Future Possibilities for Doppler and Magnetic Field Measurements in the Extended Solar Atmosphere ⋆

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Abstract

For the first time, a vacuum ultraviolet telescope can be built to observe magnetic fields, plasma flows, and heating events in the Sun's atmosphere. These observations can provide key data for space weather models. The vacuum ultraviolet (VUV) region allows remote sensing of the upper levels of the solar atmosphere where the magnetic field dominates the physics. A VUV Fabry-Pérot interferometer (FPI) will allow us to observe the magnetic field, flows, and heating events in the mid-transition region (between the chromosphere and corona). Observations of this region are needed to directly probe the magnetic structure and activity at the base of the corona where the magnetic field is approximately force-free, i.e., where gas pressures are very small. This is a key element in developing accurate models of the Sun's dynamics for space weather. The specific region of interest is the 100 km-thick transition region, between the chromosphere and the much hotter corona, which strongly emits at 155 nm from triply ionized carbon (CIV) at 100,000 K. This is best observed by an imaging interferometer that combines the best attributes of a spectrograph and an imager. We present the latest results from the NASA Marshall Space Flight Center (MSFC) FPI. The major elements of the tunable CIV VUV FP interferometer are the 35mm MgF_2 etalon plates with a plate finesse of F>25 at 155 nm, the pi-dielectric coatings, a Hansen mechanical mount in a pressurize canister, and the piezoelectric control system. The control system for the etalon is a capacitance-stabilized Hovemere Ltd. standard system. The special Cascade Optical Corporation reflectance coatings are 25 pi-multilayers of high-low refractive layers paired in phase. This CIV interferometer, when flown above Earth's atmosphere, will obtain narrow-passband images, magnetograms, and Dopplergrams of the transition region in the CIV 155 nm line at a rapid cadence. We recently measured the MSFC VUV FPI using the University of Toronto's fluoride excimer laser as a proxy for CIV 155 nm. The test demonstrated the first tunable interferometer with the passband required for a VUV filter magnetograph. The measured values have a full-width half-maximum (FWHM) passband of 10 pm, a free-spectral range (FSR) of 61pm, and a transmittance of 58% at 157 nm. The resulting VUV interferometer finesse is 5.9. With this success, we are developing an instrument suitable for a flight on an orbiting solar observatory. A description of the interferometer for this mission is described.

Key words: heliophysics, VUV magnetography, Fabry-Pérot interferometer, transition region, CIV, Fabry-Pérot interferometer

1 Introduction

This paper discusses the potential resulting from an instrument development program for a high-spectral-resolution, high-finesse, Vacuum Ultraviolet Fabry-Pérot Interferometer (VUV FPI) for obtaining narrow-passband images, magnetograms, and Dopplergrams of the transition region emission line of C IV (155 nm VUV). The reason that emission from the triple ionized state of carbon is of interest to solar physicists is that the emission comes from a region of the solar atmosphere where the magnetic field dominates to the highest degree all other forces (Gary , 2001). Hence an active region magnetic field reconfiguration induced by evolving dynamics will proceed most rapidly in this region of the atmosphere, and new important transition region observations of rapid magnetic reconfigurations are critical to understand solar eruptive events (i.e., flares and coronal mass ejections) which dominate geo-space weather. The questions which would be addressed by the mission are: What is the structure of the coronal base and how is energy transferred through it from the photosphere to the corona? What physical processes observed in the lower corona are propagated into interplanetary space? Can the monitoring of magnetic and velocity fields in the magnetic-field-dominated coronal base lead to real-time predictions of solar flares and coronal mass ejections?

