USE OF THE MOON TO DISTINGUISH THE F FROM THE K CORONA USING A ROCKET CORONAGRAPH DURING AN ECLIPSE[†]

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INTRODUCTION

The coronagraph of Lyot makes it possible from the ground to observe the inner corona, but the outer corona cannot be detected because the sky is too bright. To observe the outer F and K coronas and the streamers, a solar eclipse has been required until very recently. Rockets, orbiting vehicles, and to a lesser extent, stratosphere balloons now make it possible to observe the outer corona at any time, by lifting a coronagraph of suitable design to a position above the Rayleigh sky. This was first accomplished on June 28, 1963 by Koomen, Purcell, Seal, and Tousey (1964), (Tousey, 1965). Photographs of the corona in white light were obtained over the region extending from 3.5 to 10 R_s (solar radii) from the sun's center.

It was proposed by J. D. Purcell that a rocket coronagraph be flown at a time when the moon would be close to the sun, and within the field of view of the coronagraph. The moon would then serve to eclipse a portion of the corona, and perhaps make it possible to separate the portion of the F, or zodiacal light corona, lying between the earth and the moon, from that in the region beyond the moon. It turns out that

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the moon comes sufficiently close to the sun to lie within the field of view of the U. S. Naval Research Laboratory (NRL) rocket coronagraph only when there is a solar eclipse, and if the rocket launch site lies at a point somewhat outside the penumbra. This rare circumstance occurred for the White Sands Missile Range (WSMR) during the May 30, 1965 eclipse, and the experiment was planned for flight at 1600 MST, when the centers of the moon and sun would be 5 solar radii apart. As luck would have it, another rare event consisting of a violent sand and rain storm arose and prevented the launch. It is hoped to attempt the experiment once again at WSMR during the November 12, 1966 eclipse, when the proper conditions occur at approximately 0945 MST.

INSTRUMENTATION

A photograph of the instrumentation is shown in Fig. 1. Two Lyot coronagraphs were mounted within the instrument chamber carried in a biaxial pointing control, located in the nose section of an Aerobee-150 rocket. In the flight of June 28, 1963, one instrument was photoelectric, the prototype of the instrument placed in orbit on February 3, 1965 in OSO-II, the other employed photographic recording. A Lyot coronagraph, although entirely satisfactory for recording the inner corona from the ground, in its original form would be completely unable to detect the outer corona even in the absence of the Rayleigh sky, because of the insufficient suppression of stray light. To reduce the stray light an external occulter was placed 20 inches in front of the objective lens so as to screen the lens from sunlight. This arrangement was first employed by Evans (1948). The occulter must be especially designed however so as to prevent light diffracted from its edge from reaching the objective lens. In the instruments shown,

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the occulter was made in the form of a circular disk whose edge was a fine-toothed saw; rays diffracted from the edges of each tooth formed a circular envelope, having a central area where the objective lens was located, that was completely dark except for the small amount of scattering from the sharply pointed teeth and valleys and from the residual dirt specks on the edges of the teeth.

The instruments constructed for flight during the May 30, 1965 eclipse were both photographic. Instead of the saw-toothed type occulter which was so difficult to keep clean, a multiple-disc occulter was used, as proposed by Gillette (1961), and employed in balloon-borne coronagraphs by Newkirk & Bohlin (1963,4). This occulter consisted of three smooth-edged discs, each of a size to screen the edge of the one ahead. This formed a shadow that was somewhat darker than that produced by the saw-type occulter, after the inevitable dirt specks had accumulated during launch and flight.

The two instruments prepared for the eclipse were equipped with special polarizers in order to determine the state of polarization of the corona. In the one instrument, a polarizer of circular form was placed directly in front of the film plane so as to transmit only the component with electric vector tangential to the sun's limb. In the other instrument no polarizer was used except for a narrow strip placed along a radius from center to edge of the field. This strip contained two long slivers of polarizing material side by side, with polarizing axes respectively radially and tangentially oriented.

As mentioned above, an opportunity for a successful eclipse launch of the instruments has not yet occurred, but the flight of the photographic prototype on June 28, 1963, provided data which suggested

that there was indeed coronal material between the moon and earth, which could be revealed in a definitive manner by an eclipse experiment.

RESULTS FROM THE FLIGHT OF JUNE 28, 1963

The flight on June 28, 1963, when the moon was not in the coronagraph field, yielded 23 corona photographs, taken at altitudes between 130 and 204 km with exposure times from 1 to 56 seconds. Exposure #11, of 4-sec. duration, is shown in Figs. 2(a) and (b). The original in Fig. 2(a) contains many artifacts; these have been removed by retouching in Fig. 2(b), and a coronal photograph made during the total eclipse of July 20, 1963 has been introduced at the proper scale and orientation; this was twenty-two days later, when the sun had nearly completed 360 degrees of rotation. The shadow at the center of Fig. 2(a), extending out to the edge, was produced by the occulter and the arm required to support it. The artifacts consist of: (1) Spots that developed on a lens, presumably during takeoff. (2) A trace of diffracted light at one edge of the occulter caused by a slight mispointing. (3) Light introduced by small particles in the space surrounding the rocket. This exposure is one of the cleanest and only a trace of light from particles can be seen, just above and to the left of the top of the occulter. In many of the exposures however particle trails were conspicuous and those lying close to the instrument introduced a great deal of spurious light.

