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

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FINAL REPORT

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Principal Investigator
Dr. John L. Kohl

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Smithsonian Institution
Astrophysical Observatory
60 Garden St.
Cambridge, MA 02138 U.S.A.

The NASA Technical Officer for this grant is Dr. Joseph Gurman, Code 682, Goddard Space Flight Center, Greenbelt, MD 20771.

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 15 February 2003 to 14 April 2004. 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 observations for major flare watches, 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 radiometric stability. UVCS has not required any 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. The regions of the detector currently being used require different grating angles for direct OVI observations and redundant path H I Lyα observations, and so those can no longer be observed simultaneously. 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 after 1998. The visible light channel functioned nominally during the reporting period.

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

UVCS has resulted in 33 scientific papers in 2003. There were numerous presentations at scientific meetings.

UVCS Education and Public Outreach activities involved nine members of the UVCS team. During the reporting period, there were over a dozen events directed at students and teachers, museum audiences, and public audiences via the mass media, internet and educational literature.

2. HIGHLIGHTS OF UVCS OBSERVATIONS AND ANALYSES

The physical processes that heat the extended 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 enabling new theoretical efforts through its measurements of densities, outflow speeds, anisotropic temperatures, and abundances in the acceleration regions of the solar wind and CMEs.

Coronal Holes and Fast Solar Wind

UVCS diagnostic measurements inspire and constrain theoretical work that adds to our understanding of how the solar wind is produced.

1. As of early 2004, UVCS had measured the properties of at least 120 large coronal holes, 34 of which were observed in this reporting period. In February 2001, just after solar maximum, the north polar coronal hole began to re-form with the next cycle's polarity, and in mid-2002 the south polar coronal hole began to re-form. In 2003-2004 the UVCS-derived ion properties in these regions continued to approach solar-minimum values. The growing database of coronal hole plasma properties is revealing how heating rates scale as functions of large-scale magnetic properties. 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 (Miralles et al. 2004). 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 by UVCS seem to be indicators of the range of heights where the solar wind acceleration takes place.

2. UVCS observations from the last solar minimum (1996-1997) continued to be mined for clues concerning the dynamical status of bright polar plumes in coronal holes. A controversy emerged in 2003 as to whether the plumes are relatively slow (or even static) structures embedded in an outflowing "interplume" plasma (Teriaca et al. 2003) or whether the plumes flow faster than the interplume plasma (Gabriel et al. 2003). UVCS provides information about the outflow speeds in and between plumes at heights that are otherwise inaccessible.

3. In August 2003, a coordinated set of observations was undertaken with UVCS and VLA radio scintillation measurements of the extended corona at heliocentric distances from 4 to 7 solar radii. The goal of this campaign was to combine the analysis of radio polarimetric sounding measurements (including Faraday rotation constraints on the magnetic field strength and "screen depolarization" studies of waves) with the plasma properties as observed by UVCS. This kind of complementary study can lead to qualitatively new information about the properties of solar coronal plasma. The analysis of these observations is ongoing.

Coronal Streamers and the Slow Speed Wind

UVCS analyses of coronal streamers have continued using both archival data from early in the mission as well as data obtained from ongoing observations. The streamer study has three primary objectives: 1) empirical modeling of streamers to determine their plasma parameters and the variation of these over the solar cycle (L. Strachan, lead); 2) determination of minor ion abundances in streamers (M. Uzzo, lead); and 3) variations of O VI velocity distributions at various latitudes and at different phases of the solar cycle with emphasis on understanding anisotropic velocities at heights well above the cusp (J. Kohl, lead). Michael Baham, a summer intern from Southern University, is heavily involved in the data reduction for the empirical modeling effort.

Highlights of the research accomplishments for these ongoing activities during the reporting period are summarized below.