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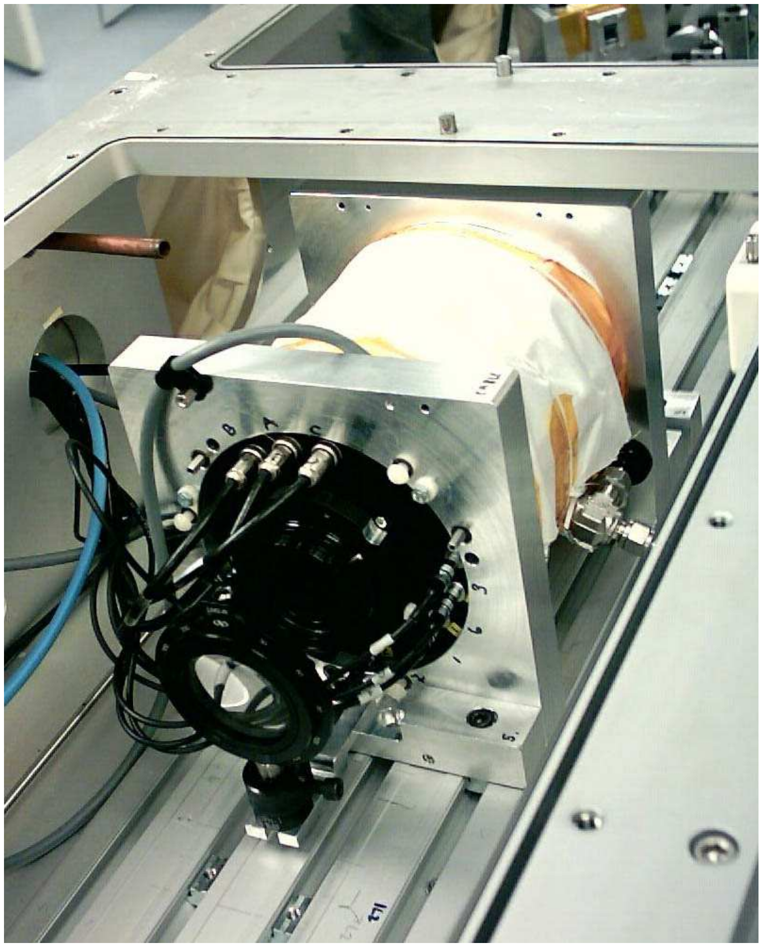

Fig. 1. VUV FP interferometer mounted in University of Torontos nanofabrication facility to perform the F_2 laser line scanning at 157 nm, the surrogate for CIV emission lines.

In this region of the solar atmosphere, the plasma temperature is rapidly transitioning from 10^3 K to 10^6 K, hence the name, the transition region. The CIV temperature of formation peaks at 10^5 K and the dual resonance lines of CIV emission are at 154.82 nm and 155.077 nm. The CIV lines are magnetic sensitive lines, albeit the Zeeman splitting is small resulting from its inverse relationship with wavelength. However the peak polarization attributed to the line-of- sight magnetic field component is $\sim 0.2\%$ for a central sunspot region of 2000G. Gary et al. (Gary et al. , 2007) calculated that an instrument polarization sensitivity of 10^{-3} to 10^{-4} can retrieve the field strength out to the edge of a solar active region (B $\sim$ 100 G). Such polarization sensitivity is easily obtainable in the VUV using an MgF_2 Wollaston prism [(West et al. , 2006)]. To deduce the normal magnetic field strength, a Stokes-V circular polarization line profile with appropriate spectral resolution is needed to compare with the NLTE radiative transfer calculations [e.g. (Uitenbroek , 2001)]. For a single active region, the line integral of the normal magnetic field gradient over the entire set of inversion lines in a photospheric magnetogram is a proxy for the total free energy. With a success rate ~ 75 %, this proxy is a strong predictor of whether the active region will produce a CME in the next few days [(Falconer et al. , 2006)]. Specifically the CIV observations will allow measurements of the magnetic preconditions for major eruptions in a significant number of active regions and measures magnetic changes produced by major eruptions.

