CORONGRAPHIC OBSERVATIONS AND ANALYSES OF THE ULTRAVIOLET SOLAR CORONA

NASA Grant NAG5-613

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.

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is a member of the
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The NASA Technical Officer for this grant is John C. Brinton, Code 810, Wallops Flight Facility, Wallops Island, VA 23337.

1.0 INTRODUCTION

The activities supported under NASA Grant NAG5-613 included the following: 1) reduction and scientific analysis of data from three sounding rocket flights of the Rocket Ultraviolet Coronagraph Spectrometer, 2) development of ultraviolet spectroscopic diagnostic techniques to provide a detailed empirical description of the extended solar corona, 3) extensive upgrade of the rocket instrument to become the Ultraviolet Coronal Spectrometer (UVCS) for Spartan 201, 4) instrument scientific calibration and characterization, 5) observation planning and mission support for a series of five Spartan 201 missions (fully successful except for STS 87 where the Spartan spacecraft was not successfully deployed and the instruments were not activated), and 6) reduction and scientific analysis of the UVCS/Spartan 201 observational data.

Research under this grant was carried out over a nearly 20 year period. During that time many scientists, engineers, and administrators contributed to its success. Beginning with the earliest contributors, some of there names are the following: John Kohl (PI), George Withbroe (Co-I), Giancarlo Noci (Co-I), William Parkinson (Co-I), Heinz Weiser (Co-I), James Crawford (Engineer), George Nystrom (Engineer), Robert Rasche (Engineer), Edward Dennis (Engineer), Roger Hauck (Engineer), David Boyd (Engineer), Vesa Kuosmanen (Engineer), Frank Licata (Engineer), Frank Rivera (Engineer), Peter Warren (Engineer), Carlos Zapata (Scientist), Leonard Strachan (Co-I), Larry Gardner (Project Scientist and Co-I), Gerry Gardner (Programmer), Peter Sozanski (Project Manager), Brenda Bernard (Project Administrator), Silvano Fineschi (Scientist), Marco Romoli (Scientist), Ruth Esser (Scientist), Shadia Habbal (Scientist), Peter Daigneau (Engineer), Mari Paz Miralles (Scientist), Peter Smith (Scientist), Danuta Dobrzycka (Scientist), Raid Suleiman (Scientist).

The Ultraviolet Coronal Spectrometer for Spartan 201 was one unit of a joint payload and the other unit was a White Light Coronagraph (WLC) provided by the High Altitude Observatory and the Goddard Space Flight Center. The two instruments were used in concert to determine plasma parameters describing structures in the extended solar corona. They provided data that could be used individually or jointly in scientific analyses. The WLC provided electron column densities in high spatial resolution and high time resolution. UVCS/Spartan provided hydrogen velocity distributions, and line of sight hydrogen velocities. The hydrogen intensities from UVCS together with the electron densities from WLC were used to determine hydrogen outflow velocities. The UVCS also provided O VI intensities which were used to develop diagnostics for velocity distributions and outflow velocities of minor ions.

The Spartan 201 missions laid the ground work for UVCS/SOHO providing verified instrument designs, the basis for observation planning before the mission, and the experience base that enabled a rapid scientific interpretation of the UVCS/SOHO observations and rapid publication of the results.

2.0 HIGHLIGHTS OF SCIENTIFIC RESULTS

2.1 Reduction and Scientific Analyses of Rocket Data

The profiles of resonantly scattered HI Ly-alpha were used to determine hydrogen kinetic temperatures from 1.5 to 4 $R_\odot$ in a polar region of the corona observed in 1980 (Withbroe et al., 1985). Hydrogen temperatures derived from the line profiles were found to decrease with height from 1.2 million K at r=1.5 $R_\odot$ to 0.6 million K at r = 4 $R_\odot$ (See Figure 1). Comparison of the measured kinetic temperatures with predictions from a semiempirical two-fluid model showed evidence of a small amount of heating or a nonthermal contribution to the motions of coronal protons between 1.5 and 4 $R_\odot$. The widths of the profiles confirmed an upper limit of 110 $\pm$ 15 km/s on the rms magnitude of the line of sight component of velocities over the same range of heights. It was also found from the combined white light and uv data that there was little or no Doppler dimming of the HI Ly-alpha intensities in the observed region, a relatively small open field region above the south solar pole (see Figure 2). The detailed analysis of the 1980 polar region showed rather conclusively that all low density polar regions do not have supersonic flows at low heights as might be inferred from the 1973 region studied by Munro and Jackson.

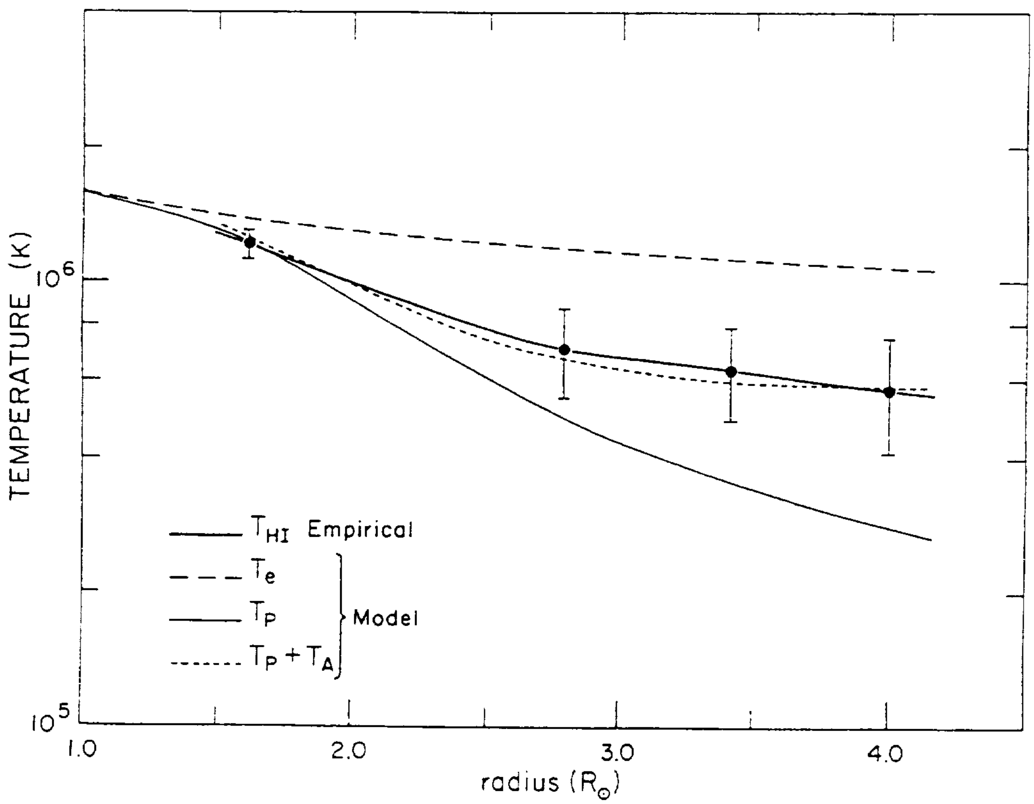

Figure 1: Empirical temperatures in a polar region observed in 1980, derived from H I Ly-alpha line profiles (points, heavy solid line); calculated electron (dashed line) and proton (light solid line) thermal temperature; and sum of proton thermal temperature and Alfven wave "temperature" (dotted line).

