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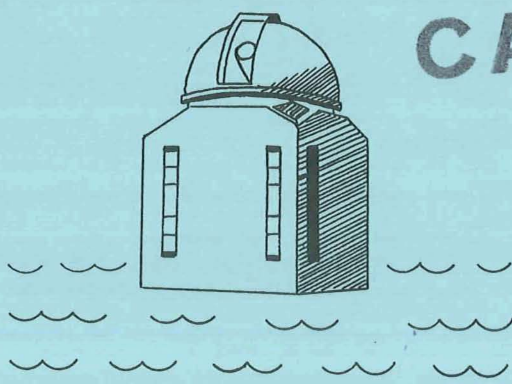
PHOTOMETRY OF THE OUTER SOLAR CORONA

FROM LUNAR-BASED OBSERVATIONS.

By

J. David Bohlin*



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HALE OBSERVATORIES

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Abstract

Two-dimensional isophotes of the extreme solar corona ($r_{max} \sim 45\ R_{\odot}$) have been derived from integrated vidicon pictures taken from the moon's surface by the unmanned probes *Surveyors 6* and *7*. These data were calibrated through use of previously published values for the coronal brightness gradient along the ecliptic. The resulting structure of the outer corona is compared to ground-based observations of the innermost corona ($1.125 \leq r/R_{\odot} \leq 2.0$) made by the High Altitude Observatory K-coronameter. The possible existence of a streamer seen by *Surveyor 7* is analyzed over the region $15 \leq r \leq 22.5\ R_{\odot}$.

1. INTRODUCTION

Eclipse measurements of the solar corona beyond 15 to 20 $R_\odot$ are precluded due to the residual sky brightness, even at stratospheric altitudes. Conversely, observations of the zodiacal light inward of a solar elongation angle $\varepsilon < 20°$ (i.e., $\lesssim 80\ R_\odot$) are prevented by twilight for ground-based observations, or by instrumentally scattered light for space probes. Thus the crucial interface zone between the corona and zodiacal light ($4 < \varepsilon < 20°$) remains poorly observed relative to the inner and outer portions.

These difficulties are overcome if the observations can be made from the lunar surface just after local sunset or before sunrise. There is no atmosphere to scatter light into the field of view, and the brightness of sunlight diffracted from the lunar limb is negligible due to the distance from the occulting horizon. This experiment was performed with four out of the seven unmanned *Surveyor* moon probes during the period 1966 to 1968. Preliminary results from *Surveyor 1* have been published (Norton *et al.*, 1967); further reduction of that data was precluded by a relatively primitive data format and calibration. An electronic failure on *Surveyor 5* left all the coronal images except those of the inner corona out of focus. Thus only the last two flights, *6* and *7*, yielded data amenable to the analyses contained in this paper.

Although the Surveyor program was originally designed to yield both absolute and polarization photometry, we found that the calibrations necessary to complete these programs for these coronal data were not sufficient. Thus only a relative photometry of individual frames could be accomplished. Details are given in section 2.

2. OBSERVATIONAL TECHNIQUES

2.1 Surveyor Vidicon Camera

The Surveyor camera system consisted of an elliptical folding mirror, a filter wheel, a variable-focus lens and iris, a mechanical shutter, and a 1-inch diameter vidicon tube (General Electrodynamics Corporation, 1335-A series). The alt-azimuth mounted mirror fed light to the vertical filter-lens-vidicon system. In Surveyors 6 and 7 the filters were polaroids (0-45-90°) plus a matching neutral density filter. The spectral response of the entire system was from 3900 to 6600 Å, with $\lambda_{eff} \sim 5200$ Å.

All of the coronal pictures analysed in this paper were taken at f/4 and 25mm focal-length settings using the non-polarizing neutral-density filter. An "integrate" exposure mode was accomplished by opening the shutter and turning off the electron scanning beam. After the desired exposure time, the shutter was closed and the integrated charge read off the target using a 600-line raster. Later each line was digitized into 684 elements; thus each "pixel" resolved $\sim 2\overset{\prime}{.}4$ arc.

