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Initial results from the High Altitude Observatory white light coronagraph on Skylab – a progress report

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[Plates 23 and 24]

The frequent, periodic observations by the white light coronagraph allow an examination of coronal variations over a broad range of temporal scales. Examples of the slowest and most rapid variations are presented. An example of extremely slow coronal variations is the gradual evolution – to a large equatorial streamer – in association with a marked decrease in solar activity, as the total magnetic flux in one hemisphere decreased. Another example is given of a long-lived quasi-stable coronal streamer, apparently associated with a stable filament channel; comparison of this streamer with coronal potential magnetic field computations show little correlation. The remainder of the paper summarizes some results on coronal transients – the most rapid variations observed. Characteristic mass and energies involved in mass ejection transients, their temporal and spatial distributions, their associations with surface phenomena and possible interplanetary signatures, and finally their role in coronal evolution are briefly noted.

1. Introduction

The flight of the High Altitude Observatory white light coronagraph experiment on the Skylab mission has allowed the identification of a broad range of temporal scales over which the corona exhibits visual changes (MacQueen *et al.* 1974*a*). In this progress report we present a collection of topics concerning the extremes of temporal variations which can now be identified: changes corresponding to periods of several solar rotations, and coronal transients, which correspond to changes on a time scale of minutes.

Instrumental characteristics of the coronagraph have been summarized elsewhere (MacQueen *et al.* 1974*a*, *b*) and will be only briefly noted herein. A sample photograph from the coronagraph is illustrated in figure 1, plate 23, showing the corona on 30 June 1973. The photograph was made at approximately the time of total solar eclipse as viewed by ground observers in Africa, and helps illustrate some of the instrumental characteristics. The diameter of the field of view of the instrument is 12 solar radii ($R_{\odot}$), and the occulting disk assembly blocking photospheric light extends slightly more than a half solar radius above the limb of the sun. The dark shadow in the lower portion of the frame is due to the pylon which supports this external occulting disk assembly. The faint annulus at approximately $3R_{\odot}$ from Sun centre is due to a shadowing by the Lyot spot in the coronagraph. The instrumental angular resolution varies across the field but is on the order of 8–10″. Each frame has imaged in the area behind the occulting disk a step wedge (not shown in the plate) calibrated with respect to the mean radiance of the solar disk. The apparent radiance

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of the lunar disk seen in figure 1 is the sum of (*a*) the earthshine illuminated disk itself plus (*b*) any instrumentally produced stray light. Preliminary measurements of the stray light (Csoeke-Poeckh 1974) indicate that its radiance is approximately 2–3 × 10^{-10} $B_\odot$ ($B_\odot$ is the mean radiance of the solar disk) in the outer field and is approximately constant above $2.5R_\odot$. This radiance, approximately 3–5 times lower than that of a typical sky background at mid-totality of an eclipse viewed from the ground, and about 2 times lower than the F-coronal radiance, implies that our ability to discern coronal forms is limited almost entirely by the actual contrast between the electron and dust scattered (K and F) coronal components.

The coronagraph observes in broadband white light (3500–7000 Å) and thus records photospheric light Thomson scattered by electrons in the solar atmosphere. Three linear polaroids with *e*-vector oriented 60° apart may be sequentially inserted in the optical path; thus information is available for determining the line-of-sight electron density in the solar corona. The polarization calibration is not yet complete, however, and results quoted herein are based principally upon measurements of the total brightness of the corona.

In § 2 we present two examples of long term coronal variations: first, an example of the restructuring of the corona as surface activity decreased over a period of months, and second, an example of a long-lived solar streamer present for five solar rotations. In § 3, we briefly summarize a number of aspects of the most rapid variations in the corona – transients: their effects on the corona; general characteristics, including their temporal and spatial distribution during the mission; their associations with surface phenomena; their possible interplanetary signatures; and finally, their role in coronal evolution.

2. Long term coronal variations

One interesting example of the evolution of the corona observed during the Skylab mission period – May 1973 to February 1974 – concerns the coronal variation apparently related to a decrease in activity on one hemisphere of the Sun. This decrease is illustrated in figure 2, which presents the calcium K intensity-area product summed over visible hemispheres whose centres are 90° apart – at Carrington longitudes 29°, 114°, 205° and 295°. The activity on the hemisphere centred at longitude 29° decreased by more than a factor of 20 through the mission, while despite substantial fluctuations, solar activity remained essentially stable over the hemispheres centred on longitudes of 114°, 205° and 295°. Additional confirmation of the decrease in solar activity on this ‘quiet hemisphere’ is found in the mean daily Zürich sunspot number for this hemisphere. The number decreased through the mission and was near zero after November 1973; thus solar activity minimum conditions were nearly achieved on this hemisphere.

How did the outer solar corona respond to this diminution of surface activity? Figure 3, plate 23, illustrates two east limb passages of longitude 30° – the approximate central longitude of the quiet hemisphere – at two widely separated times during the mission – 20 June and 28 December 1973. Coronal features became restricted in latitude during this interval, and the appearance of the corona over the quiet hemisphere in late December became quite similar to past descriptions of the solar minimum corona; i.e. the dominant forms in the corona were extended equatorial streamers. This particular form of the corona is similar to that computed by Pneuman & Kopp (1971) for a magnetohydrodynamic model of the coronal flow, employing a dipolar magnetic field. It suggests therefore that the magnetic field over the quiet hemisphere approximates a weak dipolar field.