In the 1979 flight, HI Ly-alpha measurements were obtained in another polar region of the corona. The 1979 polar data, while less comprehensive than the 1980 measurements, contain valuable information about polar regions near the time of solar maximum. The results can be summarized as follows: Measurements of the intensities and spectral line profiles of HI Ly-alpha were used to determine a mean kinetic temperature of 1.8 million K which is significantly higher, by $\sim$ 60 percent, than that obtained in a similar region observed in 1980 (see Figure 3). The densities in the two regions are similar and are a factor of $\sim$ 4 larger than in polar coronal holes observed at solar minimum. The flow

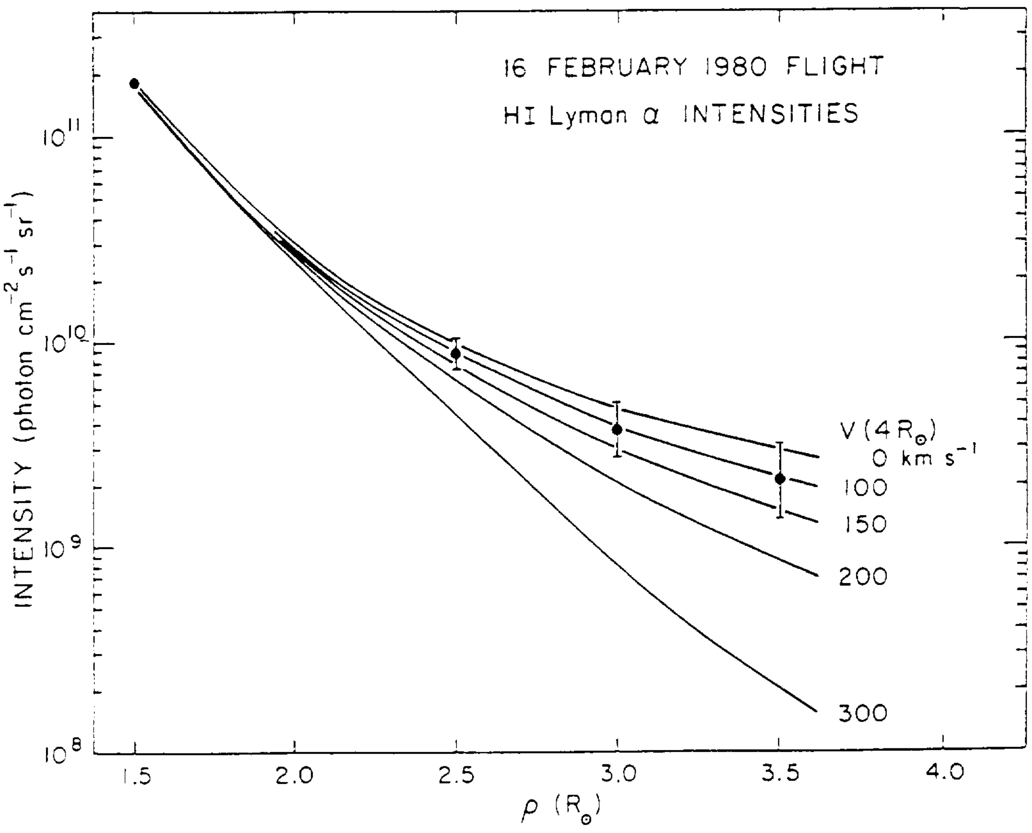

Figure 2: A comparison of measured (points) and calculated (curves) H I Ly-alpha intensities as a function of distance from sun center for a polar region observed in 1980. The curves give values calculated for models with different solar wind fluxes parameterized here by the wind velocity at 4 $R_{\odot}$.

velocities in both regions are most likely subsonic for r< 4 $R_{\odot}$. The results support the hypothesis that open field polar regions observed at different times in the solar cycle can have different temperatures, densities, and possibly flow velocities (Withbroe, Kohl, and Weiser, 1986).

A preliminary analysis of the polar coronal hole observations for the 20 July 1982 rocket flight was reported in the May 1984 Progress Report for this grant and also reported at scientific meetings (Kohl et al., 1984). To derive outflow velocities, sets of parameters were determined for electron temperatures in the hole, densities in the hole and surrounding corona, and outflow velocities in the hole that simultaneously predict the observed HI Ly-alpha intensity and the visible polarized brightness. A range of values were found for the outflow velocities at 1.5 and 2.0 $R_{\odot}$. The preliminary result was that supersonic outflows ($\sim$ 135 km/s) were present at 1.5 and 2.0 $R_{\odot}$. This lower limit for outflow allows for a substantial error budget. Doppler dimming accounted for at least a factor of 2.5 decrease in the HI Ly-alpha intensity. It was also found that the OVI 103.2 nm intensity was extremely small. The observed value was appropriate for the collisionally excited component of the line. It appeared that the resonantly scattered component was fully Doppler dimmed out. This was expected to occur for outflow velocities above 80 to 100 km/s and was then taken to be consistent with derived supersonic outflow velocities from HI Ly-alpha. Because of the significance of this result, it was decided to undertake a more detailed analysis before publishing the result.

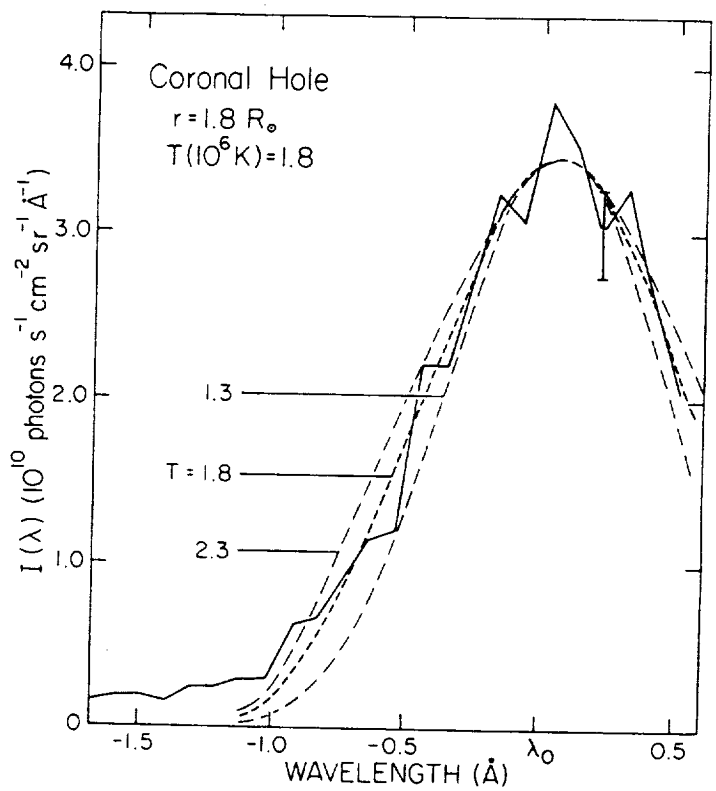

Figure 3: Empirical H I Ly-alpha profile (heavy line) measured at a projected height of 1.8 $R_\odot$ at the position indicated by the small rectangle in the eclipse photograph (upper left). The dashed lines are theoretical profiles corresponding to coronal hydrogen temperatures of 1.3, 1.8 and 2.3 million K. The instrument terminated the scans at approximately halfway down the red wing of the line. The eclipse photograph, which was taken approximately 1.5 solar rotations prior to the rocket flight has been reversed so that long -lived solar features will have the same orientation as they had at the time of the rocket flight.

Leonard Strachan undertook an extensive analysis of the 1982 observations which included a coronal model of the observed structure and a detailed error analysis. Outflow velocities were derived from a Doppler Dimming analysis of resonantly scattered HI Ly-alpha (see Figure 4). This analysis indicates radial velocities of 217 km/s at 2 $R_\odot$ with an uncertainty range of 153 to 251 km/s at a confidence level of 67 percent. These results are best characterized as strong evidence for supersonic outflow within 2 $R_\odot$ of sun-center in a polar_coronal hole (Strachan, 1990; Strachan et al., 1993). These observations contrast sharply with the subsonic velocities out to 4 $R_\odot$ that were determined for higher density polar regions observed in 1979 and 1980.

