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Next Generation UV Coronagraph Instrumentation for Solar Cycle-24

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Abstract. Ultraviolet coronagraph observations of the extended solar corona (defined here as 1.5 to 10 solar radii from Sun-center) have become a powerful tool for obtaining detailed empirical descriptions of coronal holes, streamers, and coronal mass ejections. The empirical models resulting from ultraviolet coronagraph observations provide the constraints needed to test and guide theoretical models aimed at determining the physical processes that control solar wind acceleration, CME heating and acceleration, and solar energetic particle (SEP) acceleration. Measurements to date from sounding rockets, the shuttle deployed Spartan 201 satellite and the Solar and Heliospheric Observatory (SOHO) have utilized high resolution spectroscopy over a very limited instantaneous field of view. New concepts for next generation instrumentation include imaging ultraviolet spectro-coronagraphs and large aperture ultraviolet coronagraph spectrometers. An imaging instrument would be the first to obtain absolute spectral line intensities of the extended corona over a wide field of view. Such images would provide the absolute intensities of spectral lines that can be used to determine densities and outflow velocities of specific coronal ions. Measurements from several charge states of a given element will allow electron temperatures to be determined. These measurements combined with observations of H I Lyα provide absolute chemical abundances (relative to hydrogen) for observed elements. Ultraviolet imaging would be highly complementary to a large-aperture ultraviolet coronagraph spectrometer designed for high spectral resolution observations over a small instantaneous field of view. The images would be used to select targets for more detailed spectroscopic studies with the large aperture UV coronagraph spectrometer and to provide time dependent empirical descriptions of the regions surrounding the narrow instantaneous field of view of the large aperture instrument. Descriptions of both the imaging ultraviolet spectro-coronagraph and the large aperture ultraviolet coronagraph spectrometer are provided. Recommended co-observing instruments are described.

Key words. Solar instrumentation—solar spectroscopy—solar corona—solar wind—coronal mass ejections.

1. Introduction

The first ultraviolet spectroscopy of the extended solar corona in the absence of a natural solar eclipse was carried out in April 1979 when a rocket-borne ultraviolet coronagraph spectrometer measured absolute intensities and spectral line profiles of H I Lyα in a streamer and a polar region at heliographic heights from 1.5 to 3.0 solar radii ($R_\odot$) from Sun-center (Kohl *et al.* 1980). Since that time, ultraviolet spectroscopic observations of the extended corona have been carried out on two sounding rocket flights, four shuttle deployed Spartan 201 flights and during the 12-year history of the Ultraviolet Coronagraph Spectrometer (UVCS) instrument on the Solar and Heliospheric Observatory (SOHO) satellite (Kohl *et al.* 1995). The overall scientific goal of all of these observations has been to obtain detailed empirical descriptions of coronal structures and to use these descriptions together with theoretical models to identify and understand the physical processes that release, transport, and deposit energy in the corona and produce the solar wind, coronal mass ejections (CMEs), and solar energetic particles. For a review of ultraviolet spectroscopy of the extended solar corona, see Kohl *et al.* (2006).

Although considerable progress has been made, new instrumentation will be needed to build on the discoveries of the earlier observations. A combination of imaging and spectroscopic diagnostic techniques are needed to provide more complete empirical descriptions capable of testing and guiding the development of next generation theoretical models. Imaging uniquely provides the global morphology and dynamics of the densities, flow speeds and chemical abundances of the often complex and filamentary structures of coronal plasmas. Spectroscopy uniquely provides ion temperatures, anisotropic velocity distributions, electron non-Maxwellian velocity distributions and suprathermal seed particle populations needed for CME shock acceleration of solar energetic particles. By comparing the empirical descriptions to the predictions of theoretical models, we can discard models that do not agree with the measurements and build the case for the model and associated process(es) that agree with the measurements.

2. Primary results from Ultraviolet Coronagraph Spectrometers

In the case of the solar wind, it was discovered from UVCS/SOHO and earlier instruments that the fast solar wind becomes supersonic much closer to the Sun than previously believed. In coronal holes, heavy ions (e.g., O^{5+}) both flow faster and are heated hundreds of times more strongly than protons and electrons, and they have anisotropic temperatures. Extended heating and acceleration remain strong upto and beyond the largest heights observable with UVCS. These observations have rekindled theoretical efforts to understand coronal heating, concentrating on cyclotron resonance of kHz-frequency waves in the collisionless extended corona where the primary solar wind acceleration occurs. Slow wind from bright quiescent equatorial streamers at solar minimum was observed to flow along open-field "edges" and exhibits similar high ion temperatures and anisotropies as coronal holes (but at larger heights). It remains to determine what fraction of the slow wind comes from these boundary regions and what is produced by transient eruptions.