2.2 Calibration of Vidicon Data

Effects such as frame shading and geometrical distortion were calibrated prior to flight and then removed during the basic image processing at the Jet Propulsion Laboratory. After some effort it was concluded that neither absolute nor comparative (to give polarizations) photometry was possible due to lack of adequate calibration of the vidicon integrate mode, and that only a relative calibration of frames made with the non-polarized filter might retain reasonable reliability.

This relative calibration was accomplished by requiring the vidicon signal along the ecliptic to match, point for point, the mean of published values for the extreme corona summarized by Blackwell *et al.* (1967), and illustrated in Figure 1. Although these values show a scatter of absolute brightness of $\gtrsim 50\%$ at any given elongation (illustrated by the region enclosed by dashed lines in Figure 1), their gradients are remarkably consistent, even between epochs at extremes of solar activity.

The vidicon signal was normalized to unity at the point 20 $R_{\odot}$ on the ecliptic. A calibration curve was determined which brought the ratio of the vidicon signal at any ecliptic point into agreement with the mean curve shown in Figure 1. This curve was then used to calibrate the entire field. The value of the vidicon signal used was the difference between the signal $\overline{S}$, averaged over a 3 x 3 "pixel" matrix centered on line L and element E for a given field point, and a mean background value, $\overline{S}_b$, determined at field positions far from the ecliptic.

The vidicon raster location of astronomical positions was determined by the star images contained in the frames (stars as faint as $m_v = \sim 4.6$ were recorded by a 30-minute integration in *Surveyor 7*). The problem was a standard astrometric one, complicated only by the fact that the vidicon raster, (L, E), was a cartesian coordinate system both rotated and enlarged with respect to the standard system, (x,y), used in astrometry. The final calculation of any point (L, E) from predesignated heliocentric coordinates (r, θ), where r = radius vector in solar radii and θ = position angle about the sun (N = 0°, E = 90°), was in error by $\lesssim$ 1 pixel ($\sim$ 2$'$.4 arc) as determined by star images.

2.3 Corroborating K-coronameter Observations

The High Altitude Observatory kindly supplied K-coronameter observations of the innermost ($1.125 \leq r \leq 2\ R_\odot$) corona taken on the same or nearly the same days as the Surveyor pictures. The K-coronameter is a land-based, photoelectric scanning coronagraph that separates the coronal signal from the background solar aureole by virtue of the polarization of the K-corona. Its output signal is the product of the polarization and brightness of the corona, pB, and is measured in units of 10^{-8} of the center of the solar disk, $I_\odot$. The characteristics of the data from this instrument have been covered in the recent literature (Hansen et al., 1969 a; Bohlin, 1970 a).

3. OBSERVATIONAL RESULTS

3.1 Surveyor 6: 24 November 1967

The brightness contours derived from Surveyor 6 are shown in Figure 2. These isophotes were originally generated by computer from a 5 line x 5 element grid of the vidicon picture; the final contours were then drawn by hand as smoothed envelopes, so that the contour band-width is a measure of the uncertainty (photometric and noise) in the data. The minimum (outermost) contour is that level at which the size of the signal above background equaled the propagated RMS error. The ratio of the maximum to minimum contour levels indicates a usable dynamic range of ~ 15x for this vidicon, comparable to typical photographic emulsions.

The outer corona represented by these isophotes is quite symmetric about the ecliptic and did not display any discernible structure far from the solar equator-ecliptic plane. These contours thus imply an absence of large, bright streamer structure on the east solar limb of 24 November 1967.

The K-coronameter observations during this period, which in favorable circumstances can help indicate the presence of streamer structure (Bohlin, 1970a), were quite limited by cloudy weather. The isophote picture derived from the available scans (at 1.125 and 1.25 $R_\odot$ only) are shown also in Figure 2 at both identical and 4x enlarged scales as compared to the Surveyor 6 observations. Scans of such limited extent above the limb are not sufficient to infer the presence of streamers.