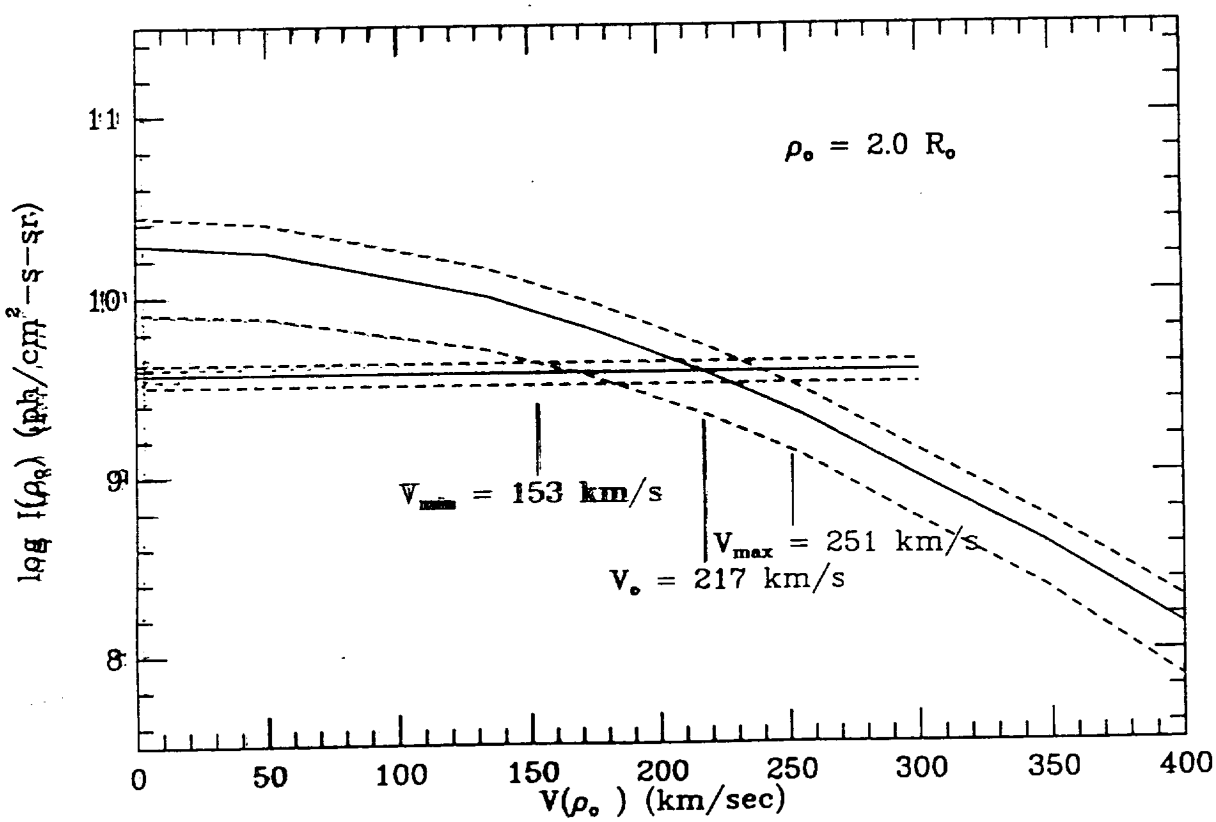

Figure 4: Predicted line of sight intensities (solid curve) versus outflow velocity at a projected coronal height of 2.0 $R_\odot$ from a coronal model with the densities, and temperatures provided in Table I. Broken curves on either side are 1 sigma uncertainties in the model. The horizontal line indicates the measured line of sight intensity with 1 sigma uncertainties (broken line). The intersection picks out an outflow velocity of 217 km/s.

Strachan (1990) also reported kinetic temperatures for the polar coronal hole observed in 1982. His hydrogen kinetic temperatures (designated T_p) are provided in Table I along with his measured outflow velocities, the modeled electron temperatures and the electron densities measured by the rocket white light coronagraph. The temperatures were corrected for the line of sight component of the outflow velocity. The result is the kinetic temperature which is a sum of the thermal temperature and the effects due to transverse wave motion.

These temperatures are similar to kinetic temperatures measured in the 1980 polar region which did not have supersonic outflow and had about four times higher electron densities.

Table I.
1982 North Polar Coronal Hole

ρ $(r/R_\odot)$	n_e (cm^{-3})	T_e (K)	T_p (K)	V_p $(km\ s^{-1})$
1.5	1.73×10^6	1.34×10^6	1.34×10^6	183
2.0	5.11×10^5	1.23×10^6	0.91×10^6	217
3.5	9.89×10^4	1.04×10^6	0.43×10^6	226

In Table I, plasma parameters are provided for the 1982 north polar coronal hole and determined at three projected heights, ρ. Empirical values are listed for n_e, the electron density; T_e, the electron temperature, T_p, the proton temperature, and V_p, the proton bulk outflow velocity.

2.2 Development of Ultraviolet Spectroscopic Diagnostic Techniques

Spectroscopic diagnostic techniques were identified and evaluated for describing the coronal source regions of the solar wind. Techniques to determine magnetic fields, flow velocities, proton kinetic temperatures, electron temperatures and absolute elemental abundances were reviewed by Withbroe (1983).

Concerns about intensity contribution fractions along the line of sight led to several simulations aimed at addressing that problem. It was found that fractional contributions to observed spectral intensities for coronal holes that co-exist with other coronal structures along a line of sight were sufficiently large to allow detailed analysis of the coronal holes. The sensitivity of observed HI Ly-alpha intensities and line widths to the kinetic temperatures and outflow velocities in the coronal holes were found to be sufficient to discern the properties of coronal holes out to at least 2.2 $R_\odot$ even in the case of a fairly narrow (60 degree) coronal hole; broader holes would dominate observations out to higher heights (Kohl et al., 1983).

A technique for determining outflow velocities of O^{5+} ions was developed. It took advantage of excitation of a coronal line by nearby chromospheric lines. The technique uses measurements of the intensity ratio of the OVI doublet at 103.2 nm and 103.7 nm. Pumping of the 103.76 nm line by C II 103.70 nm was found to allow an extention of the velocity sensitivity range beyond that of simple OVI Doppler dimming. The range increased from 100 to 250 km/s. Similar diagnostics with Mg X and other spectral lines were also investigated (Noci, Kohl and Withbroe, 1987).

Simulations of OVI Doppler dimming and pumping measurements were made to evaluate that diagnostic technique and also determine instrument requirements needed to obtain the required observations. It was concluded that it would be possible to locate where the flow changes from subsonic to supersonic and to identify source regions of the high and low speed solar wind (Strachan, Gardner and Kohl, 1992).

Considerable work was done in association with this project to interpret EUV observations of the extended solar corona. Esser, Habbal, Withbroe and Leer (1986) explored the effects of Alfven waves from the inner corona on the solar wind density profile, flow velocity, and the random motions of protons. Observations from the rocket ultraviolet coronagraph and visible polarized brightness measurements were used to place limits on the wave amplitude. It was pointed out that future measurements of polarized brightness and HI Ly-alpha along with spectral lines from heavier elements could be used to place more stringent constraints on the amplitudes of MHD waves in the corona.

2.3 Scientific analysis of the UVCS/Spartan observational data

Before the first flight of Spartan 201, there were only 15 minutes of EUV observations of the extended solar corona from the three rocket flights. The 40 hour Spartan 201-1 flight provided a major increase in the data quantity. Observations were made of a helmet streamer and the north and south polar coronal holes. The companion white light coronagraph indicated that the north polar region is a coronal hole which has a substructure consisting of polar plumes or rays.