Even though UVCS/SOHO has made significant advances, we still do not understand the physical processes that heat and accelerate the entire plasma (protons, electrons, helium, and minor ions). Our understanding of ion cyclotron resonance is based essentially on just one ion, O^{5+}. There is still controversy about whether the fast solar wind occurs primarily in dense polar plumes or in low-density inter-plume plasma. We also do not know how and where the various components of the variable slow solar wind are produced. UVCS/SOHO has shown that answering these questions is possible, but it cannot make the observations needed to fully characterize the plasma.

In the case of CMEs, UVCS observations together with observations by other SOHO instruments have demonstrated the power of combining images and spectroscopy to reveal physics that no one instrument could discern alone. There have been several key results. The first spectroscopic determination of CME thermal energy was surprisingly found to be as large as the outflow kinetic energy. UVCS observations were used to make the first determinations of CME helical rotation rates and handedness in the extended corona, which are key features of theoretical CME models. Measurements were made of the properties of shock fronts and reconnection current sheets. UVCS data have been used to characterize sites of solar energetic particle (SEP) production (e.g., CME shocks) for specific events, needed to test and guide SEP acceleration/transport models.

Even though UVCS/SOHO has made significant advances, we still do not have a comprehensive empirical model of a CME that would provide the key plasma parameters as a function of time, and the information needed to identify the physical processes that heat and accelerate CMEs. Many questions about CME evolution remain unanswered. For example: is the bright "leading edge" of the CME an arcade of active region magnetic loops, is it ambient coronal gas compressed by a shock, or is it a "bubble" of coronal plasma created by reconnection as the CME expands? What is the role of magnetic reconnection in both the eruption and relaxation of the coronal magnetic field in CMEs? UVCS has shown that answering these questions is possible, but it cannot make the observations needed to fully characterize the plasma.

3. An Ultraviolet Imaging Spectro-Coronagraph

An Ultraviolet Imaging Spectro-Coronagraph payload can consist of one or more telescopes such as that depicted in Fig. 1. Light from the solar disk enters the instrument through an entrance aperture formed by a circular external occulter and an outer aperture stop. This light passes by a series of baffles and the primary telescope mirror, and into a light trap where it is attenuated and discarded. The light from the extended corona passes through the same aperture, past the baffles and onto the telescope mirror. The external occulter blocks the light from the solar disk that would otherwise impinge on the telescope. The telescope mirror forms an image of the extended corona at the prime focus. Light forming the image passes through a field stop at the prime focus, past the internal occulter and onto a concave diffraction grating located near the entrance aperture. The mirror forms an image of the external occulter on the internal occulter, which blocks diffracted disk light from the external occulter. The grating disperses the coronal light and focuses it through a hole in the telescope mirror and onto the face of an array detector. In this way, overlapped images of the extended corona in selected spectral lines are detected. Several techniques can be used to reconstruct images of the extended corona in individual spectral lines from the detected overlapped images. Shadow sensors located in the Sunlight trap are used to determine the alignment of the occulting system with the Sun.

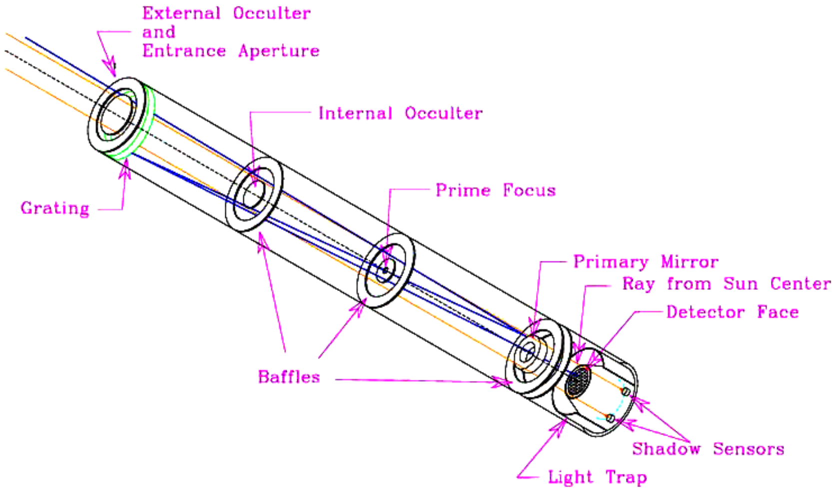

Figure 1. Isometric optical diagram of a single ultraviolet spectro-coronagraph telescope.

