SOHO ULTRAVIOLET CORONAGRAPH SPECTROMETER (UVCS) MISSION OPERATIONS AND DATA ANALYSIS

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FINAL REPORT

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1. INTRODUCTION

The scientific goal of UVCS is to obtain detailed empirical descriptions of the extended solar corona as it evolves over the solar cycle and to use these descriptions to identify and understand the physical processes responsible for coronal heating, solar wind acceleration, coronal mass ejections (CMEs), and the phenomena that establish the plasma properties of the solar wind as measured by "in situ" solar wind instruments.

This report covers the period from 01 February 2002 to 15 February 2003. During that time, UVCS observations have consisted of three types: 1) standard synoptic observations comprising, primarily, the H I Lyα line profile and the O VI 103.2 and 103.7 nm intensity over a range of heights from 1.5 to about 3.0 solar radii and covering 360 degrees about the sun, 2) sit and stare watches for CMEs, and 3) special observations designed by the UVCS Lead Observer of the Week for a specific scientific purpose. The special observations are often coordinated with those of other space-based and ground-based instruments and they often are part of SOHO joint observation programs and campaigns. Lead observers have included UVCS Co-Investigators, scientists from the solar physics community and several graduate and undergraduate level students.

UVCS has continued to achieve its purpose of using powerful spectroscopic diagnostic techniques to obtain a much more detailed description of coronal structures and dynamic phenomena than existed before the SOHO mission. The new descriptions of coronal mass ejections (CMEs) and coronal structures from UVCS have inspired a large number of theoretical studies aimed at identifying the physical processes responsible for CMEs and solar wind acceleration in coronal holes and streamers.

UVCS has proven to be a very stable instrument. Stellar observations have demonstrated its stability. UVCS has required no flight software modifications and all mechanisms are operational. The UVCS O VI Channel with its redundant optical path for wavelengths near H I Lyα is capable of observing the entire UVCS wavelength range. Since December 1998, the O VI Channel has been used for all UVCS observations. Although the H I Lyα Channel and detector are still operational, increases in the dark count up to about 5×10^{-4} counts/sec/pixel and an increase in high voltage current to within a factor of two of the maximum used in the laboratory before flight led to the decision to not use that detector at the present time. There is no significant decrease in the scientific capability of UVCS owing to the OVI channel redundant optical path.

UVCS data, data analysis software, calibration files and the mission log are available from the SOHO archive and SAO. All UVCS data is now available to scientists and the general public via the SOHO Data Archive and SAO within three months of the observations.

UVCS has resulted in 46 scientific papers in 2002. There were numerous presentations at scientific meetings. All requests for observation time by qualified outside users have been granted.

2. HIGHLIGHTS OF UVCS OBSERVATIONS AND ANALYSES

The physical processes that heat the 10^6 K solar corona, accelerate the solar wind, and produce CMEs are still not known with certainty after more than a half century of investigation. UVCS has made significant progress toward identifying these processes by measuring densities, outflow speeds, anisotropic temperatures, and abundances in the acceleration region of the wind and CMEs.

Highlights: Coronal Holes and Fast Solar Wind

The fast, low-density component of the solar wind flows steadily at about 600--800 km s^{-1} in interplanetary space and emerges primarily from open magnetic structures known as coronal holes. Variations in the fast solar wind have been shown to have an impact on the Earth's global climate as well as a direct connection to activity in the Earth's Van Allen radiation belts, sometimes leading to electrical disruptions in satellites. UVCS has made significant progress toward identifying the physical processes that heat the extended corona and accelerate the solar wind by measuring and analyzing densities, outflow speeds, anisotropic temperatures, and elemental abundances in the acceleration region of the wind. Recent UVCS results concerning coronal holes include the following.

Plasma Properties of Coronal Holes over the Solar Cycle. UVCS has been used to measure the heating and acceleration of the fast solar wind in a variety of large coronal holes from 1996 to 2003 (Miralles et al. 2001, 2002; Poletto et al. 2002).
A pattern is beginning to emerge, in that coronal holes with lower densities at a given heliocentric height tend to exhibit faster ion outflow and higher ion temperatures. However, all of the coronal holes observed by both UVCS and *in situ* instruments were found to have roughly similar outflow speeds in interplanetary space. **Thus, the densities and ion temperatures measured in the extended corona seem to be indicators of the solar wind acceleration as a function of heliocentric height**. This information has been useful in gaining further insight into identifying the processes that generate the fast solar wind, but only a subset of the full range of plasma properties has been probed.