The observations of the rapid line-of-sight (Doppler) motions are also important since the magnetohydrodynamics kinetics are readily observable with the CIV spectral scans. In the transition region, chromospheric material is being injected from below, coronal plasma is injected from above, and waves and shocks propagates heat into and through the transition region. Two dimensional spectral movies will differentiate the extent of the CIV line broadening from plasma motions that are resolved in space and time and will determine if there is more power from the waves in the resolved motions than in the unresolved motions. From the resolved motions, the observed amplitude and phase relations between the brightness and velocity fluctuations will gauge how much of the motion is in upward propagating waves and indicate whether the waves have shock fronts. For both resolved motions and the unresolved motions, the CIV brightness movies will show the extent to which they occur in microflare events. If most of the non-thermal power is in explosive events, it will be an indication that coronal heating by waves is mostly driven by reconnection events within the CIV coronal base. In particular, Pietarila et al (Pietarila et al., 2007a; Pietarila et al. , 2007b) have shown that a wave that has shock fronts in the upper chromosphere produces an oscillation in both I and V and strong asymmetries in the profiles of I and V, including disappearance and reappearance of a lobe of the Stokes V profile. The CIV observations will provide observational sequences needed for the analysis in the transition region.

Therefore, CIV magnetic and Doppler observations will provide data on (1) the fine-scale motions, events, and magnetic conditions in the coronal base that are signatures of the drivers of coronal heating, and (2) the buildup, triggering, and release of the stressed magnetic fields at the low-β coronal base before and during major CME/flare eruptions. Having this strong scientific rationale for the observations, the initial instrumental question was the feasibility of developing a FPI at these VUV wavelengths. We have answered this in the affirmative and now we will discuss these results. Following this discussion, a proposed solar orbiting telescope will be outlined using this technology.

2 Vacuum Ultraviolet Fabry-Pérot Interferometer

Gary et al. (Gary et al. , 2007) described the details of the MSFC instrument development program that resulted in a successful tunable VUV FPI

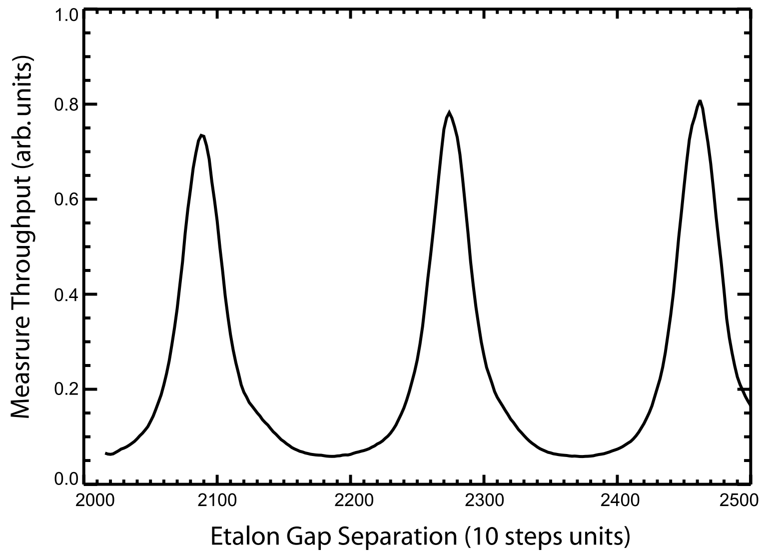

Fig. 2. VUV FPI scanning of the F_2 laser providing the etalon characteristic at VUV wavelengths. Stepping size ~0.002 nm.

(Table 1). The program successfully accomplished the following engineering goals: Two pairs of MgF_2 etalon plates were polished to better than a λ /150 at 633 nm or λ/ 24 at 155 nm (F_D>12). A primary set of test plates were coated with the designed 77% reflectance at 155 nm. The coatings were stress-free VUV dielectric coatings having low-absorption π coatings. These coatings were then applied to the second pair of etalon plates. The tunable interferometer was assembled with MgF_2 plates mounted to annular rings of silica glass of matching CTE in a novel design and was mounted as a piezoelectric-tunable, capacitance-stabilized etalon. The etalon plates were placed in a Hovemere's Hansen split-spring optical mount for low induced mechanical stress. Software programs for the control system were developed to evaluate the interferometer. As a surrogate to the CIV lines, the evaluation was preformed with University of Toronto's 157 nm F_2 laser that provided the characteristics given in Table 1. Figure 2 shows the etalon scans with the University of Toronto's F_2 laser at a voltage setting of 24 kV and pulse rate of 100 Hz at which the dominant emission line is 157.63 nm. The data shows the results from the development program of the π-coatings, the polishing of the magnesium fluoride plates, and the assembly of the etalons within a Hanson split-spring mount. The program was managed at MSFC/NASA in partnership with Cascade Optical Corporation and Hovemere Limited. The result of this program was an operational and robust CIV VUV interferometer, providing confidence that a future total finesse of greater than 15 is achievable.

