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The Far-Ultraviolet SpectroPolarimeter (FUSP)

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Abstract. The primary objective of FUSP is to test a number of potentially powerful new diagnostics of the dynamics and geometry of envelopes of hot objects using spectropolarimetry in the Far Ultraviolet. These diagnostics will be applied to hot stars, interacting binaries, and forming stars. The proposed instrument would make use of a new, small spacecraft, an autonomous groundstation, and would be operated from a control station at the University of Wisconsin.

1. Science

From a broad perspective, matter in the Universe comes in two forms, diffuse and compact, and the structure and evolution of the Universe depends on how matter and energy flows from one to the other. While there are numerous theories for how compact objects accrete from and lose mass to the surrounding diffuse medium, the frustrating fact is that the observational evidence is meager and indirect. This is because much of the interesting physics takes place quite near the compact object, in an unresolvable envelope, where neither the physics nor the geometry is simple: magnetic fields and angular momentum are fundamentally important. The objective of FUSP is to test potentially powerful new diagnostics of the dynamics and geometry of envelopes of hot objects using spectropolarimetry in the Far Ultraviolet. These tools will be applied to the fundamental question: *Under what circumstances and how do angular momentum and magnetic fields control accretion and mass outflow in hot objects?*

FUSP will obtain high-precision spectropolarimetry from 1050 – 1500 Å for hot stellar sources. It will measure the polarization produced by electron scattering, resonance-line scattering, and hydrogen Rayleigh scattering in the inner circumstellar environment, and thereby quantitatively constrain the geometry and dynamics of the system. In addition, the strength and geometry of the magnetic field will be determined from the Hanle effect

1.1. Wind Geometry and Dynamics with Line Scattering

Far ultraviolet spectroscopy is popular mainly due to the many resonance lines in the FUV. The fact that these are all potentially polarizing through scattering makes these lines potential probes of envelope asymmetry in the same way that electron-scattering polarization is used to detect asymmetry in the visible. In fact, since the resonance-line cross sections are all much larger than the Thomson cross-section, potentially much smaller asymmetries are detectable than with

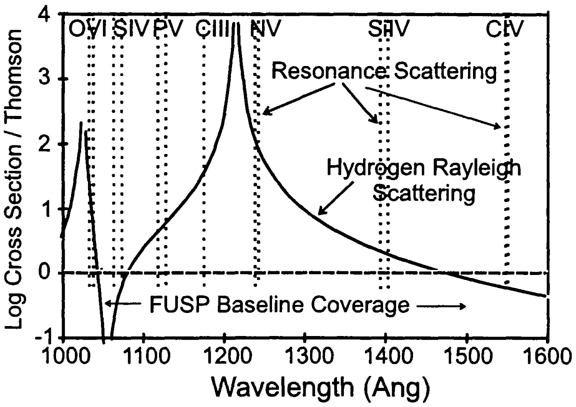

Figure 1. FUV polarizing opacities, relative to electron scattering. Dotted: wind resonance lines; Solid: Hydrogen Rayleigh scattering.

electron scattering. It is true that many resonance lines become optically thick in actual envelopes, which usually greatly reduces polarization through multiple scattering. In the FUV, however, many resonance lines are wind drivers, which tends to maintain $\tau < 1$, at least in the profile wings. Figure 1 shows the main wind resonance lines in the FUV. The net line polarization depends on the line polarizability and the envelope asymmetry. The polarizability is known: it depends only on the initial, intermediate and final atomic angular momentum in the process (Stenflo 1994). In a line broadened by expansion/rotation, the polarization at each position in the profile depends on the net asymmetry of material at one line-of-sight velocity. The polarized profile, used in conjunction with the intensity profile and wind dynamic models, thus offers a potentially powerful probe of asymmetry and dynamics in expanding envelopes. Such observations will allow us to go beyond the simplest ideas of spherical winds to build a much more realistic understanding of stellar mass loss.