The UVCS/Spartan observations at 2.1 $R_\odot$ in the north polar coronal hole appears to consist of three components, the geocorona, a narrow coronal component and a broad component. A preliminary analysis indicated that the broad component has a Doppler half width of 0.091 nm which corresponds to a kinetic temperature of about 3.0 million K (Kohl et al., 1994).

A more complete analysis of both the north and south polar coronal holes for heights from 1.8 to 3.5 $R_\odot$ yielded curve fits with both narrow and broad components. The most probable speeds along the lines of sight were 158 and 322 km/s (south) and 98 and 266 km/s (north) (see Table II). These parameters did not vary by more than 10 percent (1 sigma) over the observed heights in each polar region. The accuracy of such parameters from curve fits is not high and is difficult to quantify. Spartan 201, which operates below much of the exosphere must be corrected for the geocorona which is another source of uncertainty. The UVCS/Spartan observations indicate that there are regions within the observed coronal holes that have hydrogen and proton kinetic temperatures of 4–6 million K which is 4–10 times the expected electron temperatures (Kohl, Strachan and Gardner, 1996). Comparisons to UVCS/SOHO observations during STS 95 in November 1998 are still in process. More precise laboratory measurements of the instrument spectral line profile (i.e., response to a narrow wavelength band) for UVCS/Spartan are being made in order to more accurately simulate the effect of the instrument on the observed line profiles.

In response to the Spartan observations of relatively high proton temperatures in polar coronal holes, Mckenzie, Banaszkiewicz and Axford (1995) published a theory for the high speed solar wind based on a dissipation length characterization of wave heating of the coronal plasma close to the Sun. They found that solutions with the correct particle and energy fluxes and with a realistic magnetic field, match the requirements on the density at the base of the corona provided the dissipation length is relatively small ($\sim$0.25–0.5 $R_\odot$). The significant features of these solutions are that the acceleration is rapid, with the sonic point at about 2 $R_\odot$, and the maximum proton temperatures are high, namely 8–10 million K, which could be consistent with the UVCS/Spartan observations. Such efficient dissipation requires any Alfven waves responsible to have frequencies in the range 0.01Hz–10kHz.

HI Ly-alpha observations of the south polar coronal hole revealed variations in intensity for various position angles at 1.8 $R_\odot$. A bright region at PA = 200 degrees appeared

Table II.
Spartan 201-1 H I Lyα PROFILE PARAMETERS

Height ($R_\odot$)	P.A. (deg)	I_{tot} ($ph\ s^{-1} cm^{-2} sr^{-1}$)	I_B/I_{tot}	V_N ($km\ s^{-1}$)	ΔV_N ($km\ s^{-1}$)	V_B ($km\ s^{-1}$)	ΔV_B ($km\ s^{-1}$)
			North Polar Region				
1.83	349.3	2.91×10^{10}	0.887	73.	-36.	196.	-13.
1.83	359.3	2.47×10^{10}	0.478	132.	-41.	250.	14.
1.83	9.3	2.53×10^{10}	0.459	130.	-21.	285.	-6.6
Avg.		2.64×10^{10}	0.608	112.	-33.	244.	-1.9
2.12	347.9	1.12×10^{10}	0.714	92.	-23.	327.	-17.
2.12	357.9	7.38×10^{09}	0.758	78.	-44.	255.	-5.
2.12	7.9	8.81×10^{09}	0.732	99.	-20.	223.	-4.3
Avg.		9.13×10^{09}	0.735	90.	-29.	268.	-8.8
2.53	346.5	4.09×10^{09}	0.832	75.	-52.	326.	-9.6
2.53	356.5	2.91×10^{09}	0.642	125.	11.	292.	-6.7
Avg.		3.50×10^{09}	0.737	100.	-20.	309.	-8.2
3.52	4.3	1.17×10^{09}	0.653	92.	-5.4	243.	-13.
			South Polar Region				
1.73	189.9	4.34×10^{10}	0.336	147.	0.3	330.	12.
1.83	179.3	2.39×10^{10}	0.375	144.	10.	312.	20.
1.83	189.3	2.46×10^{10}	0.231	163.	4.5	353.	-26.
1.83	199.3	2.37×10^{10}	0.272	162.	19.	355.	36.
1.83	209.3	3.38×10^{10}	0.349	144.	22.	316.	9.7
Avg.		2.65×10^{10}	0.307	153.	14.	334.	9.9
2.12	177.9	6.93×10^{09}	0.416	188.	25.	511.	30.
2.12	187.9	7.04×10^{09}	0.516	169.	18.	275.	-4.6
2.12	207.9	6.24×10^{09}	0.804	145.	2.3	219.	43.
Avg.		6.74×10^{09}	0.579	167.	15.	335.	23.
2.53	186.5	1.93×10^{09}	0.525	170.	-22.	275.	75.
2.53	206.5	2.52×10^{09}	0.658	157.	24.	301.	39.
Avg.		2.23×10^{09}	0.592	164.	1.	288.	57.

to be coincident with a polar plume observed by the white light coronagraph. Comparison of the line profiles at the apparent plume position and a neighboring region with lower intensity revealed a narrower width for the portion of the profile attributable to the plume compared to the profile for the darker region. It appeared that the observed polar plume was cooler than the adjacent coronal hole or had smaller non-thermal velocities (Kohl et al., 1995).

The helmet streamer observed by Spartan 201-1 was located above the southeast limb. The observations provided HI Ly-alpha intensities and profiles. The resulting proton kinetic temperatures ranged from 2.6 million K at 1.5 $R_\odot$ to 3.2 million K at 2.1 and then dropped to 2.2 million K at 3.5. The observation at 3.5 could have included contributions from structures other than the streamer (Strachan et al., 1994).

Outflow velocities in the south polar coronal hole of 13 September 1994 were determined with a Doppler dimming analysis of HI Ly-alpha. A model with empirical values for electron density and electron temperature was used. The helium abundance relative to hydrogen was assummed to be 10%. Electron densities were taken from WLC/Spartan 201 and the adopted electron temperature was a "freezing in" temperature from SWICS/Ulysses. The entire intensity of the HI line was used. If any portion of the line was due to a region with smaller outflow velocities than the coronal hole (e.g., a foreground or background streamer), then the coronal hole outflow velocities would be larger than determined here. A lower limit on outflow speed in the polar coronal hole of about 153 km/s at 2.5 $R_\odot$ (see Table III) was determined (Kohl et al., 1996).

Table III.
South Coronal Hole Mean Intensities and Velocities

ρ $(r/R_\odot)$	# pts.	Avg. Intensity $(ph \cdot cm^{-2}s^{-1}sr^{-1})$	Avg. V_{SW} (km/s)	V_{SW} - 1σ (km/s)	V_{SW} + 1σ (km/s)
1.87	4	2.38×10^{10}	55	21	80
2.16	3	6.94×10^{09}	122	107	140
2.55	2	2.49×10^{09}	153	138	171
3.04	1	1.20×10^{09}	145	129	163
3.54	1	1.07×10^{09}	103	82	123

The HI Ly-alpha profiles observed by UVCS/SOHO in a 1996 polar coronal hole are reminiscent of coronal hole profiles observed by UVCS/Spartan in 1993. In the case of Spartan, the average most probable speed between 1.8 and 2.5 $R_\odot$ was 288 km/s. UVCS/SOHO 1996 values for 2.1 and 3.0 $R_\odot$ were about 200 km/s and 230 km/s respectively (Kohl et al., 1997). Both sets of measurements indicate that a significant fraction of the protons along the line of sight in coronal holes have velocities larger than those for a Maxwellian velocity distribution at the expected electron temperature.