As compared to spectrographs, these units for spectral imaging can result in a smaller optical system and hence a smaller focal-plane spacecraft instrument that can reduce the overall spacecraft cost. It also allows greater science with a higher throughput at high spectral sensitivity, shorter exposures, higher ca-

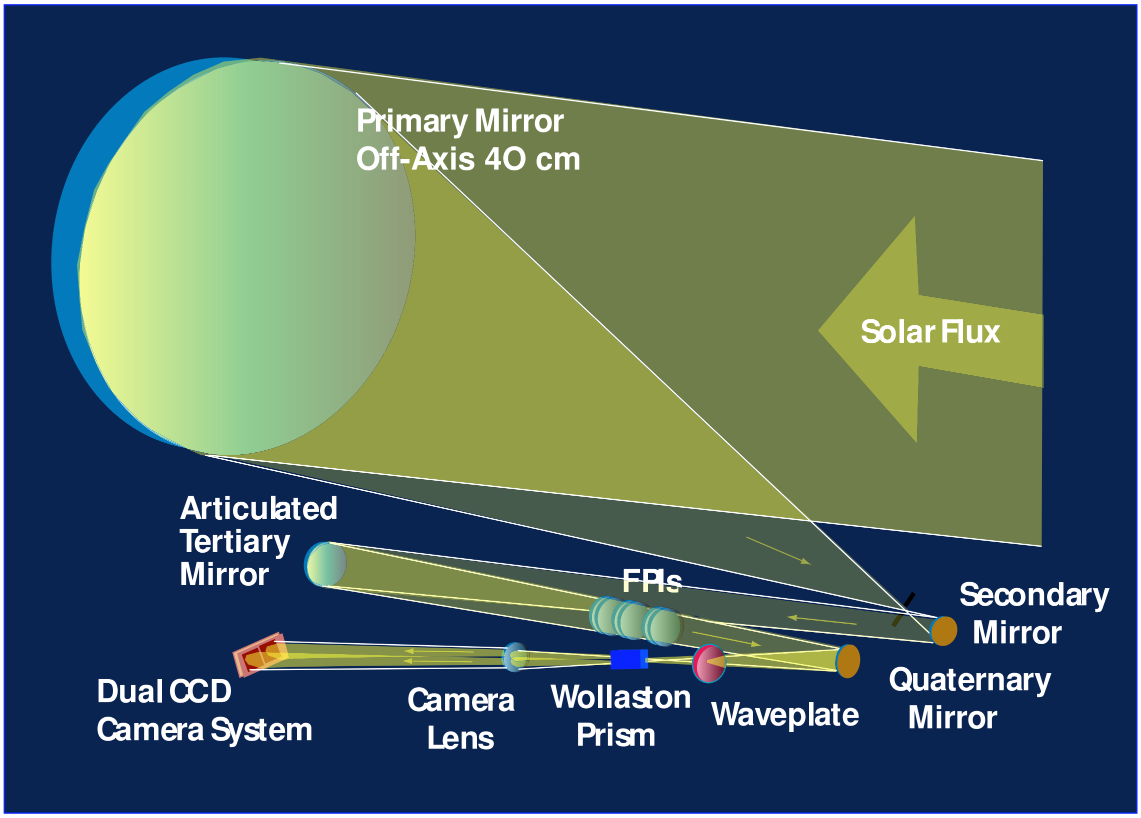

Fig. 3. Concept of an instrumental layout using three VUV FPI and simultaneously observing both states of circular polarization. The dual camera system avoids solar changes between capturing the two states.

dence, and resulting in improved magnetic sensitivity of solar magnetography. The successful development and testing of the VUV FP interferometer provides new technology for solar science which will now allow a solar transition region magnetograph for future space missions.