Theory Impact on Other Fields: Ion Cyclotron Resonance. The surprisingly extreme plasma conditions observed by UVCS in coronal holes have guided theorists to discard some candidate physical processes and further investigate others (see, e.g., Cranmer 2002). Hollweg and Isenberg (2002) state in a review paper that **"We have seen that the information provided by UVCS has been pivotal in defining how research has proceeded during the past few years."** Indeed, the UVCS results and subsequent theoretical investigations have been cited increasingly in literature devoted to other plasma environments, such as the Earth's aurora (Gavrishchaka et al. 2000), and they have guided new investigations in pure plasma physics (e.g., Mizuta and Hoshino 2001; Chen et al. 2001).

Polar Plumes and Jets over the Solar Cycle. The plasma properties derived from UVCS observations of filamentary inhomogeneities (i.e., plumes and jets) in coronal holes provide constraints on how much of the solar wind comes from impulsive reconnection events at the base of the corona. A study of transient "polar jets" with UVCS, EIT, and LASCO (both at solar minimum and during the rising phase of solar cycle 23) found that jets have higher densities, faster outflow, and lower electron temperatures than the surrounding coronal hole plasma (Dobrzycka et al. 2002). These observations seem to be consistent with the idea that jets are the result of short-lived bursts of base heating, while polar plumes are the result of base-heating events that last longer than several hours. It is still not clear, though, whether there is a significant solar wind outflow in plumes (Gabriel et al. 2003) or if the plumes are relatively hydrostatic structures embedded in an outflowing "interplume" medium (e.g., Teriaca et al. 2003).

Highlights: Coronal Streamers and the Slow Speed Wind

The slow, high-density component of the solar wind is a turbulent, chaotic magnetized plasma that flows at about 300--500 km s^{-1} in interplanetary space. This low-speed flow is believed to originate mainly from bright streamers in the corona, but the relative contribution of streamers to the overall mass and energy flux of the wind is still uncertain. Statistically, the Earth is bathed in the rapidly-varying slow wind at least two thirds of the time, and it typically is the background medium for coronal mass ejections (CMEs), which have the strongest impact on Earth's space environment. Recent UVCS results concerning streamers include the following.

Preferential Ion Heating and Temperature Anisotropies. The analysis of UVCS data has led to **evidence that the fast and slow wind share the same physical processes.** Frazin et al. (2003) determined that O^{5+} ions in the bright edges---or "legs"---of equatorial streamers have significantly higher kinetic temperatures than hydrogen and exhibit anisotropic velocity distributions with $T_{\perp} > T_{\parallel}$, much like coronal holes. However, the central streamer "core" (typically identified with closed magnetic loops below the heliospheric current sheet) exhibits neither the preferential heating of oxygen nor the temperature anisotropy. This is consistent with other UVCS evidence that points to the bulk of the slow solar wind arising from the streamer legs (Raymond et al. 1997) and not from the closed streamer core. Joint theoretical studies of physical processes such as ion cyclotron resonance that apply to both the fast and slow solar wind are ongoing (e.g., Chen and Hu, 2001).

The Geometry of Solar Wind Flow from Streamers. Strachan et al. (2002) used UVCS and LASCO observations to **map out the spatial properties of the slow solar wind** in the solar-minimum streamer belt. The magnetic cusp that divides the closed-field streamer core from the open-field streamer legs was determined via the Doppler dimming technique to be between the heights of 3.6 and 4.1 $R_{\odot}$. The latitudinal pattern of O^{5+} outflow speed was found to be consistent with the bulk of the slow wind emerging along the northern and southern edges of the streamer and merging above the cusp. This empirical information provides hard constraints for magnetohydrodynamic (MHD) models of the source regions of the slow solar wind.

