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THE OUTER SOLAR CORONA AS OBSERVED FROM *SKYLAB*: PRELIMINARY RESULTS

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ABSTRACT

The white-light coronagraph experiment has made frequent, periodic observations of the solar corona from 1.5 $R_\odot$ to 6.0 $R_\odot$ during the *Skylab* mission, and these observations will permit the determination of the three-dimensional extent of coronal forms. There are several time scales on which visual changes in coronal structures occur, ranging from approximately one-half rotation to less than hours. A number of events corresponding to the shortest time scale — coronal transients — cause major restructuring of the corona.

Subject headings: corona, solar — solar wind

I. INTRODUCTION

In other than the period of total solar eclipse, observations of the faint outer solar corona (above 1.5 $R_\odot$, measured from Sun center) present formidable difficulties. Successful observations require the quantitative detection of typical coronal radiances—10^{-7}–10^{-10} that of the mean solar disk—only arc minutes from the disk. In addition to the problem of minimizing stray photospheric light within the instrument, scattering by the telluric atmosphere effectively obscures the coronal radiance. Even high-altitude ground-based coronagraphs, employing polarization techniques to discriminate between coronal and telluric scattering, are restricted to observations of the corona close to the limb.

For coronagraphs carried above a substantial fraction of the Earth's atmosphere, only the instrumental stray light remains to obscure the faint coronal radiance. Rocket- and balloon-borne coronagraphs have successfully recorded the outer corona (Tousey 1965; Newkirk and Bohlin 1965), but only an instrument remaining above the atmosphere for an extended period can provide information to answer questions concerning the *evolution* of the outer corona.

Skylab, launched in 1973 May, contained the High Altitude Observatory White Light Coronagraph experiment as one of the six principal experiments on the Apollo Telescope Mount. This coronagraph permits, for the first time, satellite observations of the outer solar corona to within 1.5 $R_\odot$ and thus allows examination of the complex coronal structure close to the Sun where the magnetic fields can constrain the coronal material.

In this *Letter* we present preliminary conclusions which may be inferred following the return of the first coronagraph film from orbit, and particularly we draw attention to the varied time scales of observed coronal changes.

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II. INSTRUMENTATION

The f/13.7 coronagraph is externally occulted with three concentric disks shadowing the 3.2-cm diameter objective lens and an internal disk blocking the image of the external assembly (Newkirk and Bohlin 1963). The combined external and internal occultation provides an azimuthally symmetric radial vignetting at the film plane such that the effective transmission of the optical system varies across the field from 0.01 at 1.5 $R_\odot$ to 1.0 at 5 $R_\odot$. The vignetting thus acts effectively as a radially graded filter in suppressing the strong gradient of the coronal radiance, and exposure sequences of 3, 9, and 27 s are adequate to encompass the average coronal-radiance range on Eastman 026-02 emulsion. The instrument is capable of achieving slightly better than 8″ spatial resolution within its annular field of view of 1.5 $R_\odot$–6.0 $R_\odot$. Coronal images with a scale factor of 480″ mm^{-1} and images of a 19-step calibration wedge, encompassing a radiance range between 3×10^{-8} and 1×10^{-10} $B_\odot$ ($B_\odot$ is the radiance of the mean solar disk), are formed on the emulsion over the spectral band 3700–7000 Å in both unpolarized and linearly polarized light.

The stray light in the coronagraph arises principally from (*a*) diffraction from the external occulting disk and the periphery of the objective lens, and (*b*) scattering from the surfaces and interiors of the optical elements. The stray radiance originating in the *Skylab* instrument does not exceed $1\text{–}2 \times 10^{-10}$ $B_\odot$, except in the narrow region of diffracted light around the external disks near 1.5 $R_\odot$. The stray radiance is significantly lower than the sky brightness which occurs at a total solar eclipse observed from the ground (cf. Newkirk and Lacey 1970) and is comparable to the sky brightness during eclipse observed from an aircraft at 30,000 feet (9000-m) (Blackwell and Petford 1966). Thus, the coronagraph stray radiance is sufficiently low to permit a detailed study of coronal structure and form under the most favorable conditions yet achieved, limited only by the presence of the Fraunhofer coronal contribution (see § III).