An imaging spectro-coronagraph payload in geostationary orbit would be expected to observe approximately 1000 CMEs per year. A relatively small instrument could provide the needed spatial and spectral resolution in a set of spectral lines covering a broad temperature range. Spectral lines observable with such an instrument over a range of heliographic heights from 1.5 to 3.5 $R_{\odot}$ include H I 121.6 nm, OVI 103.2 and 103.7 nm, C III 97.7, Fe XVIII 97.5 nm, He II 30.4 nm, Si IX 29.6 nm, Si X 27.7 nm, Si XII 49.9 and 521 nm and Mg X 61.0 and 62.5 nm.

Ultraviolet spectroscopy of the extended corona has been limited to observations of narrow strips of the corona. An imaging spectro-coronagraph could measure, simultaneously, the absolute intensities of several spectral lines over a large portion of the corona. An imaging spectro-coronagraph could measure the helium abundance and He^{+} flow speed in CMEs, coronal holes and coronal streamers for the first time. Helium is the second greatest contributor to the mass and momentum of CMEs and the solar wind, and yet we know little about its abundance and flow speeds in the corona. Measured densities, abundances and outflow velocities of a broad range of ions are expected to provide breakthroughs in identifying how CMEs are formed, and how they evolve.

4. An advanced Ultraviolet Coronagraph Spectrometer

The basic optical design concepts for next generation ultraviolet coronagraph spectrometers are similar to that of UVCS/SOHO except that the external occulter is placed much further from the telescope mirror in order to achieve a much larger effective area and higher diffraction limited resolution in the radial direction. The basic optical designs of all ultraviolet coronagraph spectrometers flown to date are similar to the UVCS/SOHO design shown in Fig. 2. It consists of one or more articulated telescope mirrors that are placed in the shadow created by a linear external occulter, which forms one side of a rectangular entrance aperture. The mirror is used to image a portion of the extended solar corona onto the entrance slit of an ultraviolet spectrometer.

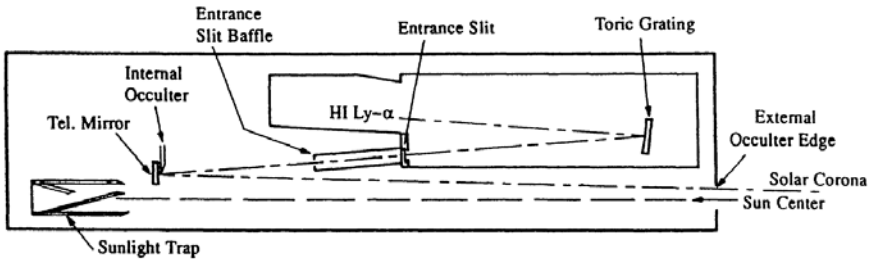

Figure 2. Optical layout of the UVCS/SOHO H I Lyα channel (from Kohl *et al.* 1995).

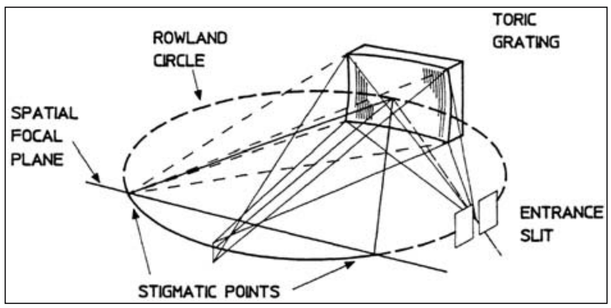

Figure 3. Isometric diagram of a toric grating spectrograph similar to that of UVCS/SOHO (from Kohl *et al.* 1995).

A linear internal occulter placed near the telescope mirror, intercepts and removes solar disk light that is diffracted towards the mirror and would otherwise be specularly reflected by the mirror onto the spectrometer entrance slit. This externally and internally occulted telescope design provides the stray light suppression at the wavelengths of interest that is needed to observe the relatively faint ultraviolet extended corona. Stray solar disk light at wavelengths outside the wavelengths of interest is suppressed by a combination of the occulting system, the optical coatings, the dispersive action of the diffraction grating and the wavelength dependent sensitivity of the detector. A Sunlight trap intercepts and absorbs solar disk light that passes through the entrance aperture, past a series of baffles, and past the telescope mirror. The spectrometer entrance slit is shielded from the illuminated surfaces of the trap by an entrance slit baffle and the telescope mirror. Each channel of the UVCS/SOHO spectrometer has an entrance slit, a toric grating and an array detector mounted in a Johnson–Onaka (Johnson 1957) configuration (see Fig. 3). The two detectors for the two ultraviolet channels are two-dimensional photon counting, centroiding, microchannel plate sensors with electronic readout (Siegmund *et al.* 1994).