Streamer Abundances and the FIP Effect. One of the most striking discoveries made during the past 7 years of UVCS measurements is the large variation of elemental abundances in streamers (see, e.g., Raymond 1999). UVCS has observed the relative enhancement of low-FIP (first ionization potential) elements such as Si and Mg in streamers, but **UV spectroscopy also provides the absolute abundances** (i.e., relative to hydrogen). These diagnostics show a wider variety of abundance enhancement, depletion, and radial dependence than could have been detected with abundance ratios relative to elements other than hydrogen (e.g., Parenti et al. 2000; Ko et al. 2002; Uzzo et al. 2003). Absolute abundances measured with UVCS are key constraints on models of gravitational settling, magnetic reconnection, and the overall coronal origin of the slow solar wind in streamers.

Highlights: Coronal Mass Ejections (CMEs)

During the past year, UVCS has observed exceptionally powerful CMEs associated with X-class flares, and new modeling efforts are helping to interpret UVCS spectra in terms of the physical processes that drive CMEs. Here, we describe major recent results.

CME-driven Shock Waves. A few shock waves have been observed simultaneously as Type II radio bursts and as changes in the UVCS emission line profiles and intensities (Raymond et al. 2000; Mancuso et al. 2002). The densities inferred from radio and UVCS observations agree, but the shock speeds inferred from the radio observations fall well below the speeds measured from LASCO images. This is largely due to the use of average coronal density profiles for converting the Type II frequency drift rate into a speed. Using instead the densities derived from UVCS synoptic measurements, Mancuso et al. (2003) derived more realistic speeds for 37 Type II radio bursts. The combination of shock speed, density, and the condition that the shock exceed the fast mode speed leads to a lower limit to the plasma β for each event, typically in the range 0.1 to 1. Thus far we have observed only three coronal shocks, so more examples are needed.

Current Sheets. Models of CMEs rely heavily on reconnection in current sheets, either trailing beneath the ejected magnetic flux rope or creating the flux rope in the first place (e.g., Lin and Forbes 2000; Antiochos et al. 1999). UVCS has observed current sheets in the wakes of two CMEs (Ciaravella et al. 2000; Ko et al. 2003). They appear as geometrically narrow features in the high temperature emission lines of [Fe XVIII] and [Ca XIV]. These observations **test the overall energetics** predicted by the idea that the current sheets power the post-flare arcades observed in X-rays and EIT images.
The duration and temporal extent of the current sheets test specific models (Lin 2003). Recent MHD models make specific predictions about post-eruption reconnection and the associated outflow (Riley et al. 2002).

Helical Structure. The approximate conservation of magnetic helicity is a powerful tool for the analysis of laboratory plasmas, and it may determine the evolution of CMEs as they travel through interplanetary space (Kumar and Rust 1996). The buildup of helicity might stop the solar dynamo were the Sun not able to shed helicity by means of CMEs (e.g., Low 2001). LASCO images often show an apparently helical structure in CME cores. Doppler shift measurements with UVCS, CDS, and SUMER provide the velocity signatures to show that the structures are indeed helical and, more importantly, to determine whether the structures are unwinding or merely stretching out.
The combination of velocity and imaging information provides a picture of the 3D structure of the CME material (Ciaravella et al. 1997) and in several cases **shows the structure to be rotating** (Pike and Mason 2002: Ciaravella et al. 2000). Lin et al. (2003) have computed the magnetic flux added to the flux rope by reconnection during the ejection. This suggests rotational motion, but that does not yet constrain the rotation rate. The Doppler shifts also determine the chirality (handedness) of the helix for comparison with that of the pre-CME prominence. In one case this worked out as expected (Ciaravella et al. 2000), but in the September 12, 2000 event the chirality is reversed. The chirality is **vital** for space weather predictions, and the connection between prominence chirality and CME chirality is a key feature of some CME models (e.g., Rust 2001). MHD models are beginning to predict rotational motions at the level needed for comparison with UVCS data (e.g., Gombosi et al. 2002).