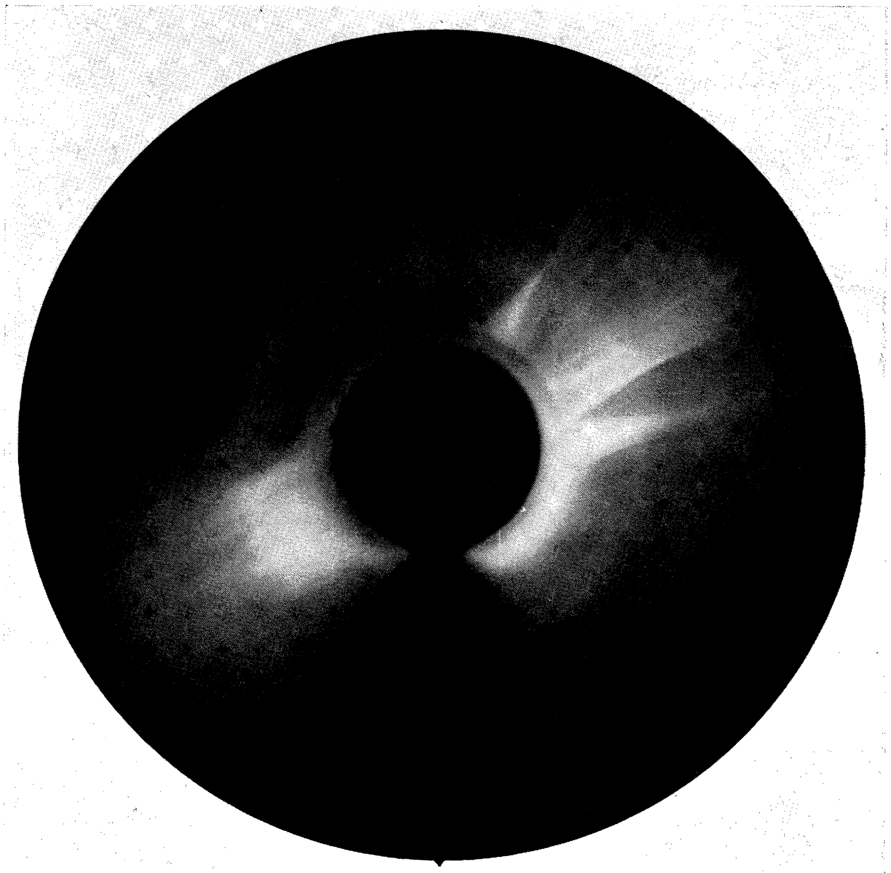

FIGURE 1. The solar corona on 30 June 1974, 12h 00 G.M.T.

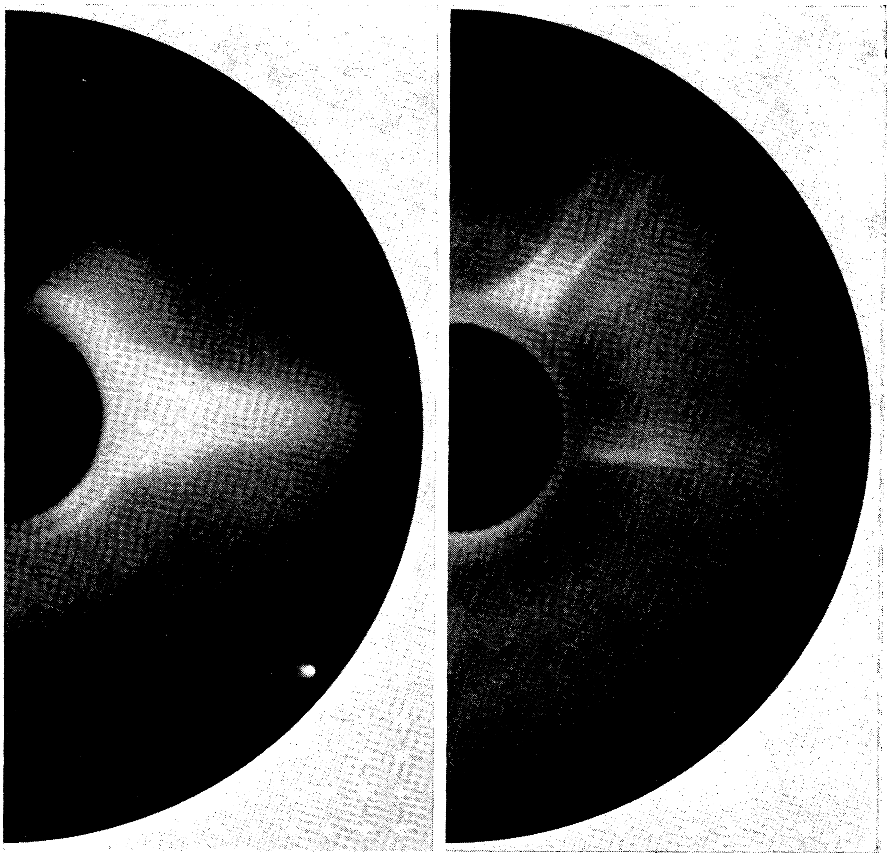

FIGURE 3. East limb passage of solar longitude 30° on 20 June 1973 (left) and six rotations later, on 28 December 1973 (right). Note the appearance of Comet Kohoutek, near minimum elongation, on the latter frame.

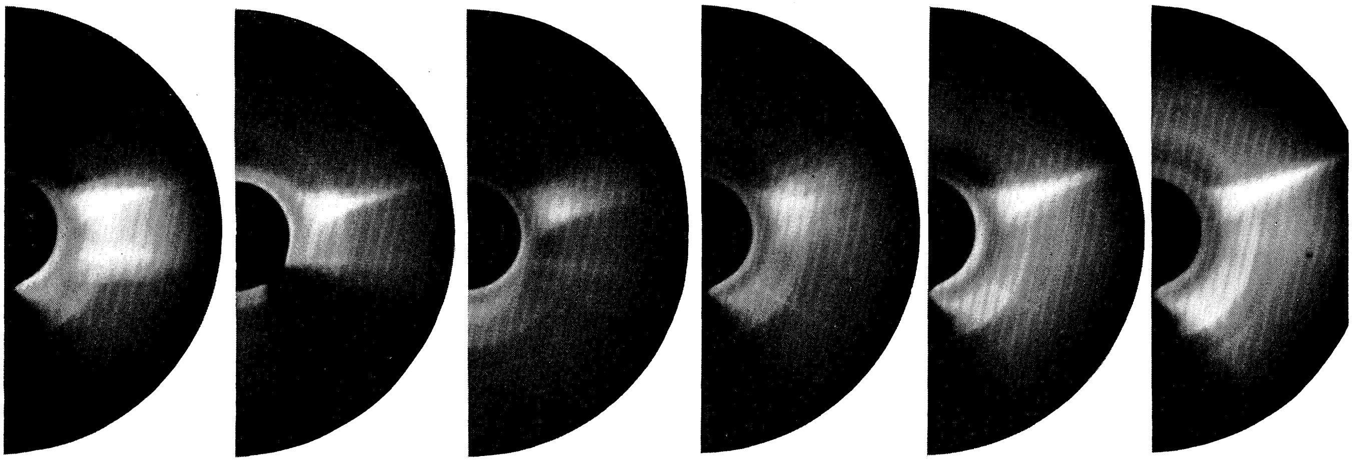

FIGURE 6. Successive west limb passages of solar longitude 115° on 16 September, 13 October, 9 November, 7 December 1973, and 3 and 31 January 1974 (left to right). Solar north is up.