3 A solar orbiting mission

A solar orbiting mission now has the potential to open a new, unexplored, window on the magnetically active solar atmosphere at the base of the corona. Over areas the size of active regions, measurements both the magnetic and velocity fields in the 10^5 K regime of the low-β transition region with unprecedented spatial and temporal resolution can be made. In the vacuum ultraviolet, the diffraction limit for the same telescope aperture results in a factor of 4 improvements in resolution compared to the visible resolution. Here the parameter (is the ratio of gas pressure to magnetic pressure; hence low (means the region dominated by magnetic forces. These VUV observations would enhance those from the solar observatories Hinode, STEREO, and SDO

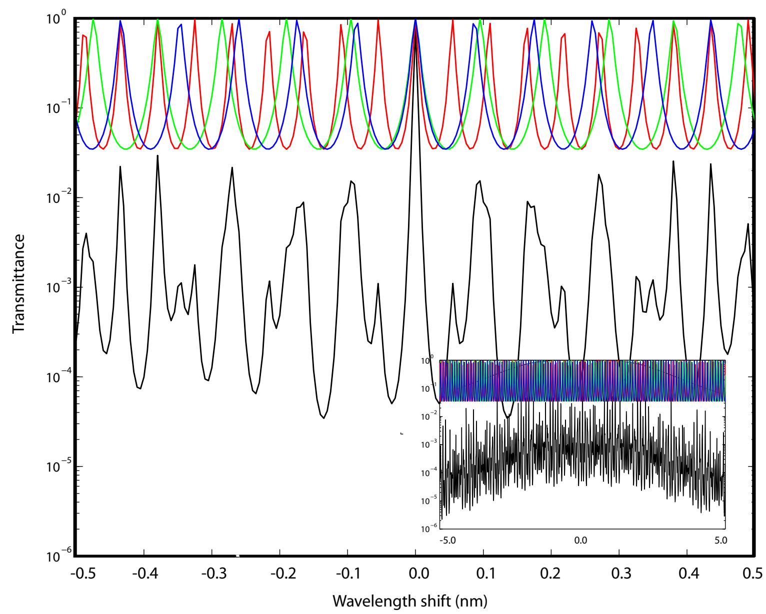

Fig. 4. The variation of transmission with wavelength over a 1 pm range; the net triple etalon transmission (single line in the middle of the graph) for an optimized 0.5 pm FPI and the three individual etalons at the top of the figure. The insert shows the transmittance over the larger 5 pm spectral range. For the FPI the DHR multiple mirrors provide the prefiltering.

to provide new insight to coronal heating and CME/flare eruptions. Using the high-transmission narrow-band Fabry-Pérot filter that rapidly scans the 155 nm CIV emission lines formed at 10^5 K , our spacecraft instrument (Figure 3) is envisioned to provide full-field (3x3 $arcmin^2$) 0.2 arcsec/pixel spectro-polarimetric magnetograms with 50 G sensitivity in 3 minutes, and full-field 0.1 arcsec/pixel intensitygrams, line-broadening maps, and Dopplergrams with 0.25 km s^{-1} sensitivity in 5 seconds.

Single and multiple etalon strategies for the FPI were explored resulting in the selection of a triple etalon system for four reasons: (1) The spectral purity and out-of-band rejection of an optimized triple FPI is far superior to those of a double design. (2) The triple FPI with each etalon of low finesse has excellent throughput without significant leakage of parasitic orders. (3) The triple etalon system matches the free spectral range to the prefilter profile. (4) The triple FPI allows us to use conservative, flight-proven designs [cf., (Gary et al. , 2003)]. Hence, to obtain the defined spectral sensitivity, FOV imaging, rapid tunability and throughput, the observatory's spectral isolator is a tunable triple-etalon Fabry-Pérot interferometer (FPI) that provides a spectral resolution of 5 pm (Gary et al. , 2006, 2007). The prefilter to the FPI system is defined by the set of CIV DHR coated mirrors. The current VUV coating technology limits the full-width half-maximum (FWHM) profile to larger than 5 nm for a transmittance of greater than 40% and determines, in part, the necessity for a triple etalon. The spectral tuning range is 2 nm that covers the CIV dual resonance lines. The FPI is rapidly (5 ms) and reproducibly (to 0.1 pm) tuned throughout its range (approximately ± 1 nm) by standard space qualified piezoelectric actuators (Bond , 2006; Yoshikawa et al. , 2007).

