and learning about the ISM as enabled science), it is also a key diagnostic of its own (since the polarization angle is expected to rotate by 90 degrees from the optical to the UV, going through zero polarization in between). This **wavelength dependence is steepest, so leads to the strongest signal, where the Planck function depends most steeply on T, which again is in the UV**.
  - Polarization is strongest where **scattering is favored over absorption, which is in the UV**.
  - Line diagnostics are strongest where there are the most lines with the highest opacity, producing deeper photospheric absorption lines to enhance the Ohman effect, and able to probe circumstellar features like disks and winds. **Higher opacity lines are from ground states, which tend to be in the UV**.

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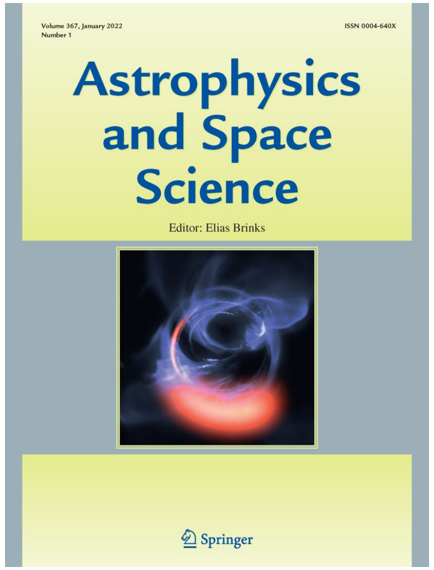
Polstar AP&SS Topical Collection

Titles in Black Remain Science Drivers, or partial Science Drivers, for the SMEX version of Polstar



Released early 2023

A topical collection of 10 science papers that describe the MIDEX science drivers, the experiments potentially to be completed and the projected impact on the field

Ultraviolet Spectropolarimetry: on the origin of rapidly rotating B stars
C.E Jones et al.

Ultraviolet Spectropolarimetry with Polstar: Interstellar Medium Science
B-G. Andersson et al.

Ultraviolet Spectropolarimetric Diagnostics of Hot Star Magnetospheres
A. ud-Doula et al.

Ultraviolet Spectropolarimetry With Polstar: Using Polstar to test Magnetospheric Mass-loss Quenching
M.E. Schultz et al.

Understanding Structure in Line-Driven Stellar Winds Using Ultraviolet Spectropolarimetry in the Time Domain
K.G. Gayley et al.

UV Spectropolarimetry with Polstar: Protoplanetary Disks
J.P. Wisniewski et al.

Ultraviolet Spectropolarimetry: Investigating stellar magnetic field diagnostics
C.P. Folsom et al.

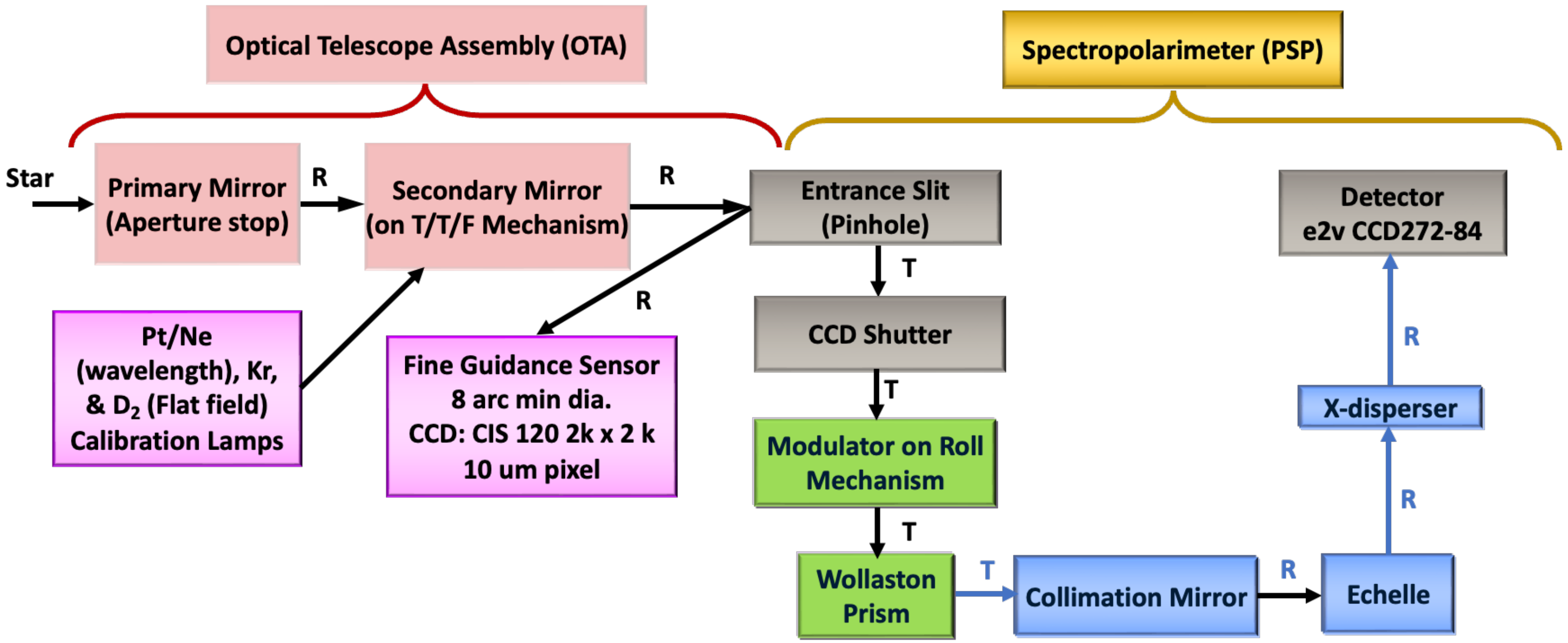
Ultraviolet Spectropolarimetry: Conservative and Nonconservative Mass Transfer in OB Interacting Binaries
G.J. Peters et al.