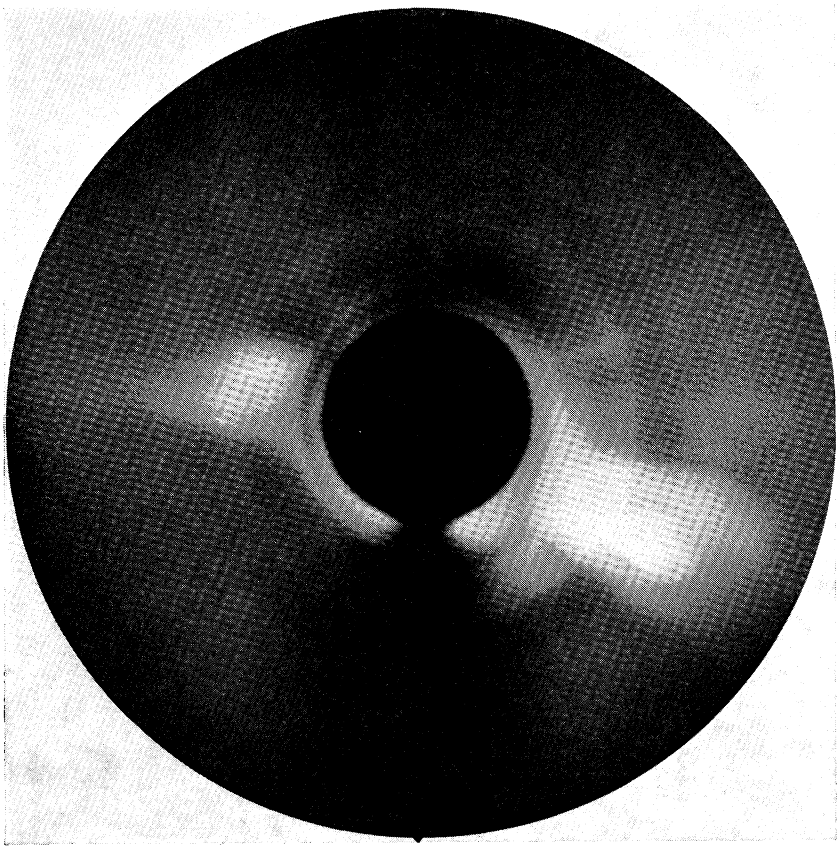

FIGURE 8. The coronal transient of 21 January 1974, photographed at 10h 27 G.M.T. Solar north is up and east to the left.

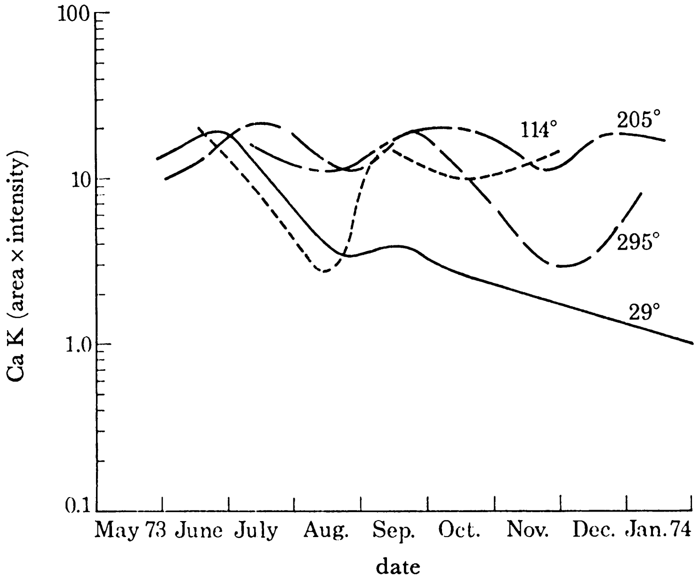

Figure 2. The calcium K normalized intensity-area product for visible hemispheres centred on longitudes 29°, 115°, 205°, and 295° throughout the Skylab mission period. Smooth curves have been drawn through data points.

The total photospheric magnetic flux on the quiet hemisphere (the sum of the absolute value of positive and negative contributions) decreased by about a factor of 2 during the mission period (R. Howard 1975, personal communication). The effect of this decrease of the photospheric (and hence the coronal) magnetic flux over the quiet hemisphere is vividly seen in figure 4 which illustrates the computed strong, potential magnetic field configuration (e.g. Altschuler & Newkirk 1969; Newkirk, Trotter, Altschuler & Howard 1973) for the central meridian passage dates of the longitudes of coronal observations in figure 3. It is evident that the photospheric source of the coronal magnetic field traced by this computation has diminished greatly between June and

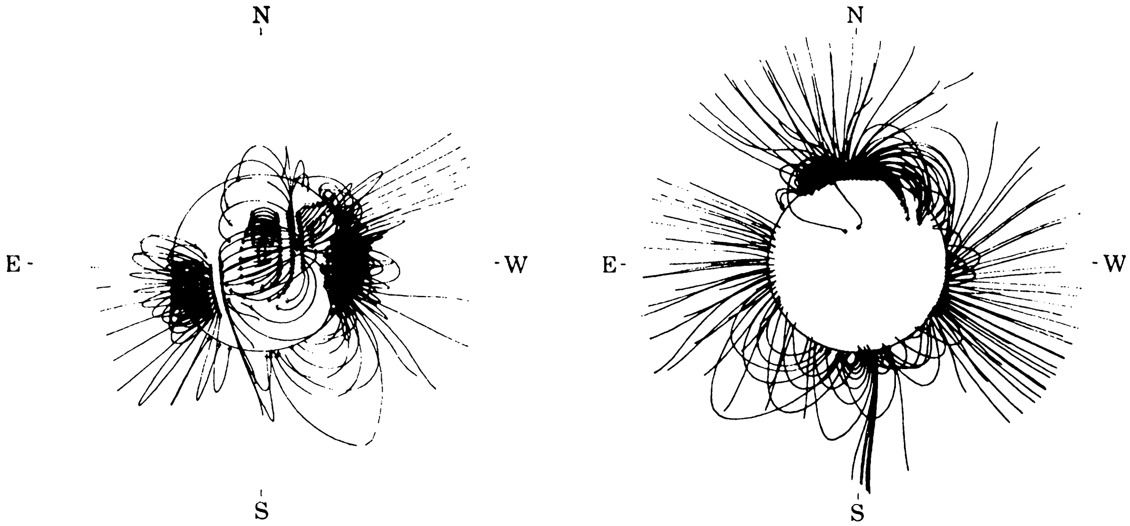

Figure 4. Calculated potential magnetic field configurations (strong field case) for central meridian passage of longitude 30°, on 20 June and 28 December 1973.

December. The study of this particular example of the evolution of coronal forms will, we hope, shed light on the formation and nature of the outer coronal magnetic field which exists at the period of solar minimum.

Of course the flight of the Skylab was *not* at the time of solar minimum, and there is the larger question of whether the solar atmosphere behaved 'typically' during the Skylab mission period. Figure 5 summarizes 2800 MHz radio flux values – from the Algonquin Radio Observatory – and K-coronal polarization times brightness (*pB*) values – from the High Altitude Observatory K-coronameter at Mauna Loa, Hawaii – for the period 1964 through 1973. Both the radio flux values and the K-coronal measurements show a decline into 1974. The 10.7 cm radio flux values have remained roughly constant over the last eight months, indicating that perhaps in 1974 the Sun became established in a minimum activity configuration. A further discussion of the nature of the solar atmosphere during the Skylab mission, and its relationship to transient activity, will be presented in § 3.