III. RESULTS AND DISCUSSION

The coronagraph has obtained observations, both by astronaut and ground command, spaced periodically throughout the mission on a time center of approximately 6–8 hours. Programs of more frequent operation—to examine short term temporal variations and transient activity in the corona—have also been run at various times during the mission. In figure 1 (plate L2) we present sample photographs. The four photographs were obtained on 1973 May 28, June 1, June 5, and June 10 and are representative of the more than 4000 photographs obtained on the first camera load of the coronagraph. Several aspects of the photographs, both instrumental and coronal in origin, should be noted. In the center of each field, superposed upon the image of the occulting disks, is the calibration wedge; at the bottom is the out-of-focus shadow of the pylon supporting the occulting disks. Within the field of view diffraction rings appear around the periphery of the occulting disks, and there is a faint annulus of slightly different scattered-light intensity due to an internal instrumental shadowing effect (Lyot spot).

The background radiance present in the photographs (except that due to distinct coronal forms) has its origin in (*a*) electron-scattered photospheric light—the "background" K-corona; (*b*) dust-scattered photospheric light—the F-corona or zodiacal light; and (*c*) instrumentally scattered light. Equatorial scans of figure 1*b* (plate L2) indicate that at 5 $R_\odot$ there is present a background radiance of approximately 6.7×10^{-10} $B_\odot$. This value is somewhat lower than *model* K- plus F-coronal radiances of 8.86×10^{-10} (Allen 1963) or 1.12×10^{-9} (Blackwell, Dewhirst, and Ingham 1967) and *measured* radiances of 7.5×10^{-10} (Blackwell and Petford 1966) or 8.1×10^{-10} (Gillett, Stein, and Ney 1964). At present the origin of this disagreement is not known. (The actual separation of the electron, dust, and instrumentally scattered components requires the detailed reduction of the observations of linear polarization, which has not yet been attempted.)

Several results and areas of future study, apparent from these photographs and other initial coronagraph data, are summarized below. Each will be treated in detail in future publications.

a) The frequent, periodic observation of discrete structures in the outer corona where the total radiance (and hence electron density) is enhanced permits for the first time the determination of the three-dimensional extent of coronal forms. For example, figure 1*b* (plate L2) shows the presence of a well-defined structure visible at approximate solar latitude NE 25°. As evidenced by photographs made during the next 11 days, this structure is a part of a complex extending over nearly 180° of solar longitude and consisting of a low-lying (less than 2.5 $R_\odot$) arcade with several extended radial features which made successive limb passage. Deconvolution techniques employing linear polarization measurements will be required to determine the precise three-dimensional geometry of these extended features and the nature of the connection (if any) between them. Another feature, a long-lived helmet streamer, appears near southwest limb passage in figure 1*b*. This feature was identified prior to the *Skylab* mission from ground-based K-coronameter observations. As a result of its particularly stable nature over several rotations, this structure is especially well-suited for studies of its three-dimensional form.

b) The elapsed time period between the photographs shown in figure 1*a* and 1*d* is approximately one-half solar rotation. Over this period stable coronal structures initially present at one limb would have rotated onto the other limb. The rather significant changes noticeable in a comparison of the outer coronal structures suggest that substantial evolutionary changes have occurred, even during this period of near-minimum solar activity. One implication of this result is that caution must be exercised in the application of coronal modeling techniques requiring repeated limb passage of features, at least in the case of larger outer coronal forms.

c) An important result of this preliminary assessment is the identification of numerous visual changes in smaller coronal structures over time periods of hours. One example of the observed changes involves the gradual change of a diffuse ($\sim 1.4 \times 10^5$ km width at 3 $R_\odot$) ray structure to a more well-defined ($\sim 7 \times 10^4$ km width) form over an 11-hour period, with little apparent change in brightness. Whether such changes, in this example and others, are a result of dynamic rearrangements in the corona or perspective effects of particular coronal geometries (i.e., thin current sheets, etc.) will require detailed study.

