STUDIES OF THE CORONA WITH THE SOLAR MAXIMUM MISSION
CORONAGRAPH/POLARIMETER

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ABSTRACT

The visible wavelength Coronagraph/Polarimeter on the Solar Maximum Mission (SMM) spacecraft is providing data on the flare processes manifested by coronal transients and on the degree of disruption of the evolutionary corona at the present epoch of the solar activity cycle. Among our first results are the discovery of frequent Hα emission from remnants of eruptive prominences in the outer corona and first observations of Fe xiv line emission to 3.2 R⊙. In the early stages of transients, cavities less dense than the ambient corona are occasionally found trailing the transient loops, with the loops being relatively thick and structureless. Some 22 transients have been identified in the initial survey of 52 days of observations; from this sample our preliminary conclusion is that transients during the SMM era (near solar maximum) occur over a wider range of latitude than, but with about the same range of speeds as, transients during the Skylab era (near solar minimum).

Subject headings: Sun: activity — Sun: corona — Sun: flares

I. INTRODUCTION

The High Altitude Observatory's (HAO's) Coronagraph/Polarimeter (C/P) on board the Solar Maximum Mission satellite is operating successfully, and preliminary data already appear to provide new insights into coronal physics, particularly into the development of transients and ejecta associated with solar activity. The unique features of this instrument, distinguishing it from previously flown or existing space coronagraphs, are manyfold, including (1) multicolor photometry/polarimetry including the isolation of Hα and the 5303 Å line of Fe xiv, (2) an optical design permitting the inner field of view to be as low as 1.51 R⊙, (3) the ability to change observational sequences as a result of on-board flare alarms or prompted alerts based upon information of eruptive prominences and/or radio events, and (4) extensive data coverage provided by 200–250 images per day. With these special capabilities, the major observational goals of the instrument include studies of coronal transients and ejecta associated with flares and other activity, study of the long-term evolution of the corona at solar maximum, mapping the direction of coronal magnetic fields from the emission-line polarization data taken with the 5303 Å filter, and better discrimination between the F (dust) and K (electron) coronal contributions.

In addressing these problems, we note that from Skylab observations it became evident that a major proportion of the energy released in flares appeared in transient disturbances in coronal density and magnetic field structure. Typically, a coronal transient of the Skylab era ejected $5 \times 10^{45}$ g at 470 km s$^{-1}$ (Rust et al. 1980), requiring an energy input perhaps an order of magnitude greater than the radiative output (Canfield et al. 1980; Webb et al. 1980) of a flare. The high frequency of such coronal transients, even at solar minimum (Hildner et al. 1976), and also their association with apparently less-energetic eruptive prominences (Munro et al. 1979) were important discoveries resulting from the orbiting Skylab coronagraph.

Obvious questions remain, however. We can now ask in more detail, What is the response of the coronal density and magnetic field structure to the passage of transients? Does the corona near sunspot maximum evolve primarily by discrete changes due to the occurrence of transients? How does one construct a valid model of the corona and solar wind if the coronal forms are routinely disrupted? A second major problem area concerns the physics of transients themselves, the physical mechanisms and forces by which they are initiated and propelled through the corona, and their role in the generation of radio sources.

In seeking to achieve the goals of the experiment, and thus, we hope, contributing to the unraveling of these and other problems in coronal and flare physics, the C/P is but one instrument in an international association of four ground-based coronographs and three radioheliographs. These instruments have overlapping fields of view in the low and intermediate corona to generate complementary data sets. Including the other SMM experiments, a formidable complement of instru-
ments is available for the study of flare physics and the active corona.

This Letter reports some highlights of the first months of orbital operation of the C/P. The data currently being acquired and the new results (some of which are presented here in preliminary fashion) arising from the continuing analysis of this data, demonstrate that the technical design goals of the C/P have been met.

II. THE EXPERIMENT

The HAO C/P is an externally occulted coronagraph and linear polarimeter with a meshless SEC vidicon as a detector (for a full description see MacQueen et al. 1980).

To give maximum spatial overlap with ground-based coronagraphs and metric radio telescopes, a doublet objective lens is used with system vignetting designed for observations as low as 1.51 \( R_\odot \) (from Sun center). The trade-off for this performance for the inner corona is a somewhat increased stray light level, about 6 \( \times 10^{-10} \) \( B_\odot \) in the outer corona.

Spatial resolution in the outer corona is 10" set by the vidicon pixel size. Good images of the K (electron) plus F (dust) coronal emission (in the green filter, 5014–5328 Å) are obtained with exposures of 8 s duration. A complete Polaroid sequence requires 7 minutes. A mirror can be inserted into the optical path to allow the vidicon to view a diffuse illuminated on its back side by the solar disk, thus providing data for photometric calibrations. It should be noted that currently some data are photometrically and geometrically degraded by a poorly understood, intermittent failure in blanking of the vidicon read beam.