1. Recent streamer abundance results, derived from UVCS data for a September 2001 streamer, have been documented in a recent publication (Uzzo et al. 2004). This publication analyzed the photospheric normalized absolute elemental abundances of several elements in terms of their spatial distribution, first ionization potential (FIP) effect, and emission measure. The results for this active region streamer were unique due to the presence of an abundance depleted core, a quiescent streamer phenomenon, and the rapid reformation of said core following a coronal mass ejection (CME) which ripped through the streamer. Ongoing efforts include a comprehensive analysis of the elemental abundances in combination with the electron temperature, electron density, kinetic temperature, outflow velocity, and velocity anisotropy for each of a variety of streamers during the declining phase in solar activity.

2. A comprehensive list of 49 UVCS streamers have been compiled from dedicated observations made between 1996 and March 2003. The streamers were organized by latitude, solar cycle phase, and activity level. OVI doublet intensities, line widths, and O VI 103.2 and 103.7 nm intensity ratios were determined as a function of height for each streamer. Intensities and line widths for H Ly-α were obtained for a subset of the data. The preliminary results confirm that the O^{5+} kinetic temperatures increase with height faster in solar minimum equatorial streamers than for high latitude streamers at other phases in the solar cycle. Work is now underway to determine if these changes are due to

intrinsic physical changes within the streamers or to geometry effects. The compilation of streamer parameters is part of an effort that includes the use of UVCS synoptic data to characterize the variation of the streamer physical properties over a complete solar cycle.

3. Empirical model results for a subset of the streamers from solar minimum show that the kinetic temperatures for protons and O^{5+} are similar at heliocentric heights below about 3 solar radii where there is no detectable outflow. Above 3 radii, the O^{5+} kinetic temperature increases while that for the protons decreases. This provides additional evidence that the minor ions are preferentially heated as was demonstrated previously for the case of coronal holes.

Solar Wind Theory

1. UVCS measurements of preferential ion heating and anisotropic temperatures in coronal holes revived interest in the idea that ions are energized by the damping of ion cyclotron resonant waves, but it is still not clear how such high-frequency (10 to 10,000 Hz) waves can be produced in the corona. Cranmer and van Ballegooijen (2003) completed and published a model of magnetohydrodynamic (MHD) turbulence during the reporting period that aimed to determine whether a turbulent cascade of wave energy would or would not naturally lead to ion cyclotron resonance. For conditions in the fast-wind acceleration region, they found that it is highly unlikely for turbulence to produce ion cyclotron waves; instead, turbulence (as currently understood) seems to produce waves that accelerate thermal electrons along the magnetic field. Voitenko and Goossens (2004) suggested that if these waves are of sufficient strength, they may also heat ions via a nonlinear type of cyclotron resonance. Work on the origin of the waves that is required to produce the observed kinetic properties continues.

2. MHD turbulence in the corona is seeded by the presence and gradual reflection of low-frequency Alfven waves that originate at the Sun. Thus, in order to better understand the necessary pre-conditions for turbulence, Cranmer and van Ballegooijen (2004) began a study of the global properties of low-frequency Alfven waves in coronal holes. This work led to a comprehensive model of the radially varying Alfven wave frequency spectrum, constrained only by observations of transverse bright-point motions in the photosphere. UVCS measurements of "nonthermal" line widths at solar minimum provided a crucial check on the model. A major result of the model -- which will likely impact future solar wind studies -- is that a commonly used "Kolmogorov" heating rate for the extended corona was found to overestimate the coronal heating, compared to a more exact calculation, by as much as a factor of 30.

3. New theoretical models of the fast and slow solar wind were published in the reporting period that use UVCS observations as key constraints (Li 2003; Peter and Vocks 2003; Vasquez et al. 2003; Chen et al. 2004; Gary and Borovsky 2004).These models largely did not address the origin of MHD turbulence or the source of the ion cyclotron waves, but the UVCS data have allowed the level of sophistication and realism in these models

to increase substantially compared to pre-SOHO models.

Coronal Mass Ejections (CMEs)

1. UVCS observed the most powerful CME/flare events of the solar cycle in October/November 2003. O VI photons generated by the flare in its impulsive phase scatter from O^{5+} ions in the corona, making it possible to derive the emission measure at transition region temperatures for comparison with theoretical models.