d) A conventional model of coronal expansion (cf. Parker 1958) predicts that material will be accelerated through the field of view of the coronagraph in about two days. Frequent periodic observations during a two-day interval are well suited for the examination of the actual material acceleration between 1.5 $R_\odot$ and 6 $R_\odot$, if the flowing material contains density clumps. Visual examination of the photographs fail to show any such material flow; but final conclusions regarding the detection of the outflow should await quantitative reduction and study of the results.

e) In figure 1*c*, south of the prominent NE structure, there is a well-defined dark lane where the electron density is substantially reduced. Several such regions, which we call coronal "voids," have been observed, and have visual lifetimes ranging from hours to days. The mechanisms which form, maintain, and end these voids are unknown. Possibly, the voids are due to a dynamic rearrangement of coronal structures which sweep up electrons, or to a fundamental lack of homogeneity of the outer background corona, or a substan-

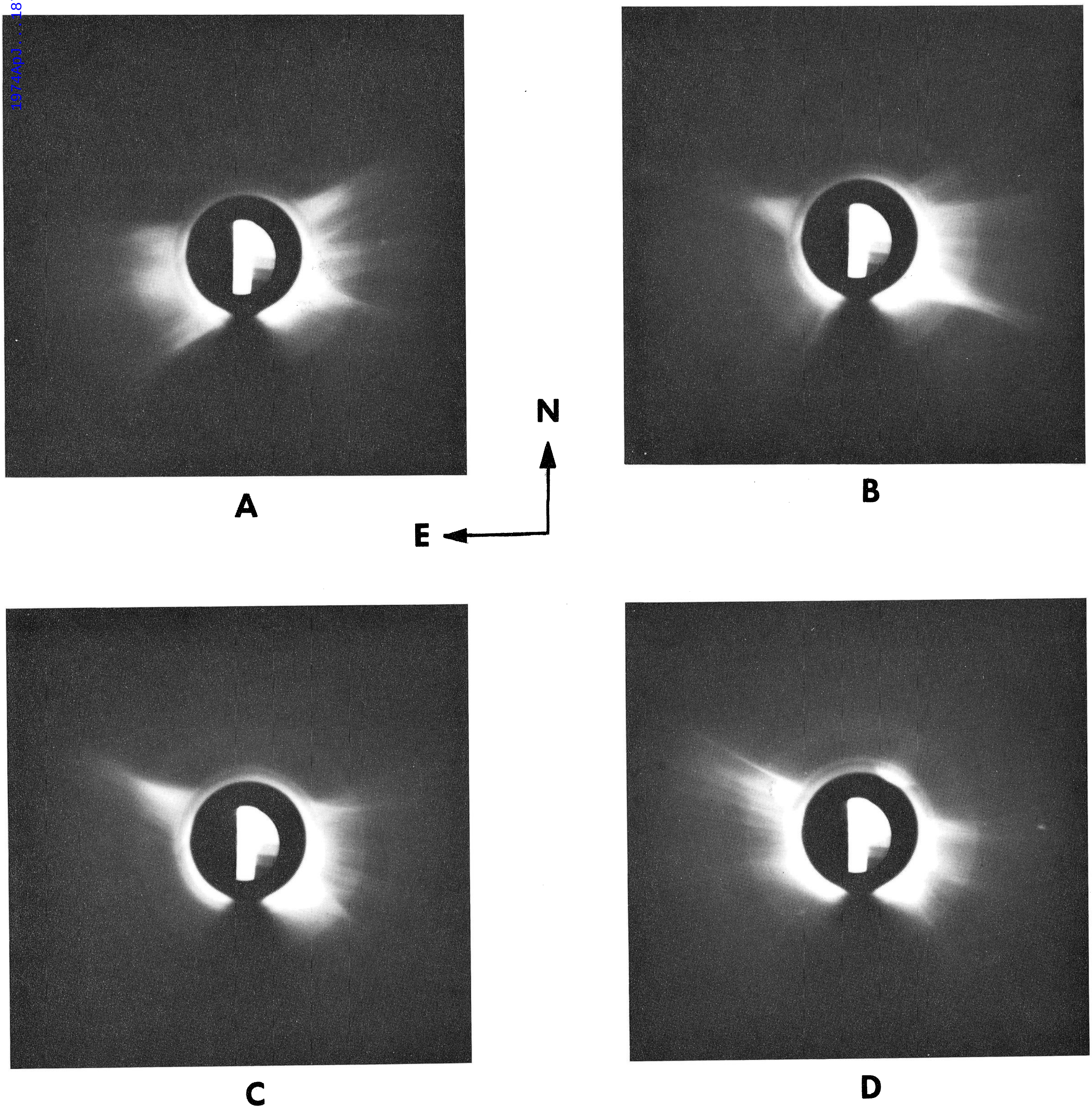

Fig. 1.—The solar corona on 1973 May 28, June 1, June 5 and June 10 (photographs A, B, C, D, respectively), in 9-s unpolarized exposures. A calibration wedge is superposed on the occulting disk image. An out-of-focus image of the disk support pylon is at solar south. Scattering from contamination (later removed by Astronaut C. Conrad) causes the cusp-like feature next to the occulting disks in the northwest of fig. 1*d*. The occulting disk has a radius of 1.5 $R_\odot$.

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tially reduced "background" K-corona, current models notwithstanding. A search of a number of past eclipse plates has not led to the identification of any such voids. However, eclipse plates show a reduced contrast —resulting from the rather high sky background present during totality—as compared to these orbital measurements.

f) Observations of coronal transient phenomena have provided some of the more spectacular results from the coronagraph (see fig. 2, plate L3). The particular case illustrated was one stage of a complex series of events associated with activity in region 137 (National Oceanic and Atmospheric Administration numbering) near east limb passage on 1973 June 10. The limb exhibited a major system of active prominences extending from the equator to N 25° and produced surges