The corona, Fig. 2(a), appears not to vary in luminance with distance from the sun. This is a result of the vignetting function of the occulting system, which rather closely compensated for the normal decrease of coronal luminance with increasing distance from the sun.

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In Fig. 3, the effect of vignetting has been removed so as to present the corona more nearly as it would have been photographed with an ordinary camera, had this been possible.

The four best coronal photographs showed a single coronal streamer, which is to be seen in Figs. 2 and 3 extending to about to $R = 8 R_s$, at approximately 15° north of west. Otherwise, the images were produced mainly by the F-corona, since under quiet solar conditions the K-corona contributes only of the order of one-quarter of the total coronal brightness in the range $R = 3.5$ to $10.0 R_s$.

The principal evidence that a significant contribution is made to the F-corona from material between the moon and the earth comes from a comparison of the coronal luminance measurements made from the rocket flight of June 28, 1963 and similar measurements made by Gillette, Stein, and Ney (1964) by direct photography from a balloon at 110,000 feet during the solar eclipse of July 20, 1963. As reported by Tousey (1965) the rocket measurements indicated luminance values two to three times greater than those made during the 1963 eclipse. The same result is obtained when the rocket measurements are compared with earlier eclipse measurements made from an aircraft at 40,000 feet (Blackwell, 1955). The rocket measurements also have confirmation in the data obtained from the coronagraph placed in orbit on OSO-II (Koomen, Purcell, McCullough, Seal, and Tousey, 1965).

The apparent high values of cornal brightness obtained from our measurements can be explained with the aid of the diagram of Fig. 4. This shows schematically and not to scale the path of light observed in the corona during a total eclipse for an observer at various points in the umbra. In the case of the eclipse, a large portion of the atmosphere extending from the earth to the moon is totally or partially

shadowed from sunlight; hence it contributes little light even though there may be present a considerable amount of scattering material. During the rocket coronagraph flight on 28 June 1963 there was no shadowing by the moon, therefore the brightness must have included the full amount of light scattered from material in this region. The regions shadowed for viewing at different angular distances from the sun are shown in Table I, for an observer at point A on the edge of the umbra. It is obvious that a region extending some 2000 km away from the earth is completely shadowed during an eclipse for viewing the corona out to 10 solar radii, and partial screening continues to 15 earth radii or more. As the observer moves to the opposite edge of the umbra the screening becomes less, in proportion to his position.

Table I

Shadowing of earth-moon space observed from edge of an eclipse umbra (see Fig. 4)

Elongation ϵ in R/R_s of point observed in corona	Shadowed distance (km) for line of sight from A		Effective fraction of non-eclipse illumination in line of sight
	In umbra	In penumbra	
1.2	86,000	254,000	0.51
1.5	34,200	263,000	0.63
2.0	17,200	230,000	0.72
3.0	8,600	176,000	0.79
6.0	3,400	101,000	0.88
10.0	1,900	65,000	0.92
15.0	1,200	45,000	0.95

THE ECLIPSE CORONAGRAPH EXPERIMENT

The nature of the eclipse experiment is shown in Fig. 5 which combines a schematic diagram of the shadowing produced by the moon

together with an estimated curve showing the brightness of the corona and the moon's shadow as a function of angular distance from the sun's center. This brightness function was estimated by accepting the rocket results which gave a coronal brightness double that of the eclipse; it was assumed that the region between the earth and moon contributes a total brightness equal in value to that coming from the region beyond the moon, and that the brightness was distributed uniformly between the rocket altitude and the moon. Further, the moon was assumed to lie at an elongation of 5 solar radii from the sun, thus placing the one limb at an elongation of 4 radii and the other at 6. Inside 4 radii the corona as shown by ray A would follow a curve such as is normally measured with a rocket coronagraph. Here the brightness consists of three parts: K, from the true electron corona; F_i, the F-corona as recorded from solar eclipse measurements; and F_e, the portion of the F-corona between the moon and the earth, contributing to the total brightness, as measured with the rocket coronagraph. The dotted curve shows the normal brightness distribution as observed to one side of the moon where there is no obscuration. The limb of the moon closest to the sun, at $R/R_s = 4$, screens the corona beyond. What does one see against the dark side of the moon? First, there is the earthshine, M_e, the brightness of the moon produced by illumination originating from the earth in full phase. This was first measured by Danjon (1936), who found an average value of $4 \times 10^{-10}\ B_s$, with variations taking place caused by the particular state of cloud cover and atmospheric conditions present on the side of the earth facing the sun, and also depending on the part of the moon observed. In any case there is a sharp decrease in brightness from the corona as the limb of the moon closest to the sun is crossed. The moon screens $K + F_i$, and