2. Published CME results include a calculation of the amount of magnetic flux and mass accumulated by a CME in the UVCS range of heights (Lin et al. 2004), constraints on the coronal magnetic field from studies of CME shocks and type II radio bursts based on UVCS density diagnostics (Mancuso et al 2003; Mancuso & Raymond 2004), and a study of the velocity structure of the Feb. 11, 2000 CME that focused on the structure of the leading edge in 3D (Ciaravella et al. 2003). The leading edge turned out to be a ribbon-like arch, rather than a simple magnetic loop or a spherical bubble. Suleiman et al (in preparation) are analyzing the helical structure of a powerful event, finding that the chirality of the pre-CME filament agrees with that of the expanding loop of cool plasma.

3.A study of fast CMEs associated with X-class flares showed that they are much different from other CMEs because they have almost no cool prominence material, but have large amounts of hot plasma seen in [Fe XVIII] (Raymond et al. 2003). They are among the fastest CMEs ever observed, with velocities as high as 2500 km/s. In one case the [Fe XVIII] was evidently produced by current sheet plasma, and in another ejected active region plasma. Preliminary results presented at the AGU (Raymond et al. 2003) show similar behavior among the October-November 2003 events.

4. Dobrzycka et al. (2003) derived densities, temperatures and velocities of several narrow CMEs, finding that while they were generally compatible with either a jet or a small CME model, one case favored the latter.

5. Ko et al. (2003) used UVCS spectra to show that a hot, narrow feature in the wake of a CME was the current sheet predicted by standard CME models. Lin et al. (2004, in preparation) observed a similar current sheet. They compared the outflow speeds of blobs in the current sheet (approximately the Alfven speed) to the speed of inflow at the sides of the current sheet determined from the narrowing of the Lyα feature to find the effective speed of the reconnection inflow.

6. Suess et al. (2004) studied a slow streamer blowout observed by UVCS and demonstrated that it is possible to identify the same event in ULYSSES data. Poletto et al. (2004) observed high ionization states of Fe in an event seen by both UVCS and UYSSES, showing that it is possible to connect the two types of observation to study the evolution of the ionization state.

7. Two papers analyzed a fairly fast CME and its associated Solar Energetic particle event. Raymond & Ciaravella (2004) showed that pumping of O VI 103.7 nm by O VI 103.2 nm and pumping of O VI 103.2 nm can be used to measure outflow speeds near the resonance velocities of 1650 and 1810 km/s and plasma densities. Ciaravella et al. (2004) analyze the shock associated with that event and discuss the unusually low charge state of the energetic O ions.

Comets

UVCS spectra of Comet Kudo-Fujikawa at its perihelion at 0.19 AU showed a disconnection event in the C III ion tail, and the event corresponded to the time the comet crossed the heliospheric current sheet (Povich et al. 2003). The outgassing rate increased by a factor of 5 during the course of about 30 hours. The most exciting result is that the comet produced more carbon than CO, indicating sublimation of organic material from dust. This presumably occurs because the comet is so close to the Sun.

UVCS analyses of two sungrazing comets study fragmentation, both far from the Sun, as indicated by fragments resolved in space and time, and close to the Sun, as indicated by sudden brightness increases (Bemporad et al. 2004; Giordano et al., in preparation). Both studies also give local, as opposed to line of sight averaged, coronal densities

Helium Focusing Cone

Michels et al. (2002) observed interstellar He atoms close to the Sun where solar gravity focuses the flow into a relatively dense cone, and they found that the density of He atoms dropped significantly as solar activity rose toward maximum due to collisional ionization. As a result of an ISSI workshop, four new papers extend this result through solar maximum and combine the UVCS observations with EUVE, CELIAS/SEM and *in situ* data to derive more accurate parameters for both the interstellar He flow and the solar wind properties (Lallement et al. 2004a, 2004b; Vallerga et al. 2004; Moebius et al. 2004).

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 under the leadership of Leonard Strachan. UVCS EPO activities involved nine members of the UVCS team. During the reporting period, there were events directed at students and teachers, museum audiences, and public audiences via the mass media, the Internet and educational literature.

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

The UVCS OVI channel continues to provide quality data.