Examination of the disk activity several days either side of 24 November 1967 is a little more helpful in inferring possible coronal structure. There was little or no significant activity at all north of 10° S latitudes, but a band of activity did exist from 15 to

30° S. Based on a previous study of the association of disk activity to coronal structure (Bohlin 1970a, b), we might expect that the northern quadrant of the east limb to have been relatively devoid of distinct streamer structures, but that some streamers may have existed in the center of the southern quadrant. In fact, a study of the brightness profiles at constant radii from the sun (Figure 5, left side) shows that the southern quadrant was brighter than the northern quadrant for radii $\lesssim 20\ R_{\odot}$. This further confirms the idea that perhaps the northeast quadrant of the 24 November 1967 corona was of a quiet or background nature.

3.2 Surveyor 7: 23 January 1968

The Surveyor 7 observations were made much later after lunar sunset than those of 6 and with a longer exposure time. (The longer integration times were possible because it was found the vidicon filament could be switched off during integration.) Thus the lunar limb cuts off the field inward of $\sim 15\ R_{\odot}$, but the measurable ecliptic brightness extends almost to $45\ R_{\odot}$. The isophotes from Surveyor 7 are shown in Figure 3, which is entirely analogous to Figure 2. Due to the inclination of the ecliptic to the lunar horizon only a limited portion of the north-east quadrant corona is visible. The inner isophotes exhibit reasonable symmetry about the ecliptic over the limited range of complementary latitudes north and south about the ecliptic.

The K-coronameter observations for this date were exceptionally good and complete to a maximum $r = 2.0\ R_{\odot}$. The resulting isophote picture in Figure 3 demonstrates that large, bright streamers were almost certainly present on the east limb at position angles of 20 and 145°. The former feature, if present in the outer corona, would have been hidden by the lunar limb. The feature at 145°, however, should have emerged clearly in the field of view in the southeast quadrant. A description of the search for this feature is given in section 4.1 below.

To confirm the possible presence of this streamer, it is useful to pursue the nature of the K-coronameter feature at 145° by comparing it to the underlying disk activity. For this purpose it is only necessary to investigate that activity within ~40° either side of the limb position for the date in question. That is, the Thomson scattering responsible for the K-corona has a sharp maximum for electrons located very near to, and in directions perpendicular to, the observer's plane of the sky (for example, see Leblanc _et al_., 1970). The combined effect of the scattering mechanism plus the rapid decrease of electron density away from the sun is to render the brightness of a streamer located ~40° from limb passage at only about 1/10 that of its limb passage value (see Hansen et al. (1969b) for review of calculations).

To this end, Figure 4 superposes the K-coronameter isophotes of 24 January 1968 around the solar disk of 26 January. The limb position for the 24th is marked on the disk as a heavy line bounded by dashed lines at ±40° heliographic longitude. The correspondence of the large polar-crown prominence at 55-60° S and the centroid of the 145° enhancement strongly suggests that this coronal feature was a large helmet streamer of classical appearance, with loop structure connecting the opposing magnetic polarities on either side of the prominence. The possibilities of such loop structure is further suggested by the fine scale structure of the isophotes themselves, and a sample coronal arch is shown by the dashed line. In basic size (~30° span in latitude) and appearance (arches to ~1-1/2 $R_\odot$) this streamer base must have been extremely similar to the multiple-arch system analyzed in detail by Saito and Hyder (1968) or the streamer-enhancement "I" by Bohlin (1970a,b).

4. DISCUSSION

4.1 Streamer Photometry from 15 to 22-1/2 $R_\odot$

The previous section established two observational facts: First, at least the northern quadrant of the corona observed by *Surveyor 6* probably represented only the background corona plus zodiacal light during this period. Second, the southern quadrant observed by *Surveyor 7* might contain an additional contribution due to a streamer at $\sim$145° as suggested by the K-coronameter observations.

These ideas are clarified by Figure 5 which contains the brightness profiles (in units relative to an ecliptic brightness of unity at 20 $R_\odot$) along those radii which both are common to *Surveyors 6* and *7* and also retain reasonable photometric accuracy ($15 \leq r \leq 22.5\ R_\odot$). The *Surveyor 6* profiles from 0 to 85° were chosen as representative of the true background illumination to be subtracted from the *Surveyor 7* profiles in a search for a streamer signal.