Under normal operation, the C/P collects data at a nominal rate of about 200–250 images per day. A small fraction of the images are available for quick-look inspection within 8 hr of their recording. The remaining data are photometrically calibrated, geometrically rectified, and transferred to gray scale image format in the HAO/NCAR computing system.

An extensive network of collaborations has been established with ground-based observatories. Reports of flares, eruptive prominences, and radio bursts are phoned or telexed to the C/P scientific team at the Experiment Operations Facility of Goddard Space Flight Center. If the \textit{SMM}'s on-board flare alarm has not already detected the event, a command is “uplinked” to initiate a response and obtain data on the event. Flare observations by ground command have not already detected the event, a command is “uplinked” to initiate a response and obtain data on the event. Flare observations by ground command have been initiated in an interval as short as 3 minutes, depending on the availability of passes over ground stations. The 24 hr C/P observing program is tailored to take advantage of the best observing hours at the cooperating observatories.

An important goal of the C/P is to determine if the corona, at the maximum of the solar cycle, smoothly evolves or is instead changed by frequent restructuring due to solar activity. A synoptic density record (in the green continuum filter with Polaroids) of all four quadrants of the corona is obtained every 6 hr. Every 12 hr, the green line emission is recorded on the east and west limbs. Coronal transients and coronal holes may perhaps affect the K corona in a different fashion than the F corona. To investigate such a possibility, every 24 hr the blue and red filters are used with the green to record continuum intensity. Unanticipated coronal activity, either originating behind the limb or otherwise unobserved by \textit{SMM} or ground-based telescopes, is occasionally detected in routine C/P patrol modes. These consist of a green continuum (with Polaroids) observation of each quadrant, usually obtained once per orbit, and repeated sequences of green polarization plus H\( \alpha \) (without Polaroids) performed on one quadrant selected for the day.

III. OBSERVATIONS

\textit{Outer corona green line emissions}.—One of the major objectives of the C/P is to determine the direction of coronal magnetic fields from measurements of the polarization in the forbidden emission line of Fe \textit{xiv} at 5303 Å. Numerous ground-based measurements of this green line radiance and polarization have been made in the past, and some are now being made on a continuing basis (House 1977). Earlier polarization measurements were made, typically, at heights of \( \leq 1.5 \) \( R_\odot \) (from Sun center), with intensity data extending to 1.7 \( R_\odot \) in a few cases. With vidicon integration times of about 300 s, the C/P records green line structure in the quiescent corona above 1.51 \( R_\odot \).

Green line observations have begun only recently, but some preliminary results may be offered. Green line emission is visible above the occulting disk at some position angles every day. Generally, the emission shows definite structure such as a single arch, rays (arches edge-on?), or well-delineated condensations as high as 2.5 \( R_\odot \). These emission line structures are only faintly, or not at all, seen in continuum (Thomson scattered) light, implying that 5303 Å visibility is not a simple density effect at this height, but special conditions of temperature and input energy flux are necessary. The brightest 5303 Å emission seen to date had an equivalent width of about \( \omega = 5.4 \) Å, referenced to the continuum K + F radiance at 2 \( R_\odot \). The radial gradient of the green line coronal radiance (proportional to \( n_e^2 \)) is generally steeper than that of the K corona radiance (proportional to \( n_e \)). When Polaroids are inserted into the beam, the normal 300 s green line exposure must be increased by a factor of 2.25. Thus, in the 56 minutes of usable daylight per orbit, one three-Polaroid sequence plus a clear exposure can be obtained. The data indicate that the line emission is polarized in a different direction than in the continuum corona, as should be the case because the magnetic field direction governs the green line polarization.

The tilt of the narrow-band interference filter used to isolate 5303 Å may be varied to shift the passband center wavelength. One intriguing data set was obtained 1980 April 6, with five exposures which effectively scanned through about 3 Å. The appearance of a prominent green line arch extending to 3.5 \( R_\odot \) changed dramatically during this scan. Either a green line transient (DeMastus, Wagner, and Robinson 1973)
was in progress, or motions of $>200 \text{ km s}^{-1}$ existed in the legs of the arch giving rise to Doppler shifts. An analysis of these data is in progress while similar, additional cases are sought.

Prominence remnants in the corona.—A new feature of the C/P over previous orbiting coronagraphs is its Hα filter of 42 Å bandwidth which allows the line emission from neutral hydrogen to be distinguished from coronal continuum. Observations with the Hα filter should give information on the rate of prominence heating during eruption, with corresponding implications on the thermal conductivity and/or insulation effective in the region surrounding the prominence.