Most probable hydrogen speeds for streamers observed in 1993, 1994 and 1995 with UVCS/Spartan as a function of height were reported by Miralles et al. (1999). UVCS/SOHO observations of an equatorial quiescent streamer during solar minimum revealed most probable speeds of 173 and 185 km/s for 1.75 and 2.25 $R_\odot$, respectively. These values are $\sim$1.3 times narrower than the values obtained by UVCS/Spartan for the mid-latitude southeast helmet streamer in 1993 (Strachan et al., 1994).

Detailed comparisons of the co-registered observations of HI Ly-alpha profiles by UVCS/Spartan and UVCS/SOHO during the STS-95 mission are being used to inter-characterize the two instruments. Observations of coronal streamers obtained by UVCS/Spartan during the Spartan 201-5 flight were reported by Miralles et al. (1999). The comparison to the Spartan profiles is awaiting the results of additional laboratory characterization of UVCS/Spartan.

There is considerable evidence that hydrogen kinetic temperatures are considerably different in various coronal structures. Not only are the hydrogen kinetic temperatures (2.9 million K at 1.8 solar radii) measured in the southeast streamer with UVCS/Spartan in 1993 considerably higher than those (1.8 million K at 1.75 $R_{\odot}$) measured with UVCS/SOHO in a 1996 quiescent equatorial streamer, but a mid latitude region observed with the rocket ultraviolet coronagraph spectrometer in 1979 revealed a hydrogen kinetic temperature of 1.7 million K at 1.8 $R_{\odot}$. The observed area of the corona was called a quiet region at the time (Withbroe, G. L., Kohl, J. L., Weiser, H., and Munro, R. H., Ap. J. 254, 361, 1982).

3.0 DEVELOPMENT OF THE ULTRAVIOLET CORONAL SPECTROMETER FOR SPARTAN 201

The Spartan Ultraviolet Coronal Spectrometer is a modification of a sounding rocket instrument which met its full success criteria during all three of its flights in 1979, 1980 and 1982. It was selected for the Spartan program in 1982, and the first flight was originally planned for 1985. Delays resulting from the time criticality of the Spartan Halley Mission and the Challenger accident led to the first launch date of April 1993. Uncertainties in the Shuttle manifest required the UVCS/Spartan to be maintained in a near flight ready condition starting in late 1985. This required periodic characterizations of the optics and detectors and replacements of components with degraded performance. The UVCS/Spartan was integrated with the HAO White Light Coronagraph (WLC) and the Spartan spacecraft on three separate occasions (1986, 1989, and 1992) for its first launch. Each time, it underwent a complete set of environmental tests and full flight duration simulation tests.

The Spartan Ultraviolet Coronal Spectrometer (see Figure 5) consists of an externally and internally occulted telescope system, a dual spectrometer, two uv detectors and electronics. There are two channels, one for observing the spectral line profile and intensity of the HI Ly-alpha line and the other for measuring line intensities of the O VI doublet at 103.2 and 103.7 nm.

The Ly-alpha channel has a spherical telescope mirror with a focal length of 47.5 cm, which is coated with Al + MgF_2 and an Ebert Fastie spectrometer with a discrete multi-anode detector. There are separate entrance slits for measuring the line profile and the integrated intensity. The size of the former slit corresponds to a spatial resolution element of 0.5 by 2.5 arcmin and the latter to 4.0 by 5.0 arcmin. The detector has two linear arrays, a 48 pixel array with effective spectral wavelength resolution elements of 0.025 nm, which are used for profile measurements, and a 42 pixel array with 0.2 nm elements for measuring integrated intensities. The detector has a CsI photocathode, a MgF_2 window and a 2 l s^{-1} ion pump.

The telescope mirror for the O VI channel is similar to that for Ly-alpha except it has an irridium coating. The spectrometer has a spherical diffraction grating on a Rowland circle mount and a detector system which includes a rectangular aperture that acts as the spectrometer exit slit, and two channel electron multipliers (CEM's) which detect the light from each of the two O VI lines. The CEMs are housed in a vacuum canister with a vacuum door, and there is a 2 l s^{-1} ion pump. The CEMs are coated with KBr. The entrance slit for O VI corresponds to a spatial resolution element of 2.5 by 5.0 arcmin. For observations

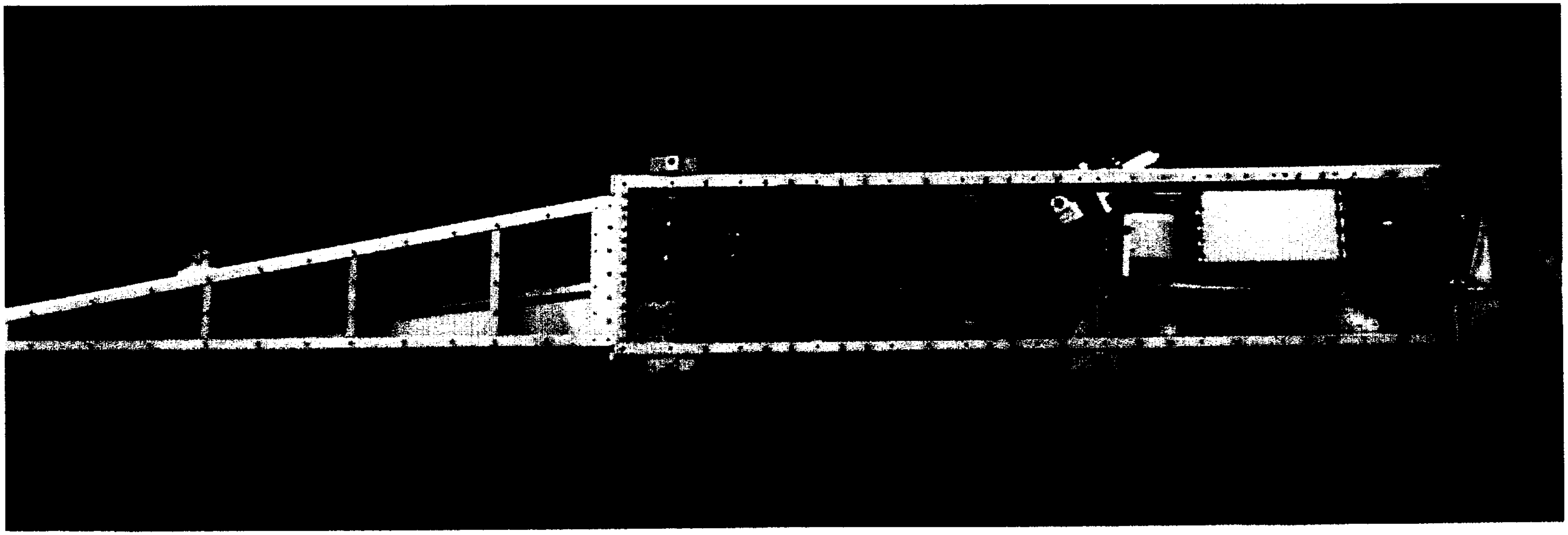

Figure 5: The Ultraviolet Coronal Spectrometer for Spartan 201 shown here with the original external occulter support structure. Direct sunlight from the solar disk enters the instrument through the entrance aperture (extreme left) and passes through baffles and into the sunlight trap (far right) where it is discarded. Coronal light passes through the entrance aperture and onto the telescope mirrors located inside the main structure and slightly above the sunlight trap. The mirrors focus images of the corona onto the entrance slits of the dual spectrometer. The light passes through the entrance slit baffle (narrow tube) on its way to the entrance slits. The OVI grating is in the covered portion of the spectrometer case. The Ebert mirror is located at the extreme left end of the spectrometer case. The O VI detector can be seen protruding through the upper wall of the main structure and the detector for H I Ly-alpha is just below the O VI detector between the spectrometer structure and the Ly-alpha detector electronics box. The plane diffraction grating for the Ly-alpha spectrometer channel is located at the extreme right end of the spectrometer case between the entrance slit and the H I Ly-alpha detector.

of the solar disk, a mechanism inserts a pinhole of about 0.01mm diameter in front of the Ly-alpha profile slit and another in front of the O VI slit.