1.2. Detection of Magnetic Fields with The Hanle Effect

Classically, the Hanle effect is a modification of the polarization from line scattering due to the precession of the atomic dipole during radiation. The Hanle effect is significant for fields $B \sim B_H$:

$$B_H = A_u \, e \, g_L / m_e \, c \approx 5 \; G \times (A/10^8 \; \mathrm{s}^{-1}) \; .$$

Lines with different Einstein A values thus have different sensitivities, ranging from 0.1 – 1000 G. This is considerably better than the Zeeman effect, which is insensitive below 1 kG. In astronomy, the Hanle effect has been used to study the magnetic field in the solar atmosphere and corona (Stenflo 1994). We suggest that in the FUV it is a powerful way of measuring magnetic fields in hot star envelopes. It is particularly valuable in dynamic envelopes, since it is not washed out by Doppler broadening, as is the Zeeman effect. Ignace et al. (1997, 1998) discuss the polarimetric profile due to the Hanle effect in a dynamic envelope. The polarimetric profile depends on the field strength, the field symmetry (dipole/poloidal vs. toroidal), the envelope density symmetry, the envelope dynamics symmetry (expansion vs. rotation), and the inclination. In many cases,

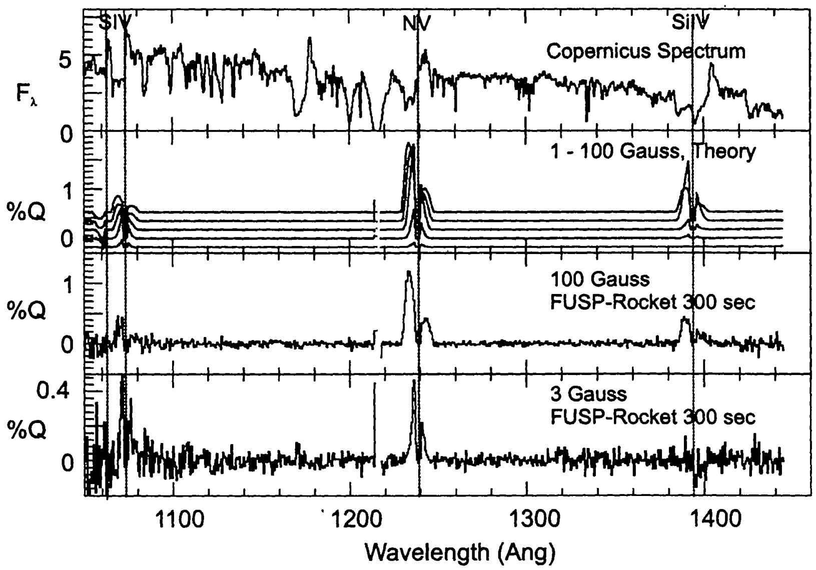

Figure 2. Hanle effect simulation. Top panel: *Copernicus* spectrum of ζ Ori O9.5Ia. Second panel: theoretical Hanle effect polarization for a dipole field embedded in a spherical wind, with a base field of 1, 3, 10, 30, and 100 G. Bottom panels: simulated FUSP rocket observations for 3 and 100 G.