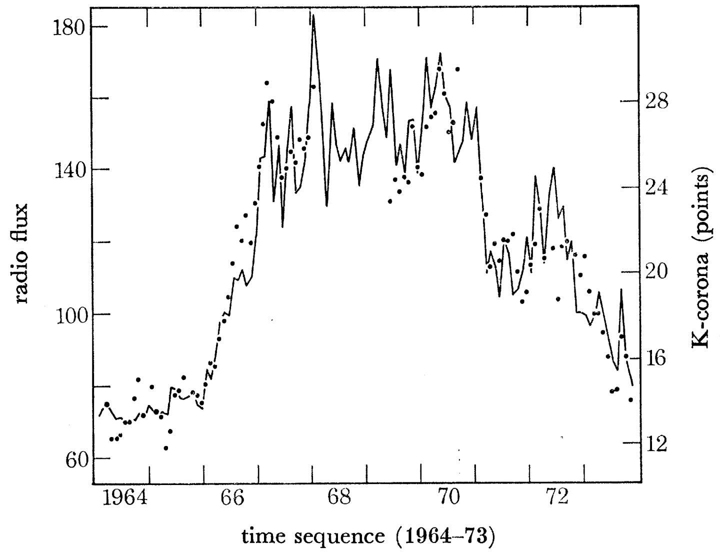

FIGURE 5. Total solar flux at 10.7 cm wavelength (2800 MHz) and coronal polarization-brightness (*pB*) product for 1964 to 1973; solar cycle no. 20.

A second example of long-term coronal variations concerns the recognition in our data of long-lived solar features, i.e. features whose appearance is similar over repeated limb passages. The regular, synoptic observations of the white light coronagraph have permitted the identification of several such stable coronal streamers. One outstanding example of such a streamer is illustrated in figure 6, plate 24, showing the west limb passages of solar longitude 115° from September 1973 through February 1974 – the end of the Skylab mission. Apparently the feature in the northwest, while undergoing some modifications and perhaps somewhat influenced by transient activity on the Sun, is a recurrent, quasi-stable feature for at least five solar rotations. Initial examination of solar surface conditions indicates that the streamer may be associated with a well defined, stable filament channel which apparently existed throughout the Skylab mission. If the shape of a coronal streamer is indicative of the coronal streamer's magnetic field, this streamer appears to be quite suitable to test the validity of outer coronal magnetic field computations, because the computations assume that the photospheric roots of the field remain unchanged from one limb passage to the next. Calculations of the potential coronal magnetic fields (Altschuler & Newkirk

1969) for the December 1973–January 1974 time period are shown in figure 7 for central meridian passages of the longitude close to that of the streamer. Preliminary examination of the results does not yield compelling evidence for a stable computed magnetic structure which might be associated with the observed streamer. Clearly, this area requires intensive future efforts.

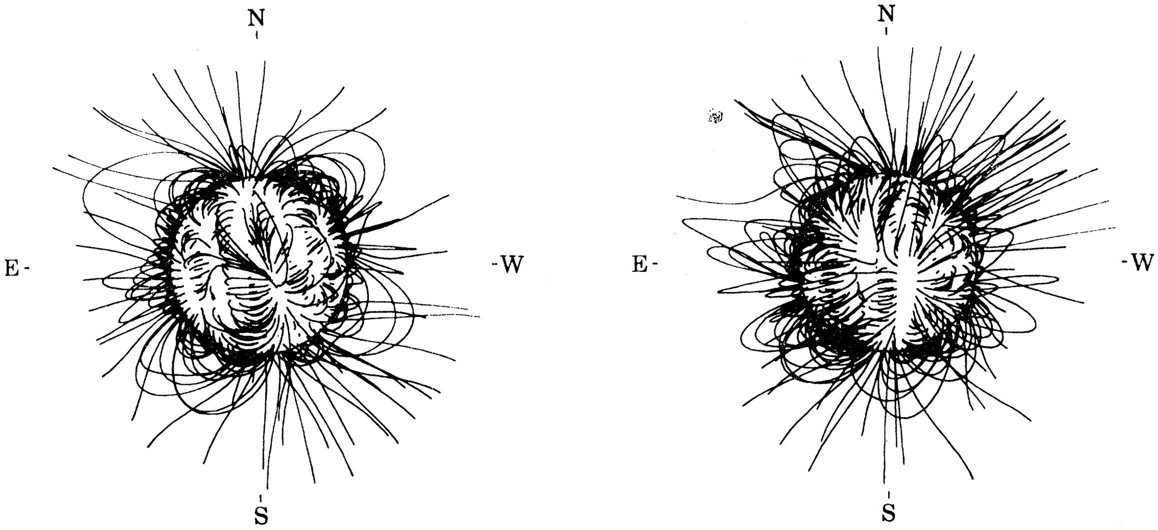

Figure 7. Calculated potential magnetic field configurations (weak field case) for central meridian passage of longitude 120° in November and December 1973.

As noted above, the streamer present from September onward is apparently associated with a long-lived filament channel; another stable coronal form, apparently associated with an active region complex present during June and July 1973, is currently under examination (Poland 1975).

3. Transient coronal activity

The slow evolution of coronal features is frequently interrupted by locally cataclysmic events known as coronal transients. These events are often characterized by major local injections of mass and energy into the outer corona from lower in the solar atmosphere, but also, some apparently are rearrangements of material in the corona. The frequency of the mass ejection events during the Skylab mission was found to be considerably higher than anticipated before the mission: a total of 66 *large* mass ejections were detected during the 227 days of coronagraph operation and more than 40 additional events of a more subtle nature were also observed.

One example of the appearance of a coronal transient is shown in figure 8, plate 24, illustrating the event of 21 January 1974; temporal sequences of other events appear elsewhere (Gosling *et al.* 1974; Hildner *et al.* 1975).

The frequency and spatial distribution of these events was such that during any given solar rotation the majority of coronal features present may have been affected by transients. This is exemplified in figure 9, which presents preliminary contours of polarization times brightness (pB) deduced from coronagraph observations made during the June–July 1973 period (D. C. Wilson 1974, personal communication). The stippled bars indicate estimates of the latitudinal extent and the longitude of transients during the period. In regions of transient occurrence, the contours are unreliable since they are an unknown mixture of stable and perturbed forms. It is apparent that virtually every coronal feature was affected by transient activity in this time period.

Examination of several of the large mass ejection transients in some detail (Gosling *et al.* 1974; Hildner *et al.* 1975) has resulted in the following estimates (even though there is a great deal of variability between events); typically the speed of the ejecta is approximately 500 km/s, the mass ejected is in the range 10^{15}–10^{16} g and the kinetic energy is on the order of 10^{31} erg (10^{24} J). Clearly, these transient events represent major local perturbations to the corona and the flow of the solar wind.