We discuss briefly observations made on 1980 May 5; these conclusions seem also to apply to generically similar eruptive prominence events with transients on April 15 and May 5. At 0411 UT on May 5, a coronal loop transient was observed at $2 R_\odot$, position angle 300°. In subsequent exposures (Fig. 1 [Pl. L5]) taken through the green continuum and the Hα filters, an eruptive prominence is seen centered within the coronal transient. No Hα disk flare or 1–8 Å X-ray radio event was reported. The Hα-emitting material in the event was undoubtedly from a filament previously seen to lie along a north-south neutral line. The loop transient moved (in projection) somewhat nonradially southward at speeds up to 700 km s$^{-1}$. The prominence has interesting detail. The bright knots looked like beads strung on a helix, and their positions in subsequent images suggest helical motions. The denser, bright, Hα-emitting knots are embedded in nebulus, wispy-appearing patches of Thomson-scattered radiance. In addition, from the sequence of frames, the prominence material appears to be untwisting.

This event permitted the first direct observation of Hα-emitting material out to $3.7 R_\odot$. The Hα equivalent width at 1153 UT is at least 110 Å of the continuum background (K + F). This is much less (by at least a factor of 100) than the radiance predicted allowing for geometrical expansion of Hα clumps in the lower corona, or extrapolated from radiance gradients reported by ground-based observatories for eruptive prominences. Nevertheless, it is significant that any cool material at these heights should remain, sufficiently insulated from coronal temperatures for more than 1 hr. To date, no images have shown noticeable Hα emission in the outer loops of coronal transients. Thus the C/P observations now confirm previous suggestions (Hildner et al. 1976; Schmahl and Hildner 1977; Poland and Munro 1974) that the source of material in loop transients is not the cool prominence.

In a very similar event the next day (1980 May 6), another portion of prominence along the same neutral line erupted and was accompanied by another coronal transient. The prominence eruption was observed with the Ultraviolet Spectrometer and Polarimeter (UVSP) on the SMM. In C iv 1548 Å spectroheliograms (Tandberg-Hanssen et al. 1981, especially Plate L9 in this issue) the northern closed loops are seen to straighten and become radial. The erupting prominence seen by the C/P at $2.5 R_\odot$ gives the impression that this event may be due to the northern portion of the UVSP event.

Coronal transient voids.—The C/P was designed to permit viewing the corona at lower heights than those imaged with other orbiting coronagraphs. One of the more interesting studies being pursued is of the behavior of coronal transients between the C/P's inner field limit of $1.51 R_\odot$ and about $3 R_\odot$. In four transients associated with eruptive prominences, the bright loops of increased density have been trailed outward by darker regions, which in turn are ahead of and surrounding the Hα-emitting material, if any. These “voids” in the brightness distributions apparently are regions where the densities are lower than they were before the transient. Examples of such voids are shown in Figures 2 and 3 (Plates L6–L7) for 1980 March 31, April 15, May 5, and May 6 events. The voids have the appearance of typical prominence cavities seen at quiescent prominences seen at eclipse, except that the void systems themselves are also “erupting,” i.e., moving faster than the prominence. It should be emphasized, also, that these voids are being observed at heights $>2 R_\odot$. Accurate polarimetry of these cavities should provide information on their extent along the line of sight, i.e., perpendicular to the plane of the sky.

These voids might be due to the expansion of ambient coronal magnetic fields, producing rarefactions of the frozen-in plasma. No clear evidence yet exists for these voids in flare-associated transients. Although we have drawn an analogy between transient voids and prominence cavities, the analogy is not perfect, as shown by the double concentric voids in Figure 2 recorded on March 31.

Transients at mid-coronal heights.—The C/P’s excellent stray light and vignetting properties near $1.51 R_\odot$ permit new observations of the early expansion of classical coronal loop transients. Virtually all loop transients recorded so far by the C/P below about $2.5 R_\odot$ have the appearance of diffuse featureless arches with constant radii of curvature. Further, the ratio of thickness to radius of curvature is large ($\sim 0.5$ for April 15). Examples of coronal transients just emerging from behind the occulting disk are shown in Figures 2 and 3. It is apparent from these examples (and especially when magnified displays of these events are inspected) that detail in other types of subjects, for example, prominence material seen in the continuum scattering, is resolvable by the telescope even relatively close to the occulting disks. Indeed, preflight measurements show resolution to be no worse than about 15” at $r/R_\odot = 2$. It is only in the interior of the loop, with its twisting and turbulent motions, or in the loop itself at about $R \geq 3 R_\odot$ that detail develops in the transient outer loop. Often, even as structure appears in the higher parts of the transient, the legs below $3 R_\odot$ remain diffuse and thick.