and sprays through the early hours of the day. From approximately 0700–0900 UT, several Hα and small x-ray flares occurred, and at 0815 an eruptive prominence was observed by ground-based telescopes to ascend to 1.4 $R_\odot$. This latter event is presumably the source of the transient observed by the coronagraph between 0929 and 1001 UT by ground command. During this period the material front moved with an apparent projected velocity of 450 km s^{-1} from 3.6 to 4.8 $R_\odot$, while the archlike structure expanded to a diameter greater than 2 $R_\odot$. The *Skylab* orbit was such that additional ground stations for radio command were not available to permit more complete observations of the event, which occurred while the astronauts were asleep.

Figure 2 shows the event at 0943 GMT; it is one photograph of the 144 obtained. Within the structure are numerous bright areas and extended substructures, apparently mapping the distended magnetic-field configuration. The spectral bandpass of the coronagraph includes the prominent Hα emission line; and this particular transient observation, made without the linear polarizers, cannot distinguish between coronal electron scattering and the Hα emission in the photographs.

The general appearance of this transient is indicative of a large magnetic loop or bottle, expanding outward from the Sun, its leading edge compressed by interaction with the ambient corona. Gold (1959) and others have long evoked a model of magnetic bottles in the interplanetary medium to explain cosmic-ray modulations observed at the Earth; satellite observations of shock-wave disturbances propagating outward through the solar wind also seem to require a mass and field ejection from the Sun similar to that reported here (Hundhausen 1972).

Although there apparently was not a metric radio burst associated with this event, other coronal transients observed later in the mission have associated metric wavelength activity.

Events similar to that illustrated in figure 2 are not rare since, even in this period of relatively low solar activity, more than two dozen eruptions have been observed over the first four months of the *Skylab* mission. These transients play an important role in coronal evolution—it appears that a major restructuring of the corona is caused by the passage of the transient material. For example, the four sharp coronal rays appearing on the northeast limb in figure 1*d* are a result of the transient shown in figure 2.