At any instant of time, the instrument observes three spatial elements corresponding to the three entrance slits. The telescope mirrors can be rotated to scan the slits parallel to a radial line that passes through the field-of-view. Heliocentric heights between 1.5 and 3.5 $R_\odot$ can be selected. The spacecraft can be offset pointed to allow occulted observations down to 1.39 $R_\odot$, and unocculted observations of the solar disk. The spacecraft is rotated to place the field-of-view at the desired position angle.

In 1982, the scientific and technical requirements for converting the rocket UV Coronagraph to a Spartan payload were established and the conceptual design for the modifications, new assemblies and electronics system were completed. In 1983, the engineering analysis and design of the flight mechanical/optical assemblies and the design of a new electronics system were completed, with the exception of some areas related to the OVI detector subsystem. The FORTH programming language was chosen for use in the selected RCA 1802 controller. Designs of the structural, electrical and thermal interfaces with the Spartan Carrier were developed. The interfaces with the Spartan Attitude Control System and the Data Handling and Power Distribution interfaces were initiated.

In 1984, the detailed design of the flight mechanical/optical assemblies and of the electronics system were completed. The discrete anode microchannel array detector for HI Ly-alpha was received and partially tested. The design of the ground support electronics (GSE) was completed. Definition of interfaces with the spacecraft continued to mature. In 1985, the fabrication of essentially all mechanical and optical components was completed. The evaluation and testing of the Ly-alpha detector continued and an SAO program was initiated to build a detector for the O VI spectral lines. The fabrication and much of the testing of the flight electronics and GSE were completed. The coding of most of the flight and GSE software was completed.

The instrument was delivered to GSFC in March 1986 where it was integrated with the WLC and the resulting joint payload was integrated with the Spartan Instrument Carrier. The Instrument Carrier was then integrated with the Spartan Service Module to form the Spartan 201 Spacecraft. Preliminary environmental and functional tests were carried out. Those tests were followed with a 6-hour performance test and a full flight duration 45-hour flight simulation. There was a preliminary thermal-balance test and a mass properties determination. The instrument was then returned to SAO where the OVI detector was being tested and evaluated and a new Ly-alpha detector was procured to replace one that had unacceptable gain loses. By March 1987, several mechanical and minor electronic changes were made and a serrated edge external occulter replaced the knife edge occulter. The testing of the detectors was completed, and they were installed into the instrument. The high voltage power supply for the vac-ion pumps failed and a considerable effort was made to obtain a suitable unit. Several changes were made to the flight software. New telescope mirrors were installed in the instrument to replace those with degraded reflectance.

The instrument was shipped to GSFC and re-integrated with the WLC and the Service Module. A full spacecraft integration and test program was completed in May 1989. During the next year, a major activity was the preparation of the laboratory for the UVCS/Spartan calibration, the installation of the instrument into the calibration vacuum system and functional tests in vacuum were carried out. The functional tests included an end to end light stimulation test. Also during this time period, software was produced for the GSE, for analysis of the Spartan data tapes, for the analysis of calibration data, and for review of the data from the spacecraft integration and test activity.

In the 1990/1991 time frame, the primary tasks were the following: 1) successful procurement and testing of flight vac-ion pump power supplies and a back-up Ly-alpha detector, 2) procurement, component characterization and change out of all grating and telescope mirrors, 3) characterization of the detectors, 5) radiometric and wavelength calibration, 6) coding of instrument observing sequences and preparation of instrument controller PROMs, 7) preparation of the observation program command sequence and delivery to GSFC, and 8) integration and test of the UVCS/Spartan, WLC and the Spartan Instrument Carrier and Service Module.

In December 1992, the Spartan 201 spacecraft was shipped to Kennedy Space Center for testing and integration with the orbiter Discovery. This activity led to its successful deployment on 11 April 1993 during the STS 56 mission, and to a series of successful reflights.

4.0 SPARTAN INSTRUMENT PERFORMANCE AND CALIBRATION ACTIVITIES

4.1 Flight Performance:

UVCS/Spartan performed extremely well for each of its deployed shuttle missions. All flight systems – optical, mechanical, electrical and software – were extremely reliable throughout the five missions. The flight optics and occulting system maintained their critical alignments which is especially important for achieving an acceptable stray light rejection level for the unwanted disk radiation. The instrument mechanisms including the mirror-occulter mechanism, disk mask mechanism, and Oxygen VI door mechanism worked flawlessly. The Ly-alpha detector and OVI detector worked as planned recording hundreds of Ly-alpha profiles and OVI intensity measurements, respectively. Also, the UVCS flight software worked as expected with essentially no changes to the original software except for the planned updates of the flight observations that were tailored for the mission objectives of each flight.

There were only two hardware failures neither of which had any effect on the science data collected. The first failure, which occurred during ground testing just prior to the Spartan 201-2 flight, concerned the miniature vac-ion pump on the OVI detector subsystem. The vacuum pump is needed for operation on the ground but experience after the first Spartan 201 flight showed that the pump could be turned off after sufficient time was allowed for outgassing on-orbit (usually after two orbits of Spartan free-flight). Thus the impact of not operating the pump was minimal. The pump was repaired before the next Spartan 201 mission. The second hardware failure was a minor intermittent problem with one of the detector accumulator boards that was discovered after the Spartan 201-3 mission. Occasionally the board would produce a null signal on every sixth pixel of the Ly-alpha array detector. The faulty board did not affect any of the science data from the mission and was replaced by a spare board before the next flight.

The only optical changeouts for the entire series of flights were for the two telescope primary mirrors. The mirrors are coated with Al+MgF_2 (for Ly-alpha) and iridium (for OVI) to give a high uv reflectance at their primary wavelengths, 121.6 nm and 103.2 nm, respectively. After the Spartan 201-3 flight, both mirrors showed a minor degradation when they were measured. It is not clear if the change occurred during flight or afterwards but nonetheless the full system calibration measurements made for all five flights were essentially unchanged within the uncertainties of the measurements (±20 %). (See the discussion in section 3.2 on the calibration results.) Both mirrors were replaced with a pair of freshly coated telescope mirrors in early 1997 before the preflight integration activities for Spartan 201-4.

Both the Ly-alpha and OVI detectors worked extremely well during the four successfully deployed flights. [1] The Ly-alpha detector consists of two linear arrays of anodes behind a C-plate microchannel array; each of the 90 anodes have their own preamplifier/discriminator electronics for signal output. The OVI detector uses two channel electron multipliers (CEMs) with special conical cathodes shaped to capture the total light from the OVI 103.2 and 103.7 nm coronal lines.

Detector background levels were acceptable for all of the Ly-alpha observations. Background signals were typically four times higher than laboratory measured backgrounds but were still at least two orders of magnitude smaller than the faintest coronal signals. The OVI detector backgrounds had variations that could be due to the fact that the OVI coronal line profiles were much wider than expected and were not always entirely within the CEM spectral passbands. These data are still being analyzed.

4.2 Instrument Calibration Activities:

The Spartan concept was originally based on the idea of flying payloads with multiple reflights. This proved extremely valuable by allowing detailed laboratory calibrations of the UVCS/Spartan instrument to be made between each mission. This ability to update the instrument calibration enhanced the value of doing a Spartan-SOHO cross calibration mission for the Spartan 201-5 flight.