The spatial resolution in the radial direction and the effective area are extremely limited in ultraviolet coronagraph spectrometers such as UVCS/SOHO. For example, the 1.8 m separation between its external occulter and its telescope mirror, together with the need to further occult with the internal occulter, results in an unvignetted telescope width of 0.8 mm when observing at $1.5\,R_\odot$. The limitation can be greatly improved with a remote external occulter supported by an extendable boom. Space qualified booms of 13 m and longer are available that can provide over 14 m separation

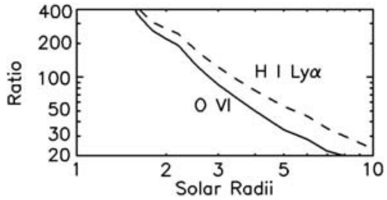

Figure 4. Ratio of the efficiencies of an advanced large-aperture ultraviolet coronagraph spectrometer to those of UVCS/SOHO for observations with the same spatial and spectral resolutions at H I Lyα and O VI 103.2 nm (from Kohl *et al.* 2006).

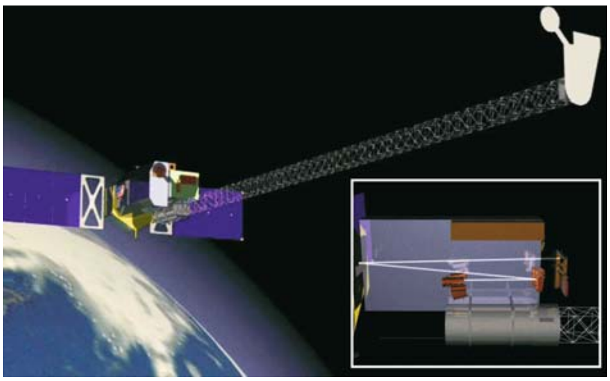

Figure 5. Spacecraft concept for advanced large-aperture coronagraphs. The inset is a diagram of the telescope/spectrometer unit of a next generation ultraviolet coronagraph spectrometer (from Kohl *et al.* 2006).

between the external occulter and the telescope mirror. This arrangement provides an unvignetted mirror width of 27 mm for observations at 1.5 $R_\odot$. Much larger unvignetted widths are provided for observations at larger heights. If telescope mirrors that are about the same size as those of UVCS/SOHO are used (width = 75 mm), then they are filled when observing at 2.1 $R_\odot$ or higher. This advantage together with improvements in mirror reflection coatings and detector sensitivity provide the gain in effective area shown in Fig. 4. An illustration of a spacecraft concept containing a large aperture ultraviolet coronagraph spectrometer and a co-observing visible light coronagraph is shown in Fig. 5. The inset shows a diagram of the telescope/spectrometer unit of the ultraviolet coronagraph spectrometer whose entrance aperture lies in the shadow of the external occulter.

Each channel of the spectrometer is optimized for spectroscopic measurements in a specific wavelength band. The ideal spectrometer for each channel would have a large radiometric throughput for the wavelengths of interest, stigmatic imagery over the entrance slit length for the primary spectral lines of that channel, good image quality for other spectral lines of interest, and a dispersion and detector pixel size that is compatible with the required spectral and spatial resolution. To accomplish the scientific objectives, it is desirable to have three channels. One channel would cover the 26–37 nm wavelength range and be capable of observing He II 30.4 nm. Another would cover 75–150 nm in first order and 49–75 nm in second order. This channel would be capable of observing a large number of spectral lines including H I 121.6 nm, OVI 103.2 and 103.7 nm, Fe XVIII 97.5 nm and many more. A separate optical path in that channel could provide polarimetry measurements that could be used to explore the possibility of determining coronal magnetic fields with the Hanle effect. A third channel could have a crossed dispersion spectrometer for observing the electron scattered wing of the H I Lyα spectral line in order to determine non-Maxwellian velocity distributions and temperatures of coronal electrons. The crossed dispersion spectrograph is needed to reduce the scattered light from the diffraction grating by about five orders of magnitude with respect to the resonantly scattered core of the line.

5. Desirable co-observing instruments

It is highly desirable to have a co-observing visible light coronagraph–polarimeter in any science payload that includes an ultraviolet coronagraph spectrometer. The visible light instrument should cover the field of view of the ultraviolet instrument, and ideally would provide two dimensional imaging of the corona upto at least six solar radii. The visible light instrument provides the electron density over its field of view and it provides the time dependent distribution of the electron density. This information is needed to complement the many plasma parameters of coronal structures that can be determined from the ultraviolet instrument observations. The combination of the two datasets can be used to build a time dependent empirical model of the observed coronal structures. It is highly desirable for the visible light coronagraph to also have a spectroscopic capability, which could obtain spectral line profiles near the limb with high spatial and temporal resolution.

Observations of dynamic phenomena such as flare/CME events would also benefit from X-ray observations of the flaring region. Ideally, the X-ray instrument could provide both spectra and imaging.

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