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just outside $R/R_s = 4$, leaves F_e. The total brightness therefore is $M_e + F_e$. As the moon is crossed however, different fractions of F_e become shadowed by the moon. The brightness therefore is $M_e + \alpha F_e$ where α is the shadowing factor (i.e., the effective fraction of normal illumination in the path) and depends strongly on R. At the far edge of the moon another discontinuity arises when the brightnesses $K + F_i$ are once again exposed to view and M_e is no longer present. Shadowing still takes place and the total brightness still includes αF_e. It seems probable that the far edge of the moon may be slightly brighter than the adjacent corona, owing to the shadow cast in F_e by the moon. Values of α are shown in Table II together with the distance from the center of the earth to the position where the particular ray crosses the center of the umbra. In principle, therefore, the umbra might be followed from the moon half-way or more to the earth, and were it possible to measure the brightness changes with sufficiently high precision, the distribution of the zodiacal light in this region could be determined.

Table II

Shadowing by the moon at $\epsilon = R/R_s$ (see Fig. 5)

ϵ for line of sight	Fraction of lunar distance to center line of umbra	Fraction of lunar distance lying in umbra	Fraction of lunar distance lying in penumbra	Fraction of normal illumination in path
5	1.0	0.183	0.108	0.774
6	0.84	0.298	0.146	0.644
7	0.72	0.222	0.187	0.703
8	0.63	0.188	0.205	0.730
9	0.57	0.142	0.216	0.771
10	0.51	0.127	0.205	0.791

In Fig. 6, the moon and its shadow have been sketched into the photograph of Fig. 2(b), at the approximate position where they would have been if the coronagraph had been flown on May 30, 1965 at a time to give a 5R separation between sun and moon. This was done in accordance with the rough calculations presented above.

Since the precise determination of F_e from the observed brightnesses involves a knowledge of M_e and this is known to vary with conditions on the earth, a separate experiment was carried out to determine M_e as near to the day of the eclipse as possible. A Danjon "cat's eye" type photometer, loaned by Dr. Fred A. Franklin of the Smithsonian Astrophysical Observatory, was employed at the WSMR by M. J. Koomen and R. E. McCullough. Separate measurements were made by R. Tousey, W. R. Hunter, and L. Dunkelman in the Andes in Peru using a variety of cameras and telephotometers. Measurements were made on May 28, and June 2, since two days from the dark of the moon is the closest for which the earthshine can be viewed without excessive correction for the twilight sky. The measurements were found to agree, approximately, with the average value reported by Danjon (1936). Since the moon is known from observations to exhibit a peak in surface brightness at phase angle 0°, the curve for earthshine, determined by Danjon and adjusted to the values determined in 1965, was extrapolated to phase 0° following the curve for the illumination produced at the earth by the moon when near full. This is the value of M_e employed in Fig. 5.

The photographs of the corona obtained with the rocket coronagraph on June 28, 1963 include further evidence of the presence of particles between the earth and the moon of a nature which contribute to the zodiacal light. Many of these were close to the rocket, but others

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were as much as 500 to 1000 feet away. Only those moving with almost exactly the velocity of the rocket could be recorded. One such is shown in Fig. 7, the reproduction of a 56-second exposure. A particle is seen slowly entering the field of view. Its termination was caused by the transport of film to the next exposure, and in subsequent exposures its path was followed all the way until it left the field. Tousey, Koomen, McCullough and Seal (1965) have presented evidence suggesting that some, at least, of these particles are of natural origin. Only those of the low velocity group could have been distinguished as tracks on the photographs. Orders of magnitude more such particles moving too fast to record as tracks, are likely to have been present, contributing to the component F_e which formed a part of the general background of the photograph.

AN ECLIPSE PHOTOGRAPHY EXPERIMENT WITHIN THE UMBRA

We would like to suggest an experiment of a similar type which might be carried out during an eclipse from an aircraft. It is, in fact, almost the one described by Professor Righini. The proposal is to photograph the corona over the range from perhaps R/R_s = 2 to 10 or 20. Photographs would be made from as high an altitude as possible, indeed preferably from a rocket, so as to be completely free from the Rayleigh sky. The photographs would cover the interval between second and third contact and would be made from the eclipse center line. Under these conditions it should be possible to follow changes in the shadow cast by the moon in the earth's outer atmosphere as it moves from the corona on one side of the sun, to a central position where it is divided equally on either side, and finally, at third contact, lies on the other side of the sun. The screening involved is illustrated