Average characteristics of transients.—A data set of approximately 1250 hr or 52 days has been scanned in a preliminary fashion, and 22 transients have been identified. Undoubtedly, some fainter events were overlooked. Speeds, available for six events, range from $\sim 200$ to $\sim 900 \text{ km s}^{-1}$, in line with transients observed...
Fig. 1.—A coronal loop transient and underlying eruptive prominence of 1980 May 5 seen in (a) at 1145 UT in continuum scattering and (b) at 1153 UT in Hα. Panel (c) is an enlargement of (b). The occulting disk has a radius of 1.51 \( R_\odot \) and solar north is at the upper left.

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Fig. 2.—Two examples of coronal transient voids. In (a) two concentric cavities surround an eruptive prominence remnant on 1980 March 31 at 1700 UT. A later stage of the event is shown in (b) at 1842 UT. In (c) (2132 UT) and (d) (2307 UT), a single void is shown within a transient on 1980 April 15, clearly less dense than the pre-event corona.

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Fig. 3.—Examples of coronal transient loops in the low corona. In (a), 1980 May 5 at 1047 UT, a relatively thick featureless loop is seen just above the occcluding disk. Later, (b) shows increased detail at 1151 UT. A full day later, 1980 May 6, a similar event occurred at (c) 1038 UT and (d) 1153 UT.

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The latitudinal extent of the individual early SMM ground corona appears to be less in red images than in spectral color differences for the outer versus the inner filters in blue (4465-4790 Å), green (5014-5328 Å), and blackwell et al. 1967), varying with radial distance in from Skylab. By measuring the position angles of a mastered by magnetic fields, while the ambient provides separate the F from the K coronal contributions in the corona is somewhat reddened in comparison with the in coronal color have been reported (see, for example, Canfield, R. C., et al. 1980, Solar Flares, ed. P. Sturrock (Boulder: Colorado Associated Universities Press), p. 451.

Besides the obvious use of this effect to provide more accurate K corona densities, it will be of great interest to look for possible contrast enhancements of the corona produced by a differential effect of transients upon these two coronal components, and for the influence of long-lived high-velocity streams rooted in coronal holes.

IV. CONCLUSIONS

Early orbital operations of the C/P have already provided a rich data set from which the following results may be inferred. Green line emission (5303 Å, due to Fe XIV) is generally visible on at least one solar limb every day, sometimes with equivalent widths of 5 Å or more. Quantitative analysis of green line images obtained through the Polaroid filters will permit the determination of the coronal magnetic field directions in the emitting structures.

Images obtained through the Ha filter show that sometimes remnants of eruptive prominences remain cool, retaining significant neutral hydrogen for an hour or more, even as they rise through the hot corona to 3.7 R☉. Nebulous Thomson-scattering material around these prominence remnants suggests that the cool knots are not perfectly insulated from the corona but are being heated and ionized gradually. Suggestions of helical motion of and within these prominence remnants are common. No Ha emission has been detected in the transient loops themselves, again suggesting a coronal origin for these structures.

In the initial stages of transients associated with eruptive prominences, dark voids are seen moving outward behind the denser fronts, together with the prominence itself. Apparently these voids are regions of lower than ambient density and may result from expanding fields sweeping out and rarefying the material. That the magnetic field is important—or dominant—in transients is demonstrated in the accompanying Letter by Wagner et al. (1981).

Most loop transients observed below 2.5 R☉ appear as featureless arches. Typically, the thickness of the arch is a large fraction of the radius of curvature at this height. As the loop rises, its thickness remains approximately constant, and the radius of curvature increases.

Transients observed with the C/P occur at higher latitudes and over a wider range of latitudes than those occurring near solar minimum, but are of about the same latitudinal width and speed.

Images obtained through filters suggest that the radiance contribution from the outer F (dust) corona is redder than the K (electron) coronal contribution.

The successful operation of the C/P has been the result of several years of intense work by many people. The effort of R. M. MacQueen, as the original Principal Investigator was most crucial for the success of the entire project. We acknowledge the excellent support efforts by the NASA SMM project team headed by P. Burr. The success of Coronagraph/Polarimeter also is due to the excellent work in construction by the Ball Aerospace Systems Division under the direction of Del Nelson. Special mention should be made of the intense efforts contributed to the C/P experiment by A. Csoeko-Poeckh, R. Lee, R. Reynolds, A. Stanger, and H. TePoe, of the High Altitude Observatory.

Earlier efforts of other team members, C. Ross and T. Blaschko, are also gratefully recognized. The entire team of coinvestigators has also contributed significantly to the success of this experiment. They include, in addition to one of the present authors (H. U. S.), G. Dulk, R. Fisher, R. Kopp, G. Pneuman, C. Querfeld, and K. Sheridan.

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