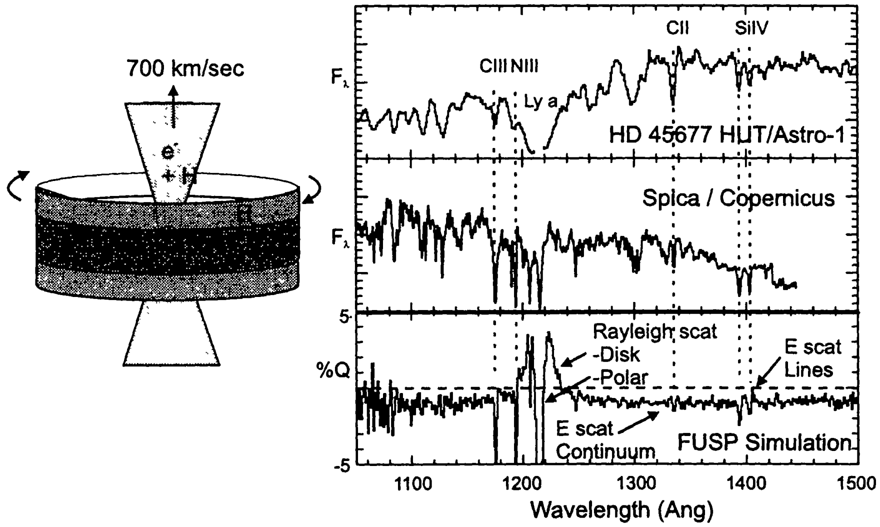

Figure 3. Simulation for bipolar flow in forming star. Top panel: HUT spectrum of HD 45677 (B2 IV). Second panel: *Copernicus* spectrum of Spica (to show FUSP resolution on similar star). Third panel: simulated observation with the FUSP Small Explorer (60 ksec) showing Rayleigh scattering from neutral H in disk (positive polarization) and from polar flow (negative polarization near Lyα).

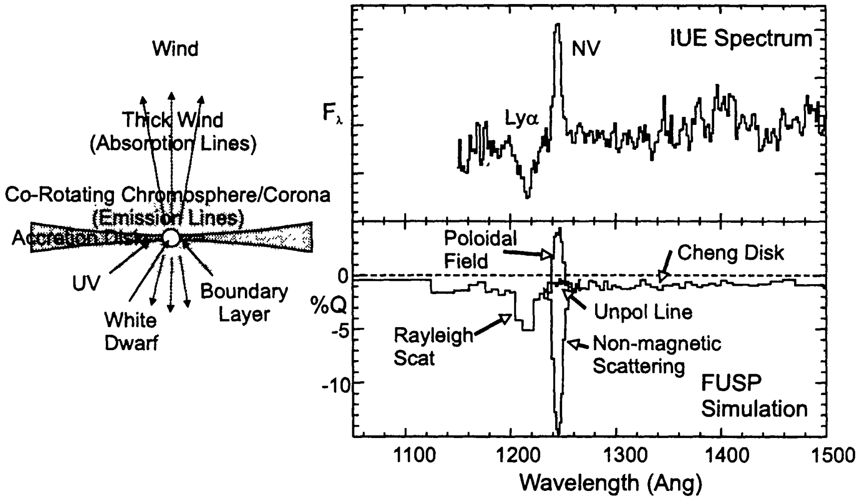

Figure 4. Simulation for cataclysmic variable. Top panel: IUE spectrum of V Sge. Bottom panel: simulated observation with the FUSP Small Explorer (20 ksec), showing negative electron scattering polarization from disk, negative Rayleigh-scattering polarization from H atoms in the disk, and line scattering polarization in the disk chromosphere with a $B = 0$ and > 100 G poloidal field.

one can use symmetry principles and compare lines of many ions to separate these effects.

Applications include: (1) Magnetic fields in OB supergiant winds (Fig. 2). In a spherical envelope, a magnetic field gives rise to a line polarization which is proportional to $(B/B_H)^2$. Fields as small as 1 G should be detectable, compared to previous Zeeman Effect upper limits of 1000 G. (2) Interaction of rotation and magnetism in rotating envelopes. (3) Magnetic fields in Cataclysmic Variable disks (Fig. 4). For the larger fields expected in these objects, the Hanle effect becomes "saturated"; a large and easily calculated signature is expected.