The differences between these sets of smoothed profiles are given in Figure 6; the propagated probable error is indicated. The profiles of the outermost K-coronameter scans are given at the bottom of Figure 6. The correspondence in position and apparent angular size between these K-coronameter and *Surveyor* data are persuasive evidence that the residuals are real and represent detection of a streamer between 15 and 22.5 $R_\odot$.

The intensity gradient from these residuals is plotted in Figure 1; the normalization brightness of 4.8×10^{-11} $B_\odot$ = 1.00 relative-brightness was used to plot these points on an absolute scale. For comparison, the streamer residual brightness values derived by Schmidt (1953), Michard (1954), and Saito (1959) are given. Considering the photometric uncertainties in such extended eclipse photometry, and the uncertainties associated with the present values, the correspondence is satisfactory. Conversely, these results in themselves are not sufficient to warrant a new electron density model, which in the last analysis would be little different from extrapolations of those given by Michard or Saito. Such derivations are no better than the physical model for the line-of-sight distance through the streamer, of course, which is still largely a speculative parameter at such radii.

4.2 Concluding Remarks

Time-integrated vidicon pictures of the outer corona were obtained by the *Surveyor* moon probe missions. An analysis of the last two such missions led to a derived streamer brightness value of $\sim 1.25 \times 10^{-11}$ $B_\odot$ at 15 $R_\odot$. These brightness values are in reasonable agreement with extrapolated eclipse measurements of streamers and represent a two-fold increase in the maximum distance at which streamer photometry has been achieved.

This experiment has shown that a properly calibrated, moon-based photometer could, by observing the rise and set of the corona-zodiacal light twice every lunar rotation, immeasurably increase our understanding of this otherwise ellusive interface region.

ACKNOWLEDGEMENTS

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Schmidt, M.: 1953, Bulletin Astron. Netherlands 12, 61.

CAPTIONS

Figure 1. Brightness (relative to the solar disk $B_{\odot}$) of the outer corona and zodiacal light as a function of elongation from the sun. The uppermost dashed lines (----) are the mean envelope around the existing measured values as summarized by Blackwell et al. (1967). The enclosed dash-dot line (—- · ——) was used to calibrate the Surveyor data in this paper; those data are normalized to unity at 20 $R_{\odot}$, at which point $\overline{B/B_{\odot}} = 4.8 \times 10^{-11}$. The left-hand curves are streamer brightnesses above background; the streamer points derived in this paper are in the lower left.

Figure 2. Isophotes derived from frame 20063 of Surveyor 6: exposed 3 minutes through a non-polarized filter starting at 15:45 UT, 24 November 1967. The isophotes are marked in terms of the ratio of the surface brightness to that of the ecliptic corona at 20 $R_{\odot}$. Calibration has required the gradient along the ecliptic to match the dash-dot curve in Figure 1. The isophotes of the innermost solar corona from K-coronameter observations are shown at 4x scale as the Surveyor data.

Figure 3. Isophotes from frame 37432 of Surveyor 7: exposed 15 minutes through a non-polarized filter starting at 14:32 UT, 23 January 1968. This figure is analogous to Figure 2.

Figure 4. Superposition of K-coronameter isophotes of 24 January 1968 about the solar disk of 26 January, as derived from the Fraunhofer Institute disk maps. The east limb of 24 January is marked as a solid line on the disk, bounded by dashed lines at $\pm 40°$ longitude. The disk within this zone most probably underlay any coronal structure observed by the K-coronameter on the 24th. The probable existence of a large helmet streamer at position angle 145° is indicated by a dashed loop about the quiescent prominence and connecting the observed coronal structure.

Figure 5. Brightness profiles along constant radius scans for $15 \leq r \leq 22.5\ R_{\odot}$. The vertical axes are in units of brightness relative to an ecliptic value of 1.00 at 20 $R_{\odot}$. Left side: Surveyor 6; the north quadrant has been reflected about the apparent plane of symmetry at 85° for $r = 15$ and 22.5 $R_{\odot}$ as dashed lines. Right side: Surveyor 7. Note the greater brightness of the "wings" for 7 as

compared to the northern quadrant of _6_.