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in Table I and Fig. 4 for an eclipse producing a shadow on the earth of 80 km width. Viewing the corona at $R/R_s = 2$, as the umbra progresses from second to third contact (i.e., observer moves from E to A in the umbra), the atmosphere above the camera is screened completely from direct sunlight out to an altitude which increases to about 17,000 km at third contact, when it suddenly becomes exposed once again to direct sunlight. Corrections would be required that allow for illumination by the sky below. From measurements of this type, however, it should be possible to learn something about the distribution of scattering material in the region out to 10,000 or 20,000 km from the earth. Precise photographic photometry would be required. From an aircraft, even at 40,000 feet, the required precision would be difficult to attain because of the residual Rayleigh sky background. From a rocket, however, it appears that it might be fairly easy to accomplish with the required precision by launching the rocket at such a time that the upper portion of its trajectory would extend from second to third contact. The difficulties of launching rockets from mobile platforms located on eclipse center lines are still very great, but we may look forward to the time when a launching of this type has a reasonable chance of success.

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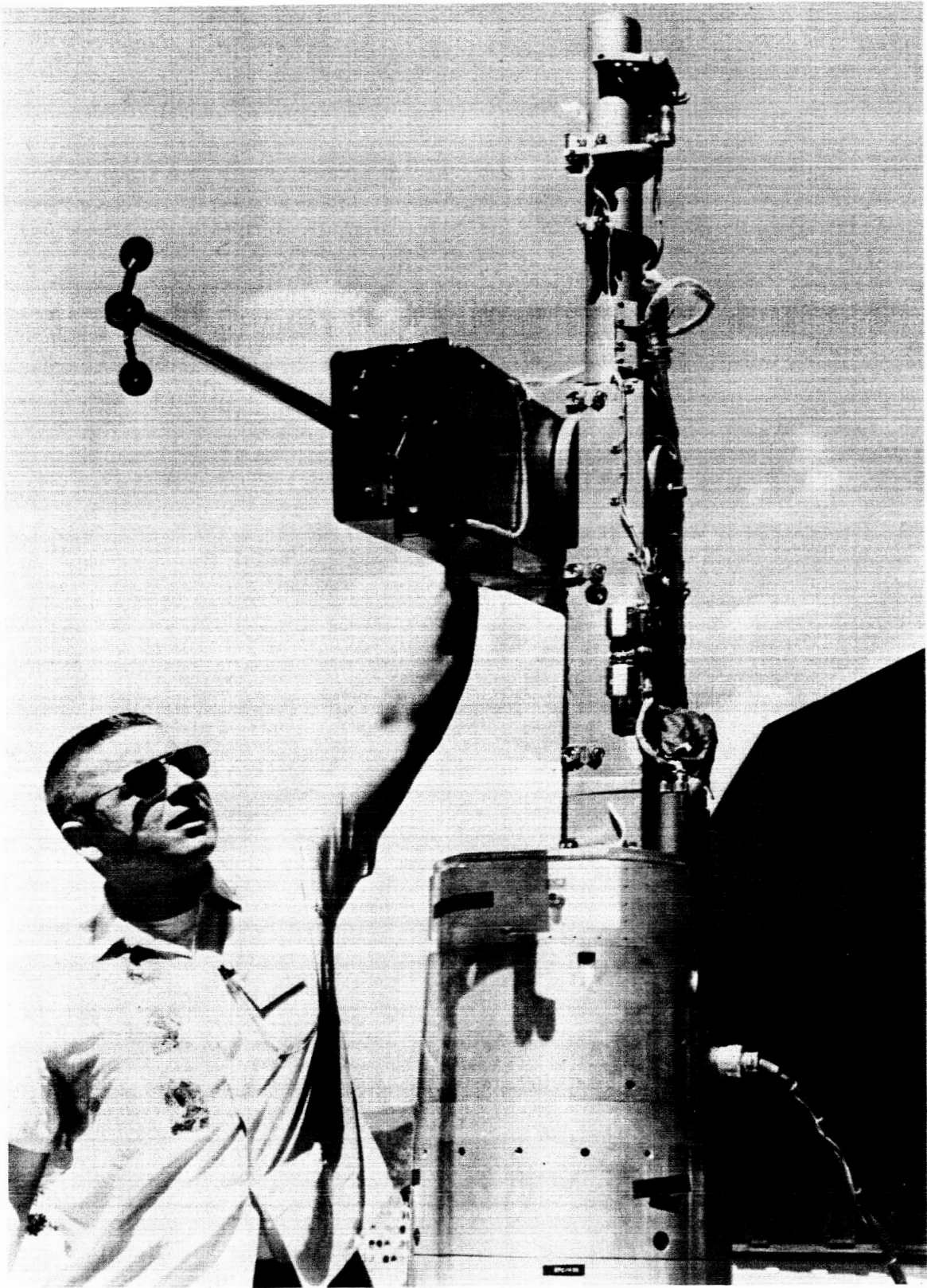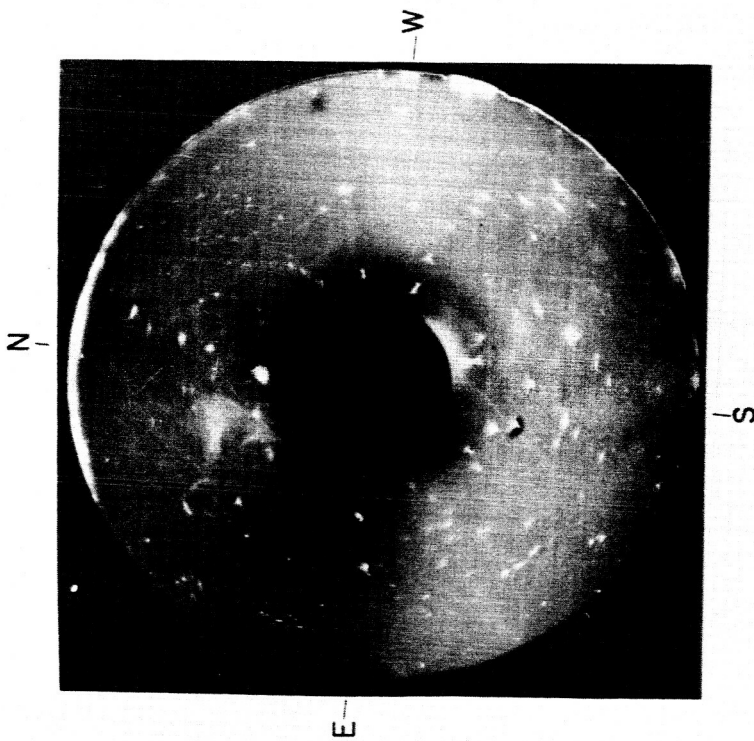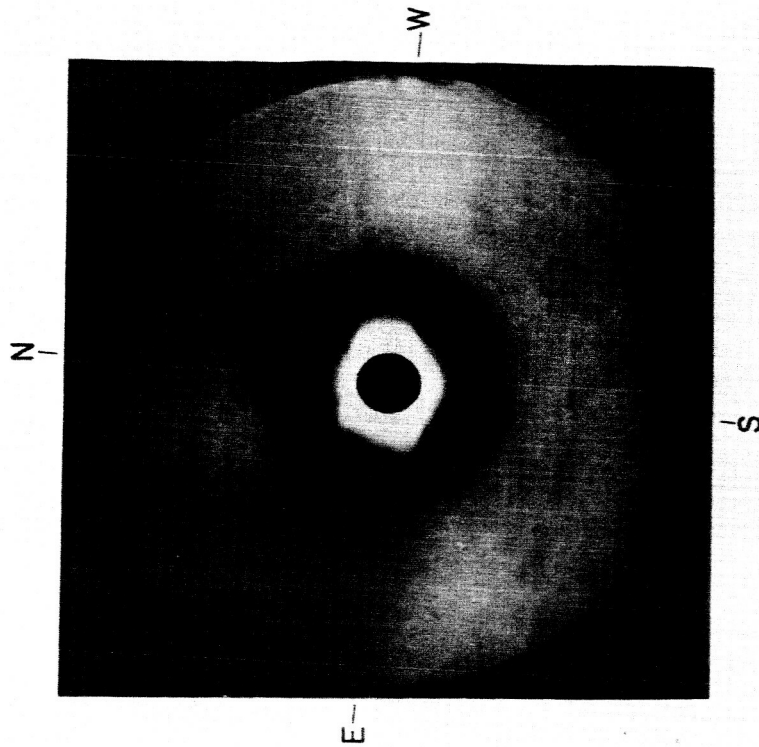
Fig. 1. Rocket coronagraphs, installed in a biaxial pointing con-
trol at the foreward end of an Aerobee-150 rocket. The
external occulters are mounted on a spar which is placed
in the position shown during flight, after removal of the
rocket nose cone. Lens openings are closed in photo.