The mechanisms are all working nominally with the exception of the Lyα grating mechanism, which is "sluggish" but still operational.

In order to keep the high voltage current of the OVI detector at acceptable levels, we lowered the applied high voltage in January, 2004. That has resulted in the gain being low on the areas of the detector that have received the most use. The response of the remaining parts, comprising more than half of the original active area, has been characterized and are "nominal." The entire UVCS wavelength range is still observable with the OVI channel, but wavelengths near OVI 103.2 nm and wavelengths near HI 121.6 nm are now observed at separate times.

In order to slow the rate of rise of the high voltage current draw of the OVI channel, its temperature was lowered. This was done by turning off the Lyα detector completely. The Lyα high voltage had been off since 1998, and it was not used, since then. The OVI detector temperature is lower now by about 10 C. The current draw of the OVI detector has not increased measurably since the Lyα detector was fully shut off.

The Visible Light Detector functioned normally during the reporting period.

6. CALIBRATION

The radiometric response of UVCS has been tracked using observations of a set of stars which have been observed annually since the beginning of the mission. The relative response of the UVCS telescope as a function of unvignetted aperture has been tracked using observations of stable streamers. Grating scans have been carried out to establish the "flatness" of the "redundant" portion of the OVI detector.

The turn-off of the Lyα detector in January 2004 and subsequent cooling of UVCS has significantly altered the telescope mirror pointing calibration and the grating mechanism wavelength calibration. Data have been acquired to re-establish these calibrations to high precision. The analysis is in progress. Further observations (e.g., Alpha Leo on 29-30

1. John Kohl took the lead in educating the public about the solar causes and possible consequences of space weather during the October/November 2003 solar events. Millions of people heard the news stories over radio and TV. In addition to the broadcasts, print and Internet coverage helped to make this story one of the most widely covered SAO news stories ever.

2. UVCS material was used for three presentations that were prepared for K-12 students and their teachers. In the first one, Strachan delivered a video conference presentation on the subject of space weather that was delivered to four different high school classrooms. The COSI organization (Columbus, Ohio) provided the coordination and logistics for this event. In the second event, Yuan-Kuen Ko gave a SOHO presentation on the Web for adult educators that was broadcast on a Korean language TV station. Finally, Strachan spoke about the Sun and space weather to a teacher workshop (K-9) held at the CfA Science Education Department.

3. There were several activities aimed at undergraduates. In the summer of 2003, Strachan was the research advisor for a Southern University student, thus continuing the UVCS outreach efforts to minority institutions. Also, in the fall of that year, Steven Cranmer met with physics students at Southern and presented a seminar on the solar wind. Other presentations were made to undergraduates in the CfA Summer Intern program and to students at Tufts University.

4. Informal education talks were presented at the Museum of Science, Boston, for NASA's Sun-Earth Day 2003. Mari Paz Miralles and Strachan spoke to a mixed audience of adults and children about the aurora. A portion of the presentation was devoted to a demonstration using emission line spectral lamps. In Summer 2003, the two gave a similar presentation to students in a local high school summer program.

5. UVCS members have also provided educational materials to publishers. Kohl wrote an article on space weather for an encyclopedia of science and technology (McGraw Hill). Strachan and Nigel Atkins provided materials for use in a middle school earth science textbook (Prentice-Hall).

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.

August) will be carried out in the near future to further quantify the telescope mirror temperature induced shift.

The radiometric calibration results (through 2002) have been incorporated into a new version of the DAS and associated files. Revised wavelength calibrations and pointing calibrations have also been incorporated into the new version.

7. ANOMALIES

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

There have been no other indications of hardware component failures, and no intermittent failures during the reporting period.

8. 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 during this grant period and none have been needed.

9. 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 on CD is also sent to the Smithsonian Astrophysical Observatory where it is reformatted to Level 1 FITS files within two days of receipt.

All UVCS data are made available from the SOHO archive and SAO within three months of the observations. This schedule requires timely receipt of CD ROM telemetry data from NASA. UVCS distributions of level 1 data include calibration files and data analysis software.

A complete set of Level 1 data plus backups exist 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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