Figure 6. Residuals between the smoothed profiles of the southern quadrant from _Surveyor 7_ and the northern quadrant from _Surveyor 6_. The bottom two profiles are the outermost K-coronameter scans from 24 January 1968 showing the position of the 145°-enhancement on that date (see also Figure 3).

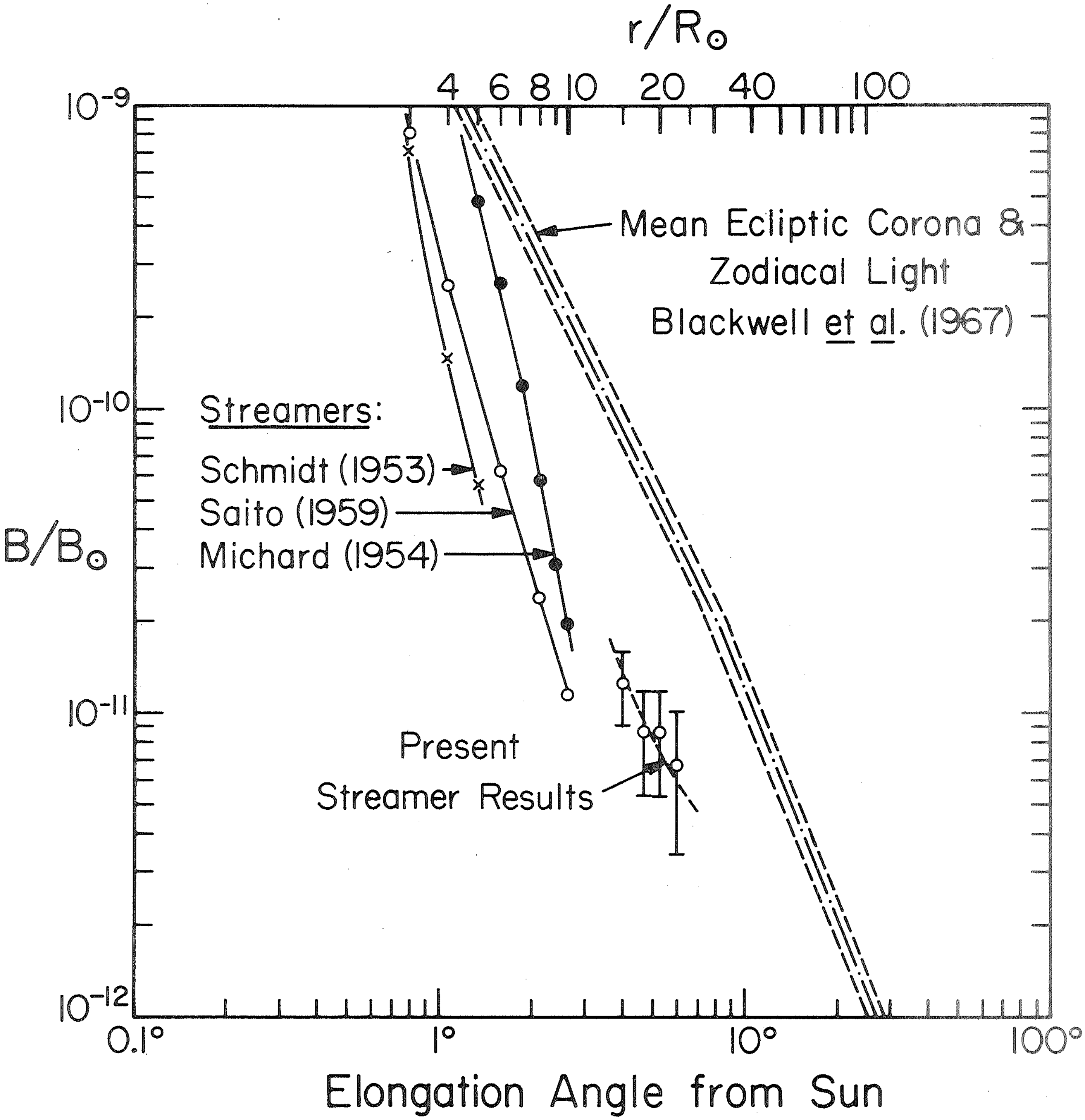