1.3. Geometry of neutral material: H Rayleigh Scattering

In addition to the scattering opacity due to FUV resonance lines, there is an important FUV continuum process, hydrogen Rayleigh scattering. Rayleigh scattering is essentially the far wings of resonance scattering. It is normally small in the visible, except for H I and H_2 in cool supergiants and in planetary atmospheres. In the FUV, however, it becomes very large for hydrogen near Lyα. Figure 1 shows that the H I Rayleigh cross-section is larger than the Thomson cross section from 1100 – 1500 Å. Unlike electron scattering, it is a tracer of neutral, not ionized material. Particularly significant, it has a rapidly changing and well-known cross section, $\sigma(\lambda)$, which is easily recognized. Near Lyα, it may become optically thick, causing a polarization turnover. This may result in a recognizable "bipolar signature" in which the polarization position angle rotates by 90° when a thick disk becomes opaque, revealing a thin polar flow.

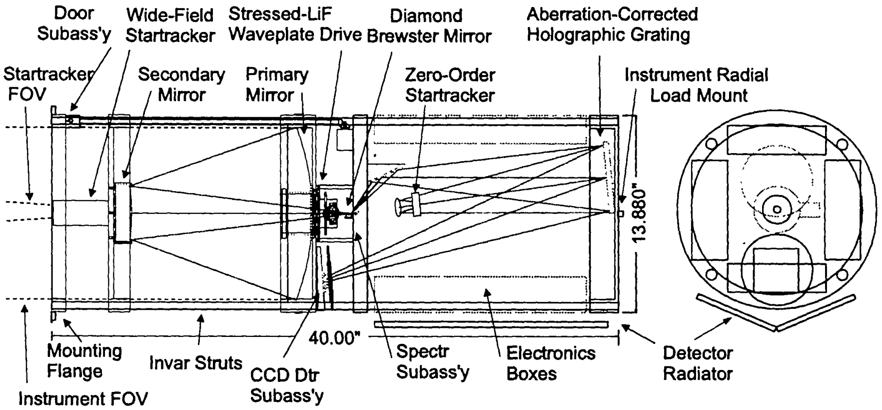

Figure 5. The FUSP instrument (satellite version).

Applications include bipolar flows in forming stars (Fig. 3) and in cataclysmic variables (Fig. 4). This part of our program tests the standard picture for the origin of bipolar flows in stellar objects near the disk/star boundary.

2. Instrument/ Mission

The FUSP instrument is a holographic spectrometer with new FUV polarimetric optics. The instrument is being tested as a sounding rocket, aiming at a small satellite. The design is driven by the need for very high polarimetric precision ($\sim$ 0.01%) across line profiles in the FUV. The spectral coverage will be 1050 – 1500 Å with a resolution $R = \lambda/\Delta\lambda = 1800 - 3000$ ($\Delta\lambda = 0.3 - 0.5$ Å; $\Delta v = 100 - 180$ km s^{-1}). It will use a CCD detector (needed to accommodate photon rates approaching 10^8 Hz). The polarimetric modulator will be a rotating stressed LiF waveplate, and the polarimetric analyzer a very small natural-diamond Brewster-reflection mirror. The spectrometer uses a aberration- corrected spherical holographic grating. A sounding rocket version of FUSP (in development) uses a F/2.5 prime-focus telescope with 0.5 m aperture and $R = 1800$. The scheduled first FUSP rocket launch is in 1999-2000.

A version of FUSP proposed for a Small Explorer (Fig. 5) uses a F/4 Ritchey-Chrétien telescope with aperture 0.3 m and $R = 3000$. The intended science time is greater than 1 year. The FUSP satellite would use a small spacecraft suitable for a highly-focused investigation with specialized instrumentation: the SPARTAN-Lite platform developed by GSFC. The instrument requirements on spacecraft are: pointing $\pm 1.5''$, volume 14 × 40 inch cylinder, weight 100 lbs, power 40 W, and telemetry $\sim$ 100 MB/day. With an experiment-provided coarse and fine star tracker (at zero-order of spectrometer) it will achieve $\pm 1''$ pointing jitter. The ground system would use an ALEXIS-derived autonomous antenna/ ground system (developed by Los Alamos National Laboratory), and operations would be performed from University of Wisconsin.

References

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