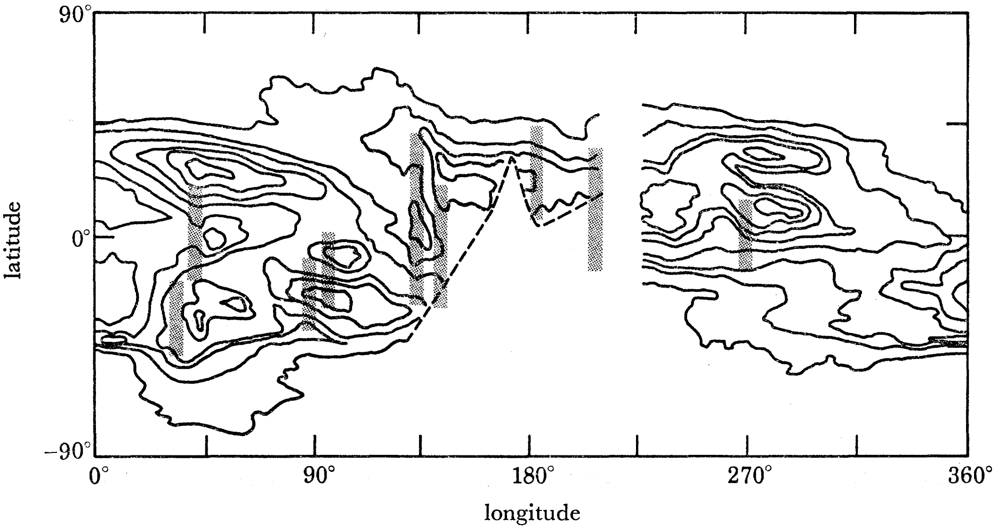

FIGURE 9. Preliminary contours of polarization-brightness (pB) product from photographs made in June–July 1973. Stippled areas indicate the approximate longitude and latitudinal extent of transients during this period.

Hildner (1974) has summarized the temporal and spatial distribution of more than one hundred transient events observed during the Skylab mission. When solar activity was not confined to one band of longitudes there was no particular clustering of the occurrence of coronal transients; however, during rotations late in the mission, the occurrence of coronal transients began to cluster more strongly in time. This temporal clustering, of course, implies a spatial clustering, and it was found that transients generally clustered about solar longitude 200°. This increased clustering corresponded in time to the development of the active and quiet hemispheres discussed earlier; the spatial clustering of transients was coincident with the active longitudes.

The identification of transients with solar activity does not, however, necessarily imply a correlation with solar flares. Gosling *et al.* (1974) and Munro (1974) have found that flares were *not* the principal sources of transients during the Skylab mission. In the latter study, 66 transients described as large mass ejections were examined. Thirty of these transients were associated with solar surface phenomena; the remaining 36 large transients could not be so associated, but it is assumed that the majority of these 36 transients originated on the backside of the Sun. Of the 30 transients with known associations, 6 were associated with flares, 19 with eruptive prominences, 3 apparently with infall-impact processes, and 2 with nearly simultaneous eruptive prominence and flare occurrences within the same active region. Significantly, if flares combined with eruptive prominences are neglected, eruptive prominences produced nearly three times as many coronal transients as did flares.

The size of a flare appears to be an important factor in determining whether or not the flare will cause a coronal transient. Because the coronagraph is most sensitive to coronal changes near the plane of the sky, flares within 45° of the limb, with concurrent coronagraph observations, were examined for coronal transients. Taking the Hα importance as a measure of the flare activity, it was found that each (of 5) importance 2 or 3 flare within 45° of the limb produced a coronal transient; however, only 18% (3 of 17) of importance 1 flares within 10° of the solar limb produced transients, and *no* transients were caused by (29) importance 1 flares occurring further than 20° from the limb. The same strong correlation was found when the X-ray flux from the flaring region was used as a measure of the flare's importance. In addition to the association of energetic flares with transients, there was a strong correlation between coronal transients and Hα material ejected from a flare. In fact, every flare within 45° of the limb which produced a coronal transient also had a Hα mass ejection.

In sum, flares produced only a small fraction of the mass ejections in the corona during the Skylab mission. While the more energetic flares had a higher probability of causing coronal transients, disturbances in the corona above 2 $R_\odot$ associated with flares seem to be directly correlated with the ejection of material from the flare site.

Are there signatures of these transient events in the interplanetary medium? The answer to this question is, and will prove to be, elusive since (*a*) the coronagraph is biased toward events occurring near the solar limb, (*b*) there are relatively few spacecraft transiting the interplanetary medium that are favourably situated for the detection of solar limb events, and (*c*) those spacecraft do not regularly transmit data over extended periods. In the case of *one* coronal transient associated with a major flare on the Sun on 7 September 1973, a strong shock wave was observed near 1 AU (*ca.* 150×10^9 m) by the Pioneer 9 spacecraft 44 h after the flare (Gosling *et al.* 1975). For this event it was found that coronal energy and mass estimates based upon coronagraph observations were in close agreement with estimates based upon interplanetary spacecraft observations. However, this transient appears exceptionally energetic and massive as compared with other transient events during the mission and the solar wind disturbance at 1 AU was also unusually large. A search for interplanetary disturbances correlated with more typical coronal events has thus far proven unsuccessful; however, a clue to the type of disturbance which *might* be expected at 1 AU may be found in work concerning another coronal transient event – that of 14–15 September 1973 (Dulk & Gosling 1974; MacQueen & Sheridan 1974). This event was one of few observed simultaneously with the metric radio wavelength spectroheliograph of the Commonwealth Scientific and Industrial Research Organization (CSIRO) and with the white light coronagraph. A stationary type IV burst associated with this event has been examined; under the assumption that the radio emission was gyro-synchrotron radiation, the magnetic field strength during the transient event was determined. For the first time, then, the relative importance of magnetic, kinetic, and thermal energy densities in a transient event could be made. It was found that, in contrast to the normal solar wind expansion, the magnetic and kinetic energy densities in this transient event were roughly equivalent and greatly exceeded the thermal energy density. This result suggests that it may be fruitful, within the constraints imposed by the limited data coverage, to examine available interplanetary records for correlations between transient coronal activity and anomalously strong magnetic field perturbations and/or ordered field configurations.

The importance of the role of coronal transients in the coronal evolutionary process as deduced from the Skylab observations has been emphasized. It is important to question if this importance is typical for other stages of the solar cycle. An examination of ground-based observations of the innermost coronal regions leads to some interesting conjectures concerning this question.