THE WHITE LIGHT CORONA OF THE SUN

PHOTOGRAPHED FROM AN AEROBEE —HI ROCKET
U. S. NAVAL RESEARCH LABORATORY
JUNE 28, 1963

Fig. 2. Coronal exposure No. 11, shadowed by the occulter and its supporting arm. Picture (a) shows dirt specks on optics and out of focus tracks of sunlit particles. In (b) all artifacts have been removed by retouching, and a photograph of the corona during the July 20, 1963 eclipse (courtesy High Altitude Observatory) has been introduced at the proper scale and orientation. A coronal streamer is present at 15° N of W.
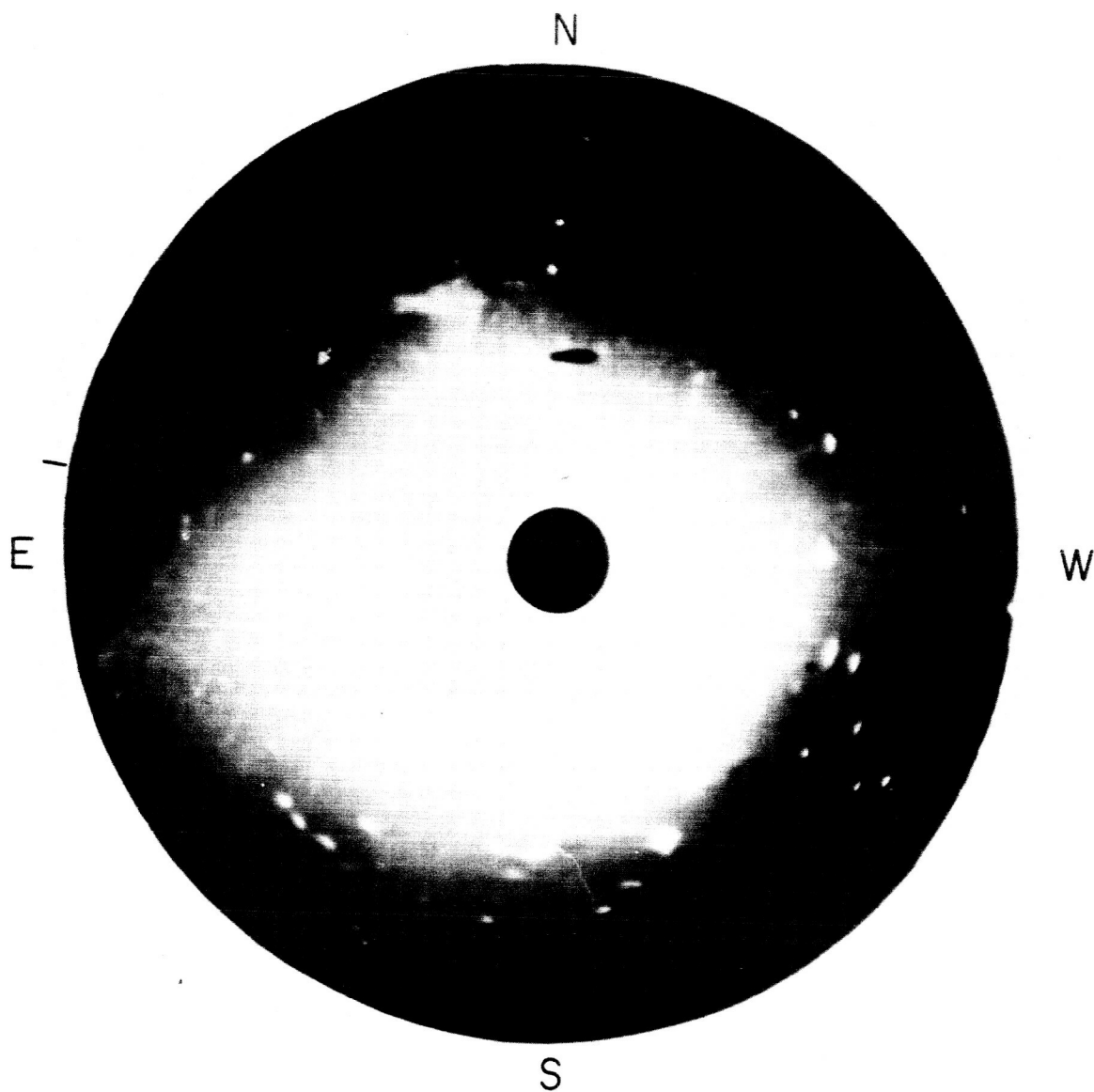
Fig. 3.   The corona printed from the original negative of exposure No. 11, with compensation for the vignetting function of the coronagraph.   The opaque central spot shows the size of the sun.
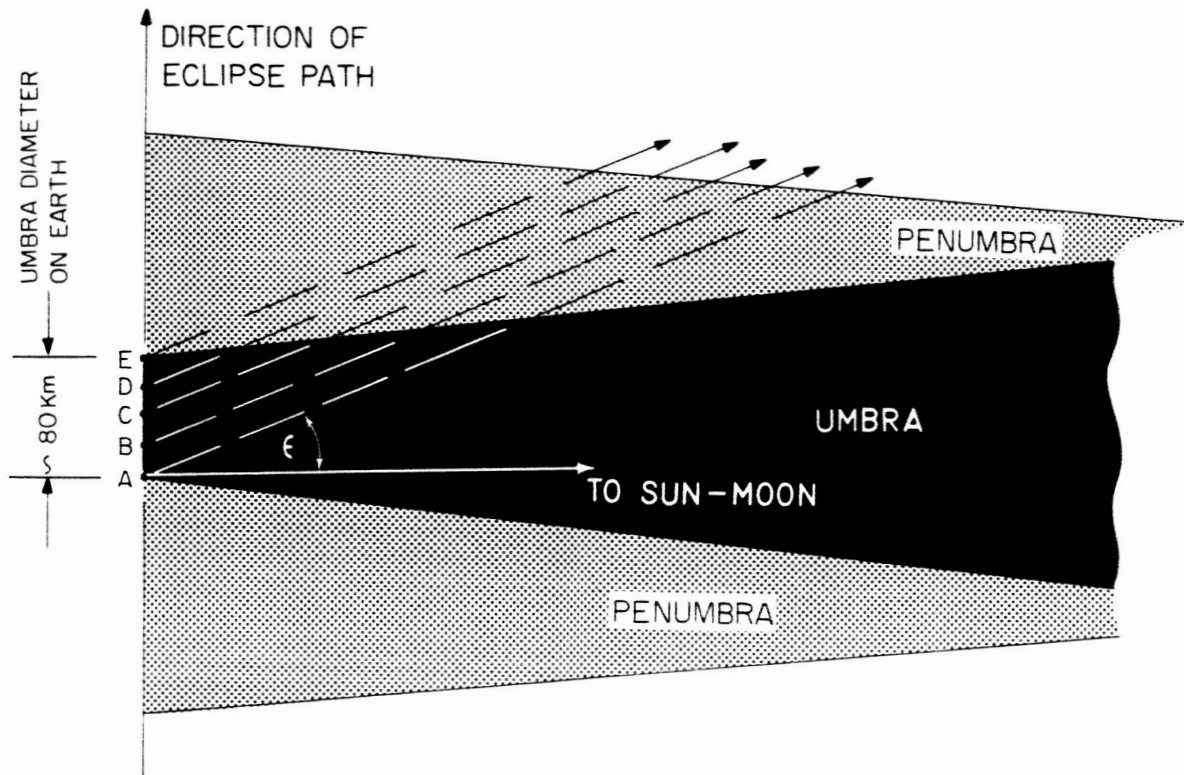
Fig. 4. Shadowing of the region between earth and moon, as observed from points in the umbra, but not to scale.