Energy Budget. White light coronagraph observations of CMEs provide the masses and the speeds in the plane of the sky. Doppler shift measurements with UVCS, SUMER, and CDS provide the velocity in the other dimension, and therefore the velocity in 3D and the kinetic energy. UVCS measurements of UV line intensity ratios give tight constraints on density, temperature, and ionization state of the expanding CME plasma. In the events analyzed thus far, plasma expelled from the solar surface cannot reach the physical conditions observed without continued heating (Ciaravella et al 2002; Akmal et al. 2001). UVCS and LASCO data show that in order to balance adiabatic expansion and radiative losses, heating well above the solar surface is required. The integrated heating rate by the time the plasma reaches 1.5 to 3.5 R_o, where it is observed, implies a **thermal energy input comparable to the kinetic energy**. This startling result was predicted by Kumar and Rust (1996) on the basis of conservation of magnetic helicity, though in detail their specific model deposits too much heat too quickly at the start of the eruption. Their self-similar model predicts such intense heating that elements such as carbon and oxygen would be more highly ionized than observed by UVCS. The energy budget analysis requires a fairly complete observation of the CME, both in terms of spectral coverage and time, and only a few events are well enough observed so far.

CMEs from X-Class Flares. The *RHESSI* satellite has observed several X-class flares during Major Flare Alerts from the Max Millennium campaign. UVCS participates in these campaigns when the target is within 20 degrees longitude of the solar limb.

In all 3 such campaigns thus far, UVCS has caught an exceptionally fast CME, with a speed above 2000 km/s. The three CMEs were similar to each other and different from other CMEs in two ways. First, all showed very high temperature emission from [Fe XVIII], seen in the CME front or void in only one previous CME. This must be related to the high ionization states measured *in situ* only in magnetic clouds from CMEs. Second, the pre-CME streamer is disrupted in a spectacular manner, with O VI line profiles suddenly split by 1300 km/s and the splitting propagating rapidly along the slit. The O VI lines remain narrow, indicating a lack of shock heating. The combination of the lack of a shock with the densities of the pre-shock streamers gives a lower limit of 4 Gauss for the April 21, 2002 event (Raymond et al. 2002), because the CME speed must be less than the Alfven speed. While the CMEs from X-Class Flares appear to be a distinct class, we have only three examples.

3. UVCS/SOHO EDUCATION AND PUBLIC OUTREACH ACTIVITIES

While there is no formal budget for UVCS Education and Public Outreach (EPO) activities, UVCS scientists have participated in a variety of quality EPO activities over the past two years. The *SOHO* 5th Anniversary events (April 2001) were tremendously successful in reaching out to large and diverse audiences. Over a dozen UVCS scientists participated in 10 events at a variety of venues including SAO, science centers, and K--12 schools. Since that time UVCS has participated in National Astronomy Day events at the Boston Museum of Science and the NASA SECEF Sun-Earth Days (2001 and 2002) and "Live from the Solar Eclipse in Africa" (2001). Popular lectures on the *SOHO* discoveries about the Sun were given at all these events.

In 2002, John Kohl gave a Harvard-Smithsonian "Open House" public talk on what *SOHO* was learning about Space Weather. The talk was well received and was featured prominently in an article published by the Harvard Gazette.

UVCS scientists (Y.-K. Ko and M. Uzzo) and others each gave public talks about *SOHO* and the Sun-Earth Connection as part of the 2002 Maryland Day activities at the University of Maryland. Three PCs were set up to run from *SOHO* CD-ROMs and many *SOHO* educational materials were distributed as well.

A press release featuring an animation showing the reversal of the solar magnetic field was made in conjunction with Sun-Earth Day 2002. The subject of the press release concerned the results of Miralles et al. (2001) on the reappearance of polar coronal holes for the new solar cycle and on the different nature of the acceleration of the fast wind from coronal holes at different latitudes and times of the solar cycle. UVCS determined that the wind speeds were slower in the equatorial holes than at the poles, but since the 1 AU terminal speed for both types of coronal holes are the same, this implies that there must be a faster acceleration in the polar holes near the Sun compared to the equatorial holes.

UVCS comet observations by Raymond et al. were selected as a *SOHO* "Pick of the Week" in 2002. The highlight described the "Lyman alpha tail" of the sun-grazing comet detected with the UVCS spectroscopic measurements.

Leonard Strachan continues to answer questions emailed to *Dr. SOHO*. He typically answers one or two questions a week, on average, that are sent in by students, teachers, and parents. Topics range from *SOHO* science to general astronomy and astrophysics.