Figure 10 presents isopleths of the product of coronal brightness and polarization (pB) at 1.5 $R_\odot$ from Sun centre for a period of time which precedes, includes, and follows the Skylab mission. These data were obtained by the K-coronameter of the High Altitude Observatory, Mauna Loa station. The contours are in steps of 50 % pB. Periodic structures near the equator are seen to be present during the latter part of the Skylab mission and into 1974. The isopleths reveal that the inner corona had markedly different character during most of the 1973 period, for the pattern is considerably more irregular and less intense during the Skylab mission period than before and

K-corona at 1.5$R_\odot$

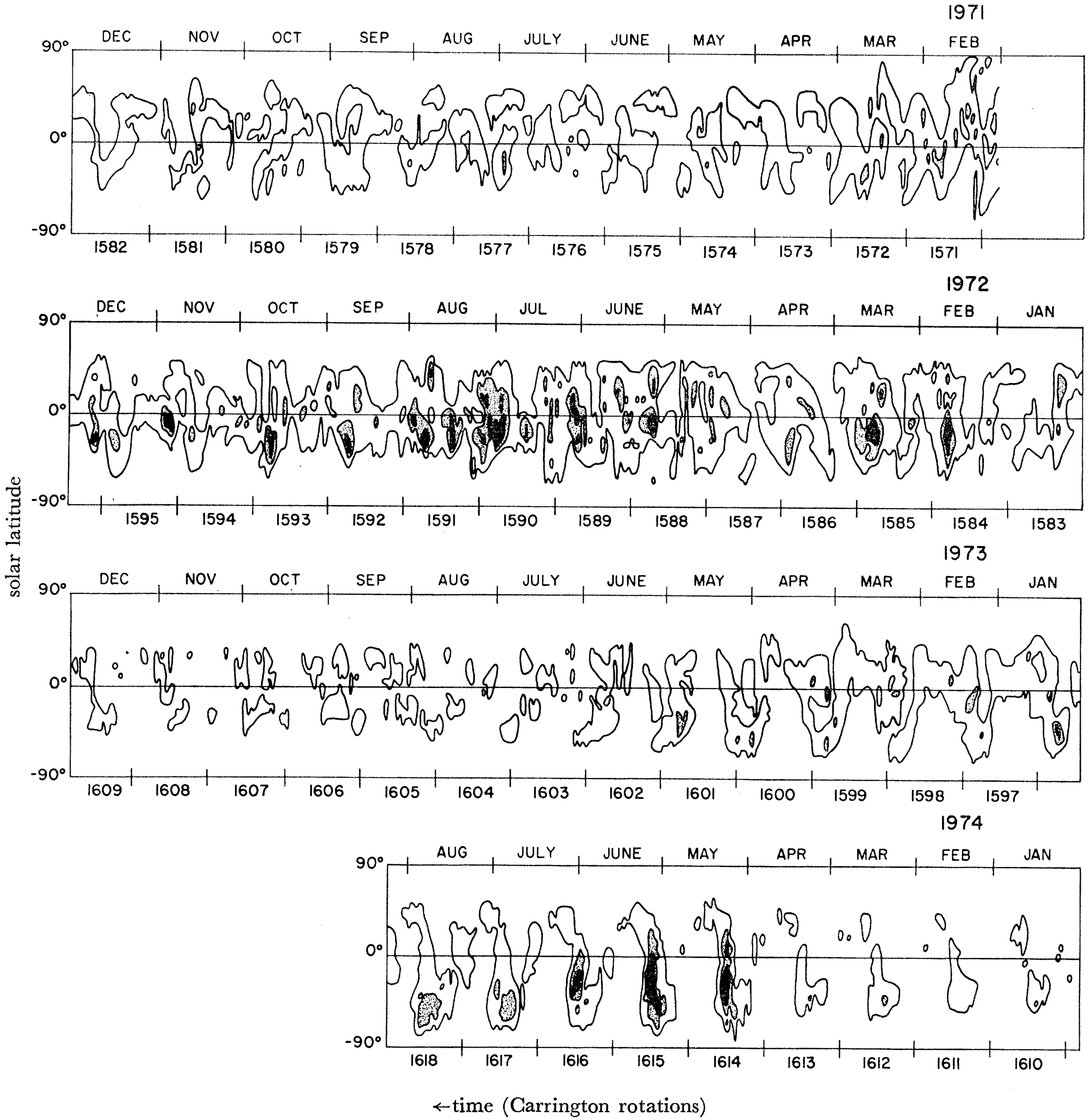

FIGURE 10. Contours of polarization-brightness (pB) products at 1.5 $R_\odot$ from the High Altitude Observatory K-coronameter (Mauna Loa), from 1971 to 1974.

after. If this irregularity and weakness is a result of a high frequency of transient activity then it might be suspected that transient activity greatly diminished following the Skylab mission; that is, one *possible* inference from these observations is that transient activity was anomalously high during the Skylab mission. If this is the case, then caution must be exercised in extrapolating results concerning the structure of the overall magnetic field as indicated by outer coronal structures observed with the High Altitude Observatory Skylab coronagraph to other phases of this solar cycle, or to other cycles. Another possibility is that, assuming there exists an (unproven) correlation between coronal density and magnetic field strength, the corona during the Skylab period was comprised of relatively weak fields, i.e. the mean magnetic energy density of the corona was reduced. It might then be possible that the *effect* of transient activity would be enhanced. By the same token, greater coronal radiance at other times may imply the presence of stronger fields and hence a lessened effect on the coronal form due to transients. Pneuman (1973), on the other hand, has argued that the magnetic field geometry, as opposed to field strength, determines the resultant coronal density. At this time these points must be regarded as purely conjectural, but it is clear that a clarification of these questions is of extreme importance in the interpretation of the Skylab coronal results.

4. SUMMARY

This discussion has centred upon two extreme temporal scales: firstly, that corresponding to the long term evolution of coronal structures and secondly, the scale corresponding to the most rapid and spectacular events – coronal transients. Between these two extremes there exist a broad range of variations detected through the frequent observations obtained by the white light coronagraph on Skylab. We fully expect that the study of these variations will occupy coronal physicists for a number of years and will shed new light upon dynamical processes in the solar corona.

The authors are indebted to G. Newkirk and J. Eddy for their important roles in the initial establishment of the program; to the personnel of the Ball Brothers Research Corporation for the construction of the coronagraph; to the personnel of the Marshall Space Flight Center and Johnson Space Center for their roles in the construction, testing, and flight of the Skylab; and to the astronaut crewmen for their dedicated efforts in obtaining the observations.

We also thank G. Heckman and R. Hansen for making available and discussing results concerning surface activity and the inner corona, respectively; and A. Csoeke-Poeckh and R. Broussard for their efforts in examining the data.