IV. SUMMARY

The initial coronagraph observations of coronal structures near limb passage experimentally verify that there are several time scales on which visual changes in coronal structures occur: (*a*) approximately one-half rotation, presumably accompanying major reorientations of the coronal magnetic fields governing large-scale coronal structures, (*b*) hours to days, wherein changes to smaller coronal features are due either to structural changes of particular coronal features, or to perspective effects, and (*c*) less than hours—during coronal transients—which cause major reorientation of coronal structures by their passage through the coronal medium. We note that the visual changes occurring on time scales of hours to a day and the frequency—and overall influence—of major transient coronal phenomena are particularly unexpected results.

Observations by the coronagraph over the approximate eight-month *Skylab* mission will permit the evolution of the outer solar corona to be examined in an unprecedented manner. Since the conventional assumption is that the density structure of the corona "maps" the extension of surface magnetic fields into the corona, we anticipate that these observations will provide a unique body of information on the evolution of outer coronal fields. Also, in conjunction with inner coronal ground-based (K-coronameter) and satellite-borne (X-ray) observations, the *Skylab* observations will permit the specification of the line-of-sight electron density and temperature.

The success of this program is the result of numerous persons' contributions over nearly 10 years of effort.

The instrument was skillfully constructed by the Ball Brothers Research Corporation, Boulder, Colorado and we gratefully acknowledge their engineering and mission operations efforts.

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Finally, we recognize the highly motivated, diligent efforts of Astronauts C. Conrad, J. Kerwin, and P. Weitz in obtaining these observations.

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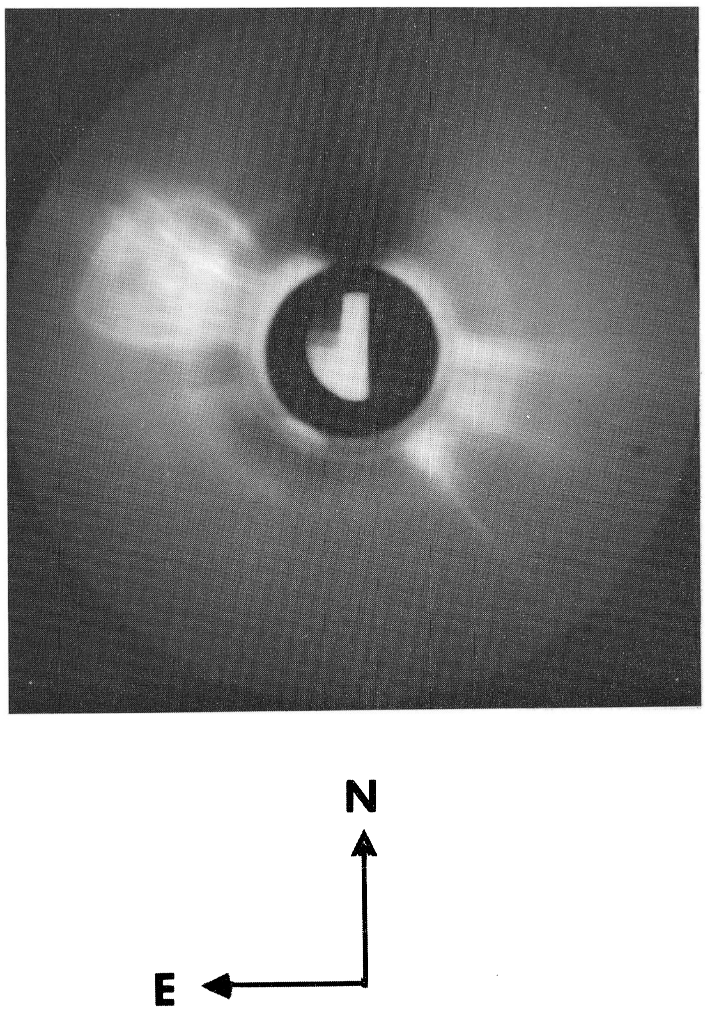

FIG. 2.—A coronal transient, 0943 GMT, 1973 June 10, in a 9-s unpolarized exposure

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