The radiometric and spectral characteristics of the UVCS/Spartan are measured as part of these calibration activities. Because of the short interval between the Spartan flights, the postflight calibration from one flight would sometimes serve as the preflight calibration for the next mission. The primary goal of these tests is to establish the definitive values to be used for converting the acquired observational data to absolute intensities and line widths that can be used to test or to develop physical models of the corona. Figure 6 shows a plot of the system efficiency for the Ly-alpha intensity path for all five Spartan 201 flights. The solid boxes show the efficiency measurements obtained with the original mirror used for the first flight and the open boxes show the measurements with the replacement mirror. Note that the system efficiency is the product of the spectrometer efficiency (including the area and solid angle of the entrance slit) and the telescope mirror reflectance. The larger error bars for the efficiency measurement before the Spartan 201-4 flight are due to the uncertainty in the reflectance of the mirror. The postflight calibration with its smaller uncertainties is being used for the 201-5 data.

Four internal UVCS calibration reports on the results from the first three Spartan 201 flights have been prepared. The reports describe component and system level radiometric efficiency measurements and also measurements for the telescope vignetting function, detector flat fields, cross-talk characteristics, and dark count rates. The instrument profile function for the Ly-alpha spectrometer channel was also carefully determined. A final report on the Spartan 201-5 postflight calibration activities is in preparation. The major parts of that report will be published in an archival journal.

[1] The Spartan 201 spacecraft, including the UVCS, was not activated during the Spartan 201-4 (STS-87) mission.

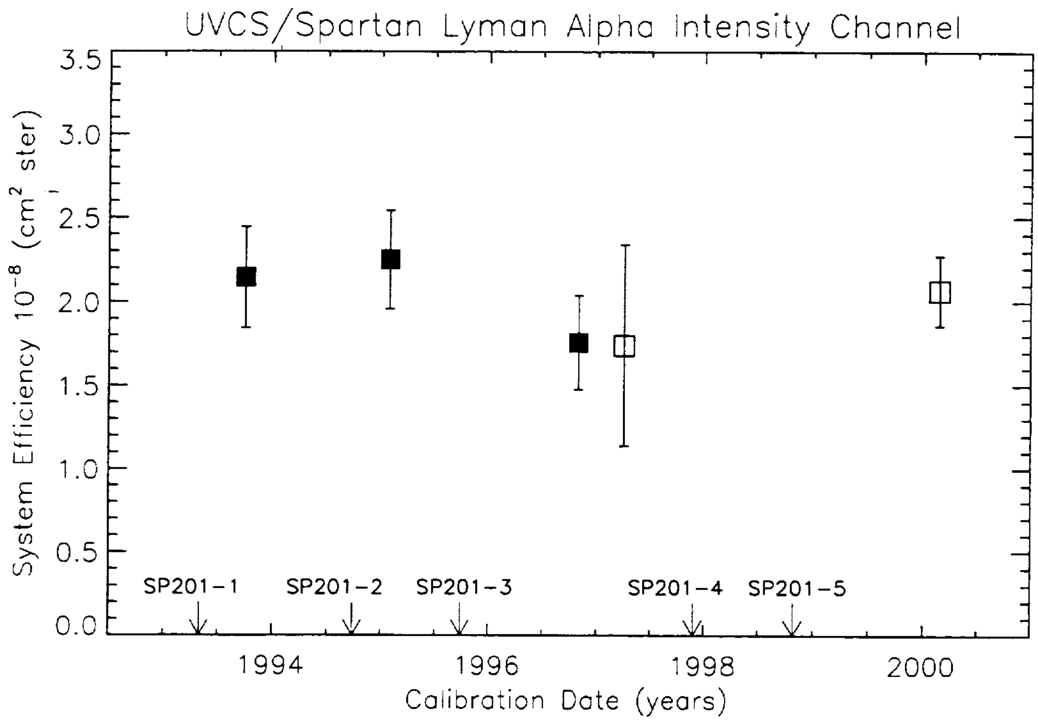

Figure 6: System efficiency measurements for the Ly-alpha intensity path with solid (open) boxes used for measurements with the original (replacement) telescope mirror. Error bars of $\pm 1\sigma$ are reported for each point. Arrows across the bottom of the plot show the times for each Spartan 201 mission.

5.0 DATA PROCESSING, ARCHIVING, AND ACCESS POLICY

Each of the four deployed missions returned approximately 450 Megabytes of raw UVCS science and housekeeping data, totaling almost 2 Gigabytes. The raw data tapes were preprocessed at NASA/Goddard before they were shipped to SAO where they were read using UVCS/Spartan data reduction software to obtain specific science and housekeeping data. Higher level data reduction programs were then used to perform tasks such as correcting the data for backgrounds, flat fielding the data, removal of cross-talk, and correcting for the geocorona contribution. Additional programs were used for fitting line profiles and calculating profile statistics.

Data from all Spartan flights are currently stored on a dedicated hard disk which is backed up routinely each day by the SAO Computation Facility. This disk has primarily higher-level processed data (both calibrated and uncalibrated) that are useful for further scientific analyses. Backup copies of the original NASA tapes have been made on 4mm data cartridges (2GB Capacity) with one original and one backup cartridge made for each of the first three flights. However the data from the last flight was delivered on a CD-ROM which is a more preferable storage medium. Plans are underway to create CD-ROMs for the raw flight data from the first three missions as well since this storage medium is easier to use.

Spartan data processing and analysis software for reducing the data reside on the same machine that currently has the processed flight data from all Spartan 201 flights. Preliminary discussions are underway to place these data in an archive at SAO to be maintained indefinitely together with data from other SAO space experiments.

Although no formal data access policy exists for the Spartan 201 missions, it is the desire of the PI to make the UVCS/Spartan results available to all interested researchers.

6.0 TECHNICAL INNOVATIONS

The UVCS instrument and Spartan carrier provided a very cost-effective approach for achieving the science objectives for the mission while laying the groundwork for the next generation solar missions. UVCS/Spartan performed its mission flawlessly despite the fact that by the time of the Spartan 201-5 (STS-95) mission, some of the original components used in the UVCS were more than 20 years old. Besides the proof of concept for reflyable instrumentation, there were other innovations in space flight technology that are mentioned briefly below.

One example of a technology benefit derived from the Spartan missions concerned the use of an innovative vacuum door mechanism for the OVI detection system. UVCS proved that a potassium bromide (KBr) detector coating could survive for over 18 years and several short duration missions and keep its original detector quantum efficiency if the detector is kept in a high vacuum system with a window that could be opened in orbit. The high quantum efficiency was maintained for so long because of a highly reliable door mechanism that could be opened and closed in flight thereby keeping moisture and air from contaminating the detector when it is on the ground in one atmosphere. The door mechanism proved to be so reliable that a similar door mechanism design is being planned for future missions. Attached to the OVI detection vacuum chamber was a miniature vac-ion pump. The experience of running a vac-ion pump that was continuously operated during preflight testing, shuttle launch operations, on-orbit activities, and landings was a technical innovation.

The Spartan 201 team developed procedures to ensure that the required vacuum conditions were met for the UVCS instrument during the relatively short duration orbital flight. A vacuum compatible Instrument Carrier was designed for this purpose. It was pre-evaluated on the ground to a specified leak-up rate requirement. A special "bay vent door" allowed for additional evacuation of the Instrument Carrier while Spartan was in the shuttle cargo bay prior to deployment. This procedure shortened the amount of time required for instrument outgassing and therefore increased the time devoted to scientific observations.

The manufacture of the UVCS spectrometer case was another first for a small satellite scientific instrument. The entire UVCS spectrometer case was machined from a single slab of Super Invar to provide mechanical stability for the mission. In order to achieve the thermal requirements, a new heat treatment process was used that consisted of carefully controlled annealing with periods of heat treatment and cooling between machinings. The final temperature stabilized structure was machined to tolerances of 25 micrometers (5 micrometers for critical surfaces) and nickel-plated.