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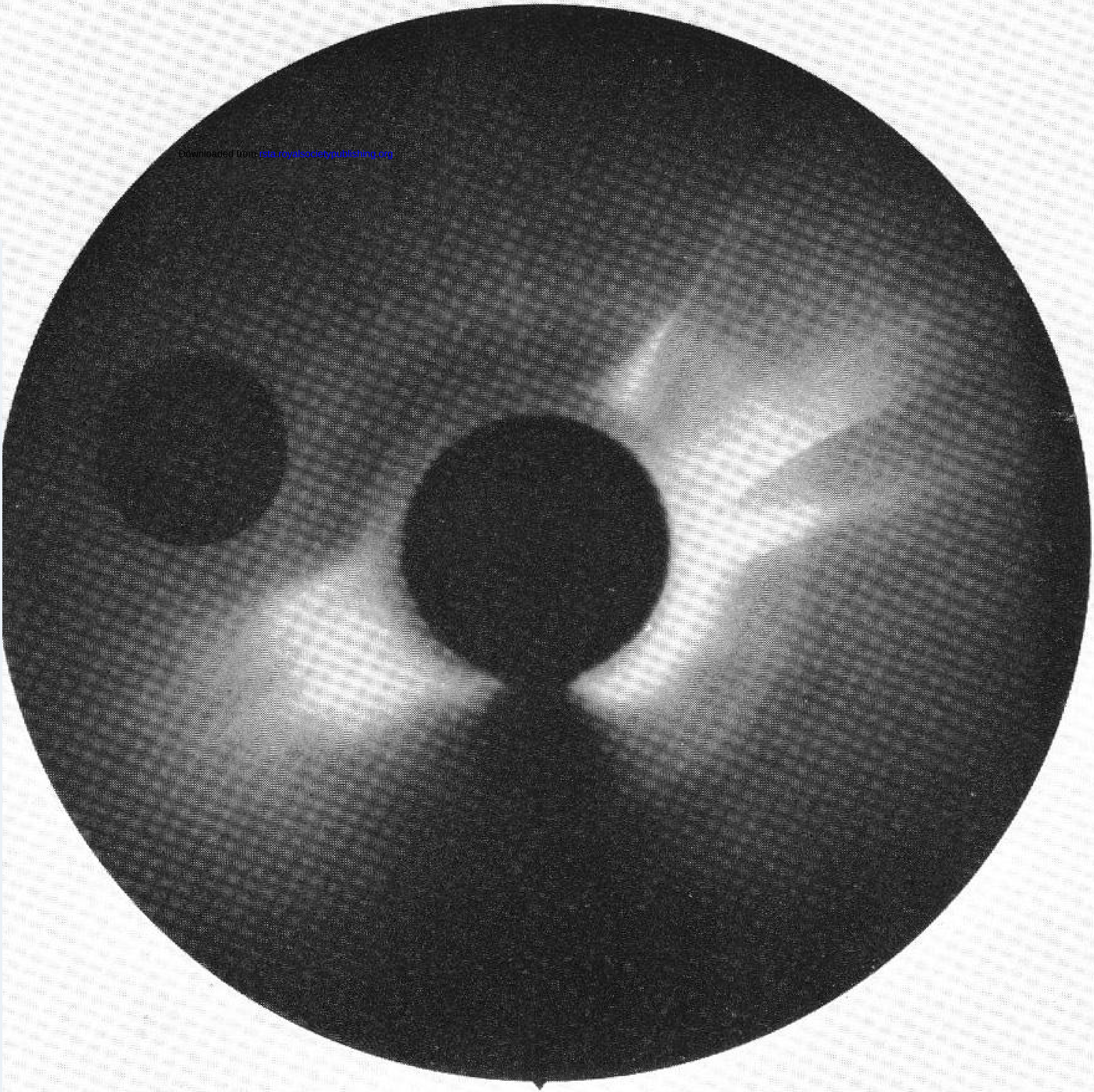

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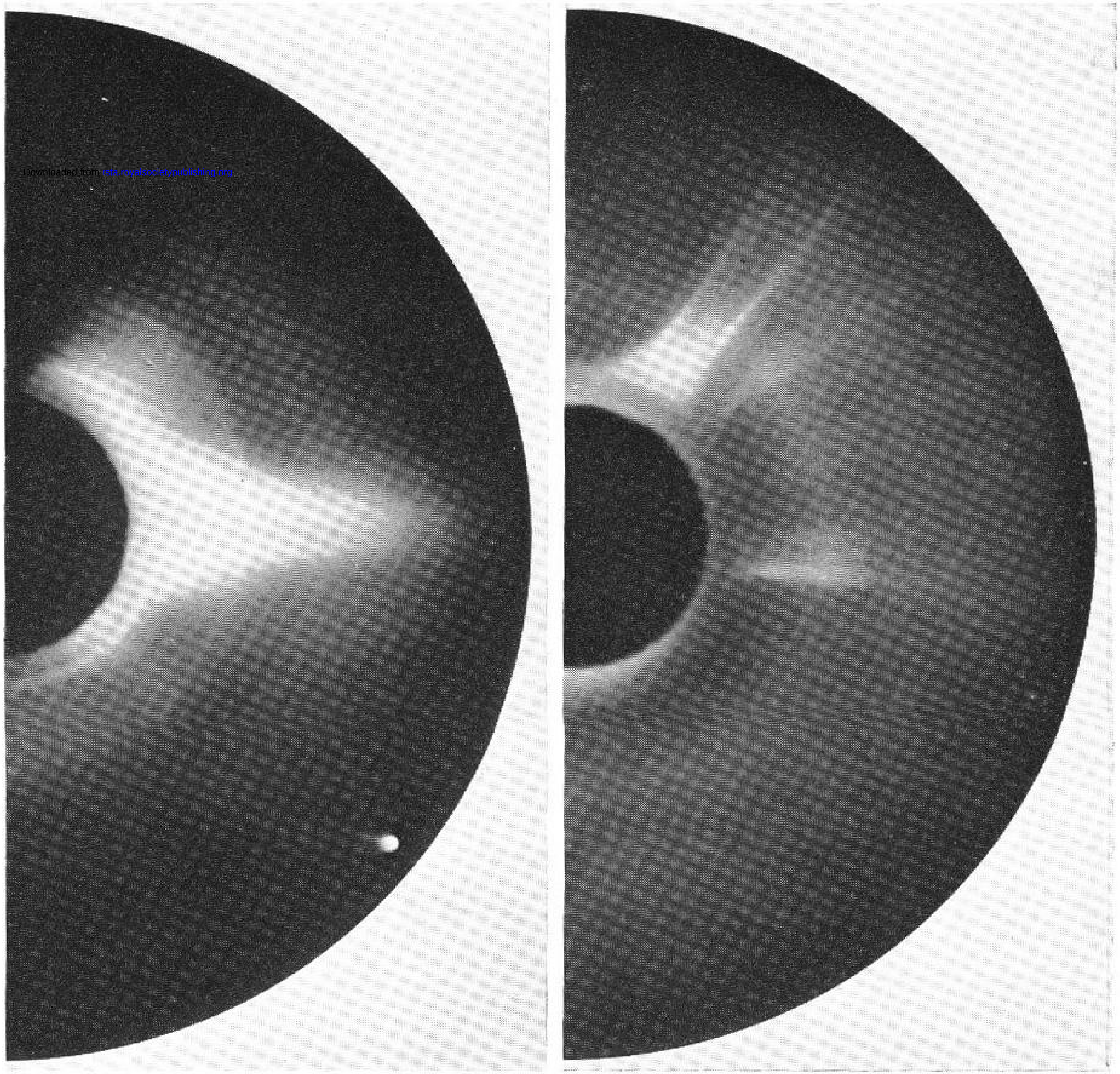