Table 2 gives the basic parameters of the triple etalon system and Figure 4 shows the three etalon transmission functions and the net FPI transmission. The spectral purity of the FPI and therefore the high-resolution etalon is set at 3.6 pm by the scientific requirements for quantitative spectro-polarimetry. The figure of merit that drives the parameters of the other two etalons is polarimetric and radiometric purity. The off band leakage of the FPI is the difference in transmission between the actual filter and an ideal filter that has no sidebands from other orders (no transmission beyond the first minimum of the actual filter). For CIV measurements, it comes predominately from only a few nearby SIV emission lines and from the continuum. When observing one of the emission CIV resonance lines, polarization leakage arises from the sideband response to the other lines. This FPI design was numerically optimized to minimize the polarization and radiance leakage.

Using this key element, the 3-etalon Fabry-Pérot interferometer providing the spectral tuning at 5 pm resolution with high throughput and rapidly tunability, a complete observatory concept has been developed. It is shown in Figures 3 and 5 employing a 40-cm aperture off-axis Gregorian telescope for spatial resolution. The prefiltering of the emission is performed by VUV-dielectric, high-reflective coatings on all mirrors to reduce out-of-band transmission. The polarimeter consists of a $\lambda/4$-waveplate and double- Wollaston analyzer with a high VUV extinction ratio of 10^{-5}. A dual camera system would use two 4k x 2k frame-transfer CCDs with 0.1"/pix. Such an observatory would provide the key transition region data sets of (1) line-of-sight magnetograms with 2 x 2 binning, sensitivity of 50 G, and 2.5 min cadence; (2) high-cadence Dopplergrams with < 1 km s^{-1} sensitivity, 0.1" pixels, and 5 s cadence; and (3) full-profile intensitygrams with 1 s cadence to allow very rapid integrated line profiles.

The mission objectives would be to (1) observe the fine-scale magnetic structure and activity in the 105K temperature regime of the low-beta base of the corona and (2) to measure the line-of-sight component of the magnetic field and velocity field in the low-beta coronal base over active and quiet regions with unprecedented spatial and time resolution. Specifically, the observatory would measure CIV VUV emission lines at 155 nm to obtain rapid, high-resolution (0.2 arcsec) spectro-polarimetric images to determine Doppler velocities to a sensitivity of < 1 km s^{-1}and magnetic fields to a sensitivity of $\preceq <$ 50 G in the low-beta coronal base. The expected discoveries would include