UVCS/Spartan was one of the first space missions to have a flight software system written entirely in the FORTH programming language. FORTH is a highly flexible language which allows the user to build more complex commands from a relatively few low level system commands. This choice of software language proved to be extremely useful for rapid development of customized software. A major advantage of FORTH is that it can be used to control instrument mechanisms without timing conflicts for sending and receiving commands.

The procedure for selecting observation roll angles just before release of Spartan 201 for its autonomous 45-hour mission was another new technique that originated with the Spartan 201 program. The solar corona is a dynamic, constantly changing environment that requires flexibility in planning for the selection of desired targets to observe. The procedure to select target angles about the Sun required the use of the shuttle's remote manipulator system to fix the initial Spartan orientation with regard to the orbiter. The initial orientation of the orbiter and three Spartan spacecraft roll adjustment parameters that were placed into the observing program by a shuttle crew member allowed selection of four coronal targets. The four roll parameters were selected by Spartan science team members on the ground $\sim$ 12 hours before deployment after the latest coronal images from ground-based and other space-based instruments were examined. In this way the preprogrammed observation procedures could be optimized for specific types of coronal targets.

A final example of an innovation used for Spartan 201, which was extremely beneficial to later flight programs, was the procedures used to co-register the fields-of-view for the two independent coronagraphs on Spartan (UVCS and WLC). The White Light Coronagraph 2D field of view provided spatial context images and electron densities for the UVCS observations. The procedures developed allowed UVCS and WLC coregistrations to be known to an uncertainty of better than 22 arcsec which is the width of the WLC detector pixels.

7.0 EDUCATION AND PUBLIC OUTREACH ACTIVITIES

While a formal Education and Public Outreach Program (EPO) was not a required component for this NASA grant, UVCS/Spartan scientists were involved in a number of outreach activities including: the participation in a NASA Space Science Update, providing answers to questions sent to an expert "Ask the Astronomer" Web site, maintaining a UVCS/Spartan Web site, and presenting talks on solar physics subjects to K-12 students and college undergraduates.

UVCS/Spartan and UVCS/SOHO scientists appeared on a NASA Space Science Update (SSU) held on 8 July 1999 to describe to the general public the results from a paper on the ion-cyclotron resonance heating of the corona (Cranmer, Field, and Kohl, Ap.J. 518, 973, 1999). The story, which was called "Surfing the Solar Wind," described a major advance in solving the mystery about how the solar wind is accelerated. Although the analysis involved primarily UVCS/SOHO data, the STS-95/Spartan 201-5 mission provided the confirmation that the outflow speeds of the protons are less than those of the oxygen ions. The event was broadcast live on NASA TV with widespread coverage by the mass media, including TV networks, radio programs, and newspapers. A multimedia Web page about the SSU was created in conjunction with this event. The site contains video clips and images from the SSU, background information on source papers, and links to solar related EPO Web sites.

UVCS/Spartan scientists participated in a NASA sponsored CU-SeeMe Internet video conference during the SP201-3 mission. Space science related questions from student classrooms all over the country were answered in a live broadcast using this Internet video technology. In association with this event, NASA Goddard set up an "Ask the Astronomer" Web site which could be used by anyone from around the world to ask space science questions. Leonard Strachan was one of the people responsible for supplying the answers to these questions. He has answered hundreds of questions from the site which is now linked to other "Ask the Expert" sites on the Internet. As of August 2000, the original page had almost 20,000 hits with an unknown number of additional inquiries coming from other Internet expert sites.

The UVCS/Spartan program also maintains its own Web site which provides information and current events about the program. The site explains the UVCS/Spartan science goals and capabilities, describes the UVCS instrument, and provides information on the solar coronal targets selected for observation during each mission. An updated section included a picture gallery of highlights from past missions, a planning page using mosaics of disk and coronal images from the SOHO spacecraft, and links to other related Web sites. The site proved popular during the Spartan mission operations because it allowed interested parties to follow where on the Sun the observations were being made.

Perhaps the most significant opportunities for public outreach occurred during the Spartan 201-5 (STS-95) mission with astronaut John Glenn. The PI John Kohl and Glenn are both alumni of Muskingum College in Ohio. This connection brought much attention to the UVCS/Spartan program. Kohl gave a live interview on HDTV (high definition television) to selected audiences around the country during the day of the launch. Also, Dr. Kohl was afforded several opportunities to give talks to students and faculty at Muskingum College. One result of these meetings was to establish a program where undergraduates can spend time at SAO working on research projects in space science. The students work directly with scientists involved in laboratory work, data analysis, or theoretical modeling. In addition to the Muskingum activities, there were several informal talks about the Spartan program given to student audiences from grade school level to pre-college level.

Other activities related to public outreach include the NASA TV presentations given by UVCS/Spartan scientists during each of the Spartan shuttle missions. The public broadcasts were aimed at informing the press and general public about the science objectives, instrument description, and mission status for each of the Spartan flights. Many of these events and follow-up stories were covered by television, radio, and newspaper organizations.

8.0 PUBLICATIONS AND PRESENTATIONS

8.1 Refereed and Conference Publications

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8.2 Primary Invited Talks

1. *The Ultraviolet Light Coronagraph – A New Spectroscopic Tool for Studying the Solar System*, Kohl, J. L., presented at Harvard-Smithsonian Center for Astrophysics, 1982.

2. *Future Observations of Solar Wind Origin*, Kohl, J. L., at the Solar Wind V Conference, Woodstock, Vermont, 1982.

3. *Spectroscopic Constraints on Solar Wind Models,* Kohl, J. L., at the Arcetri Observatory Colloquium, Italy, 1983.

4. *Probing the Solar Wind Acceleration Region*, at the Naval Research Laboratory, Washington, DC, February, 1983

5. *Observations Related to Waves in the Solar Wind Acceleration Region,* Withbroe, G. L., at the Solar Terrestrial Physics Workshop, Berkeley Springs, W. Virginia, June 1983.

6. *Spectroscopic Measurements of Solar Wind Acceleration,* Kohl, J. L., at the Center for Earth & Planetary Physics Colloquium, Harvard University, 1983.

7. *Solar Wind and Coronal Structure,* Withbroe, G. L., at the National Academy of Sciences – European Science Foundation Workshop on Solar System Space Physics, S. Carolina, September 1983.

8. *Evidence for Supersonic Wind Velocities at 2.1 Solar Radii,* Kohl, J. L., Munro, R. H., Weiser, H., Withbroe, G. L. and Zapata, C. A., at the AAS/Solar Physics Division Meeting, Baltimore, Maryland, June 1984.

9. *The Solar Wind Generation Experiment for the Spartan 2 Mission,* Kohl, J.L., Weiser, H., Withbroe, G.L. and Munro, R.H., at the International colloquium on EUV and X-ray Spectroscopy of Astrophysical and Laboratory Plasmas, IAU Colloquium No. 86, Washington, DC, August 1984.

10. *Ultraviolet Coronal Spectroscopy from POF*, Kohl, J. L., at the Conference on Soft X-rays, XUV, and EUV Observations of the Solar Atmosphere with the Advanced Solar Observatory, Carmel, CA, January 1985.

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21. *Measurement and Interpretation of HI Lyman-alpha Profiles from the South Polar Hole Observed During Spartan Mission 201-1*, Strachan, L., L.D. Gardner, and J.L. Kohl, at the AGU Fall Meeting, San Francisco, December 1994.

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24. *Kinetic Temperatures and LOS Velocity Distributions in Polar Coronal Holes from UVCS/Spartan Observations*, Gardner, L.D., et al., at the AGU Spring Meeting, Baltimore, MD, 1996.

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