UV Spectropolarimetry with Polstar: Massive Star Binary Colliding Winds
N. St-Louis et al.

The Polstar High Resolution Spectropolarimetry MIDEX Mission
P.A. Scowen et al.

Design

Scientific Mission Concept



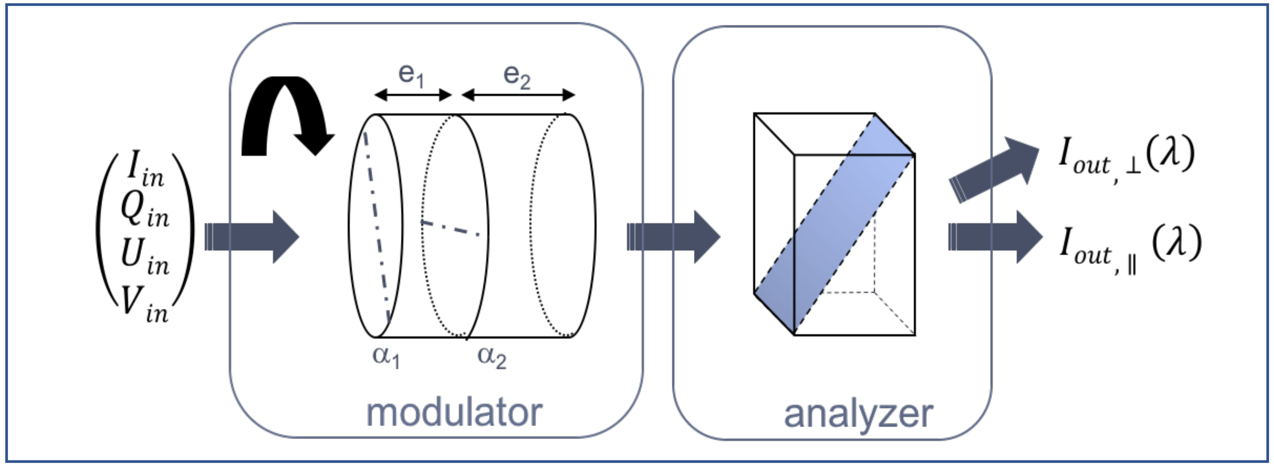
Optical Block Diagram

R ~ 10k
Wavelength Range: 122-320nm
Aperture: likely 40cm
Pointing performance: ~80 mas over 600 seconds

Scientific Mission Concept

❑ Instrument:

- Modulator = 2 thin double-plates of MgF_2 rotating as a stack at 6 optimized angular positions
- Analyzer = Wollaston prism in MgF_2



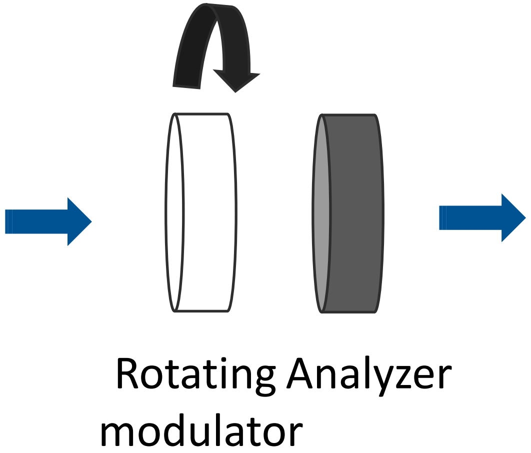
- → the parameters of the plates (thickness, orientation) and modulator angles are optimized to obtain the best efficiency in the extraction of the polarization information

Scientific Mission Concept

❑ Instrument:

- Rotating modulator (at discrete positions) to modify the entrance polarization
- + Analyzer (= fixed linear polarizer) to select a certain polarization

$$\begin{pmatrix} I_{in} \\ Q_{in} \\ U_{in} \\ V_{in} \end{pmatrix}$$



$$I_{out}(x,\lambda) = I_{in} + \alpha_Q(\lambda)Q_{in}(\lambda) + \alpha_U(\lambda)U_{in}(\lambda) + \alpha_V(\lambda)V_{in}(\lambda)$$

→ polarization information is encoded in the output intensity signal

- → the combination of several measurements taken at various modulator angles provides the full characterization of the entrance beam

Summary

- Polstar will use UV spectropolarimetry to infer the response of internal stellar structures to rapid rotation, dictating the evolution of the star, and its impact on the Galaxy.
- Polstar will discriminate between theoretical predictions of how rapid rotation affects chemical mixing and angular momentum transport, leading to surface consequences for abundances and degree of criticality.
- Polstar will open up space-based access to FUV spectropolarimetry for the first time in 25 years.
- Polstar is responsive to both 2020 and 2010 Decadal Survey priorities.
- Polstar brings together both heliophysics and stellar astrophysics in an interdisciplinary collaboration.
- Polstar will provide a new window, a new capability to view the Universe with.

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