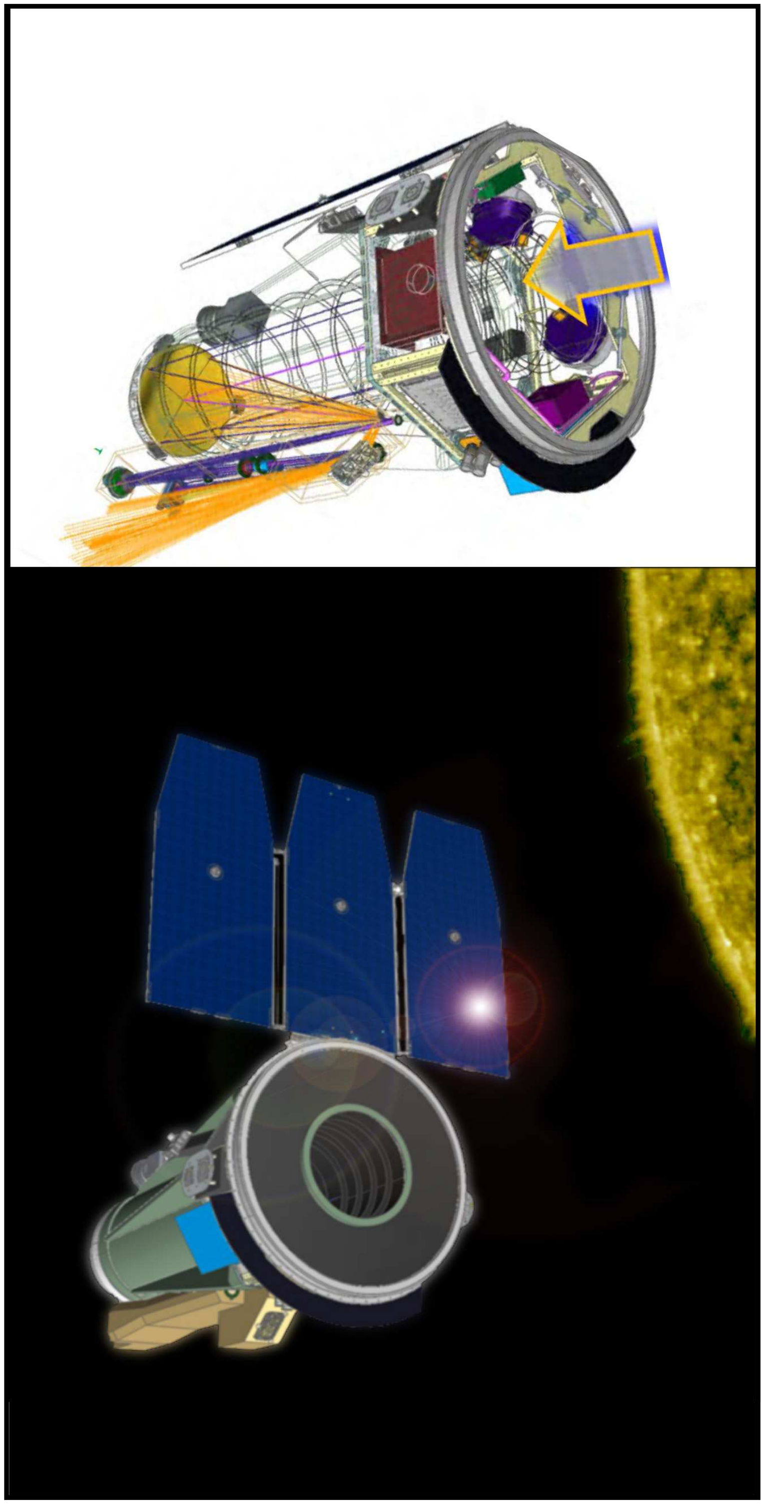

Fig. 5. A orbiting solar observatory for rapid measurements of the transition region magnetic field, velocities, and intensities Courtesy of Ball Aerospace and Technology Corporation, Boulder, CO. The upper image is a cutaway interior view.

(1) the role of the magnetic field in the (β-minimum coronal base region in the production of coronal heating and eruptive events, (2) the partition of coronal heating between field braiding and MHD waves, (3) the contribution of CIV micro-reconnection events to coronal heating via MHD wave generation, and (4) precursor CIV magnetic evolution and/or activity signifying that a major eruption will soon occur.

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Table 1
Measured Characteristics of the VUV FPI Interferometer

Parameter	Value
Operating Wavelength	$\lambda = 155$ nm
Clear Aperture	25 mm
Coating Reflectance	0.77
Effective Reflectance	0.59
Reflective Finesse	$F_R = 12$
Defect Finesse	$F_D = 6.8$
Total Finesse	$F = 5.9$
Optical Gap	$d = 200\ \mu$m (OPD)
Free Spectral Range	61 pm
Passband Width	10 pm
Order	$M = 2580$
Transmittance	$T = 58$ %
Loss	$L = 4.2$ %