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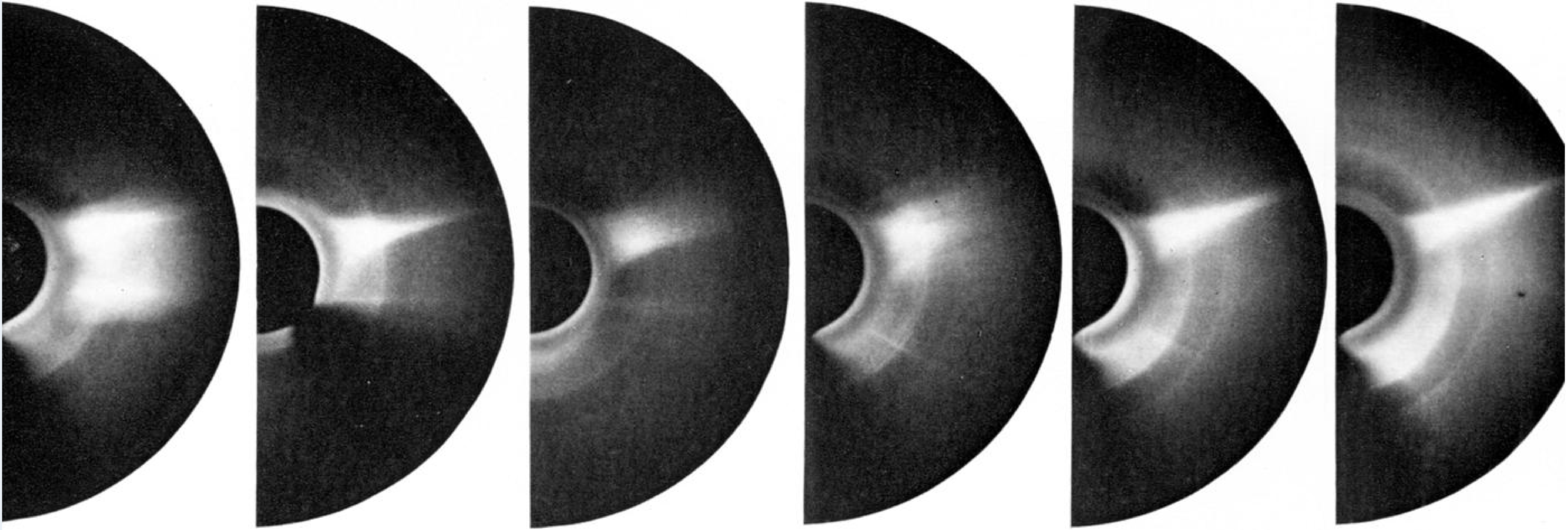

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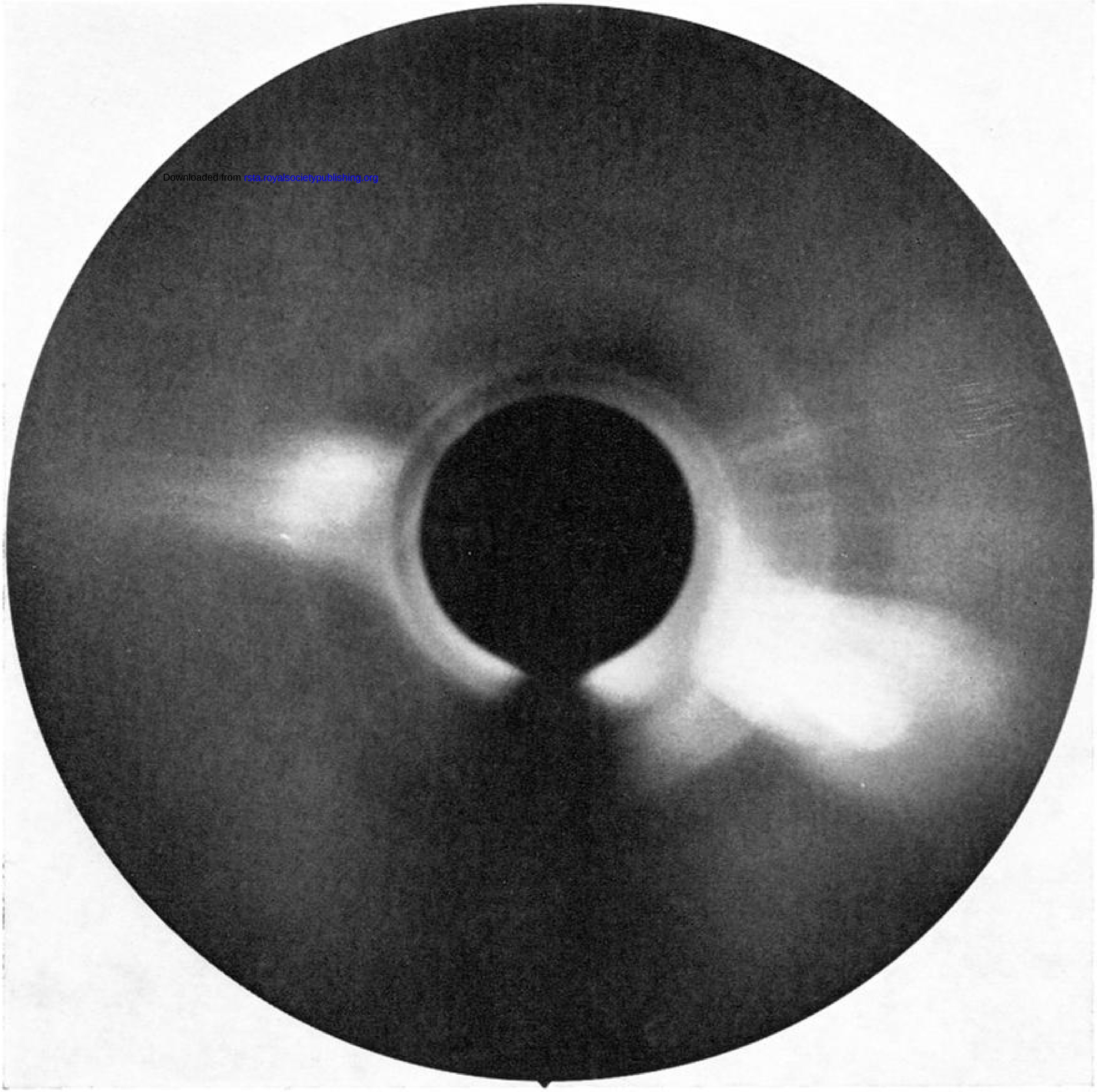

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