SHADOWING OF OUTER CORONAL MATERIAL BY MOON AT $\epsilon = 5$ R/R_0
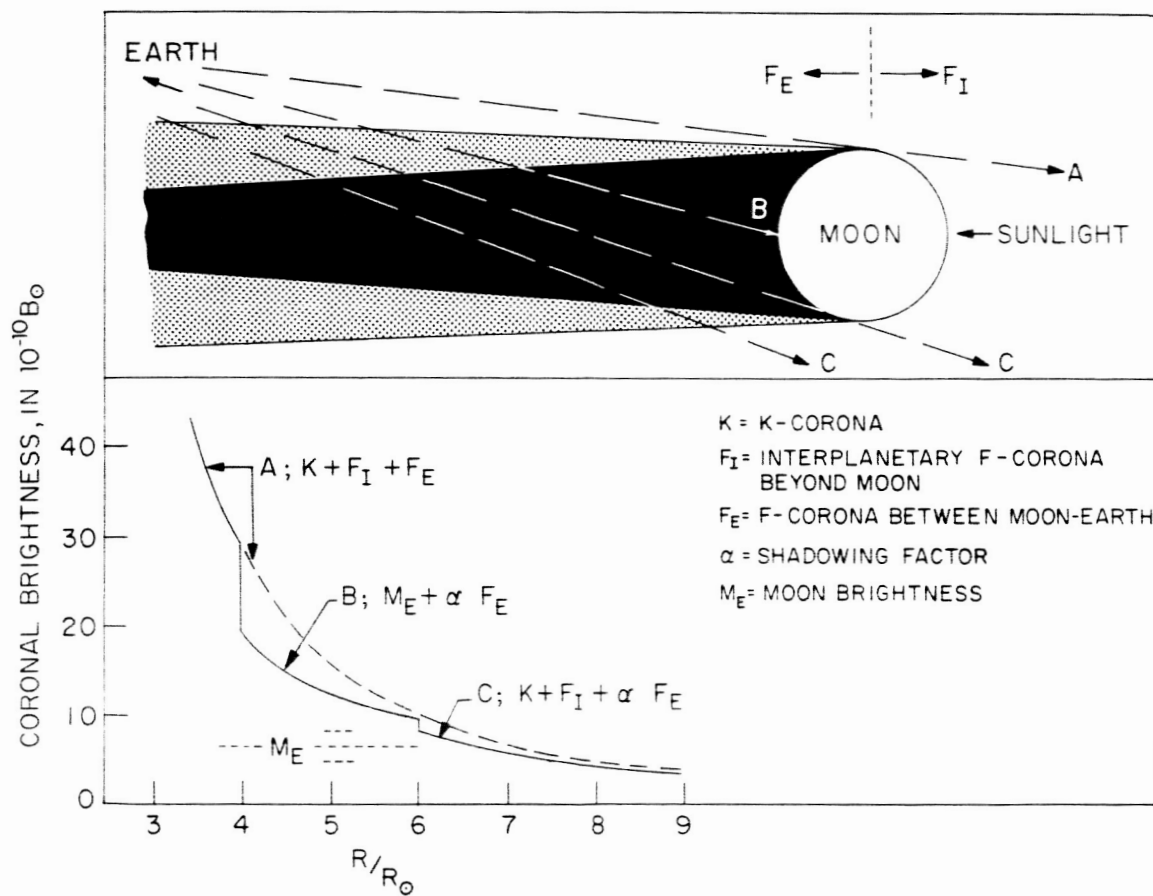
Fig. 5. Shadowing of the region between earth and moon, as
observed from a point outside the penumbra. The curve
shows the brightness of the moon and the shadow cast by
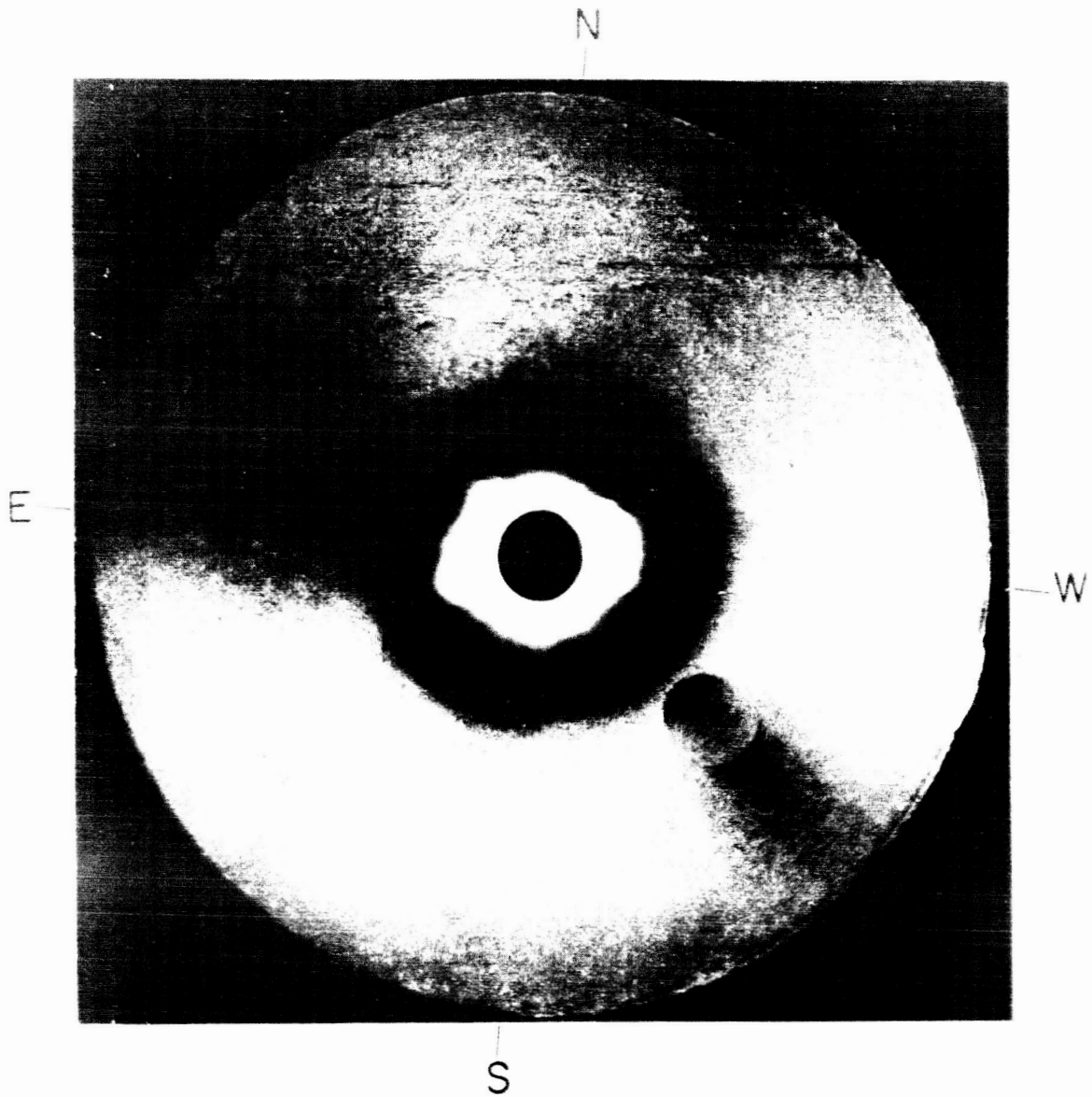it, estimated from the rocket results of June 28, 1963.

Fig. 6.   The moon and its shadow as they were expected to appear had the flight taken place.   Relative brightnesses were deduced from the geometry and curve of Fig. 5.

Fig. 7. Enlarged portion of the 56-sec coronal exposure, No. 19, showing the track of a distant sunlit particle. Pointing jutter caused the track to be roughly sinusoidal. The particle was in the field during most of the exposure.