UVCS scientists are also involved in providing research opportunities to students at minority institutions and small colleges. Strachan supervised the first summer student (Gerard Sims) in the Southern University Partnership with SAO. One of the goals of this program is to encourage minorities to pursue careers in space science. Another student, Bogdan Valcu, just completed his research as a John Glenn Fellow from Muskingum College in Ohio. His research resulted in a paper, submitted to *Solar Physics*, on tracking changes in the radiometric calibration of UVCS with data from star observations.

UVCS and other *SOHO* materials (education portfolios, posters, and stickers) are being used to support Project Astro classroom visits to Boston Area schools.

4. SOFTWARE, COMMANDING, AND TELEMETRY

UVCS makes extensive use of observation sequences stored in on-board memory. These consist of multiple instrument commands with various parameter sets. A particular sequence and parameter set is selected by an uploaded command. Recent commanding sessions for UVCS last about 1 hour and typically occur once per day. Intensive commanding sessions occur from time to time for special observations. More than 170 commands per day, on average are sent.

UVCS losses due to instrument problems such as software resets or reconfigurations remain at about 1 day per month on average. Ground/DSN problems affect the quality of the data received, but are negligible except for rare occasions.

There have been no patches to UVCS flight software to date, and none are planned or needed.

5. UVCS INSTRUMENT STATUS

UVCS is expected to continue performing at full scientific capability for many more years. Star observations are used to track the UVCS radiometric calibration, which has remained remarkably stable. The absolute radiometric calibration in the primary wavelength ranges is believed to be known to within $\pm$ 20% which is sufficient for all proposed observations. All mechanisms are performing nominally except the Lyα channel grating drive which continues to degrade; use is restricted, but scientific function is redundantly provided by the O VI channel grating drive and a redundant optical path that is used to observe wavelengths near H I Lyα. That path is also used to observe spectral lines in second order such as Mg X, Si XII, and several others. The second order calibration is known to about ± 50%. Spectral and spatial resolutions, the wavelength scale, flat field variations, the pointing and absolute spatial scale, and stray light levels are stable and well characterized. The number of operations for all mechanisms is within design limits. Instrument operational temperatures are expected to remain within acceptable ranges. The UVCS XDL detector for the O VI channel is performing well. There is no significant degradation to the efficiency except on about 20% of the photosensitive area which is used to detect Lyα. Incremental increases in high voltage are used to maintain the efficiency for the Lyα portion to within 5% loss. Voltage increases of 5 EU every 1.2 years is expected to keep efficiency loss at <5%. The high voltage for the Lyα channel XDL detector has been turned off since November 1998 because it draws about 50% of the maximum tested high voltage current and because it has regions of elevated background up to X5. This detector is still operational and is treated as a back-up detector for Lyα observations.

6. ANOMALIES

There have been no hardware components lost and no intermittent failures.

UVCS has detected one single event upset since the beginning of mission. It occurred on 12 April 1998 and triggered the watchdog timer.

7. INSTRUMENT GROUND SOFTWARE

The UVCS Mission Operations Software developed by SAO and used for UVCS commanding has functioned flawlessly throughout the operations phase of the mission. There have been no significant updates and none have been needed.

8. DATA PROCESSING AND ARCHIVING

Processing of SOHO level zero telemetry is reformatted and converted to FITS files almost immediately at the EOF to monitor instrument health and function during all NRT periods. It is also made available to the Lead Observer and Operations Team on the day following an observation to determine the success of the observation. The UVCS Lyα and OVI synoptic and composite images are normally made public within 12 hours. Level zero data is also sent to the Smithsonian Astrophysical Observatory where it is reformatted to Level 1 FITS files within two days of receipt.

The UVCS synoptic data sets and sit and stare watches for CMEs are made available from the SOHO archive and SAO within one month of receipt of Level zero telemetry data from NASA. The special observations data are made public and put on the SOHO archive within 3 months of the observation date. UVCS distributions of level 1 data include calibration files and data analysis software.

A complete set of Level 1 data plus backups exists at the Smithsonian Astrophysical Observatory. This archive also includes calibration files, data analysis software and mission logs.

Currently through the UVCS Web Site, one can find a list of observations planned and completed, a list of all published papers and abstracts by UVCS scientists and guest investigators, the UVCS data analysis software and calibration files, a tutorial on using the UVCS data and the analysis tools including a coronal model code and a user's guide. Also the mission logs are available on the web site in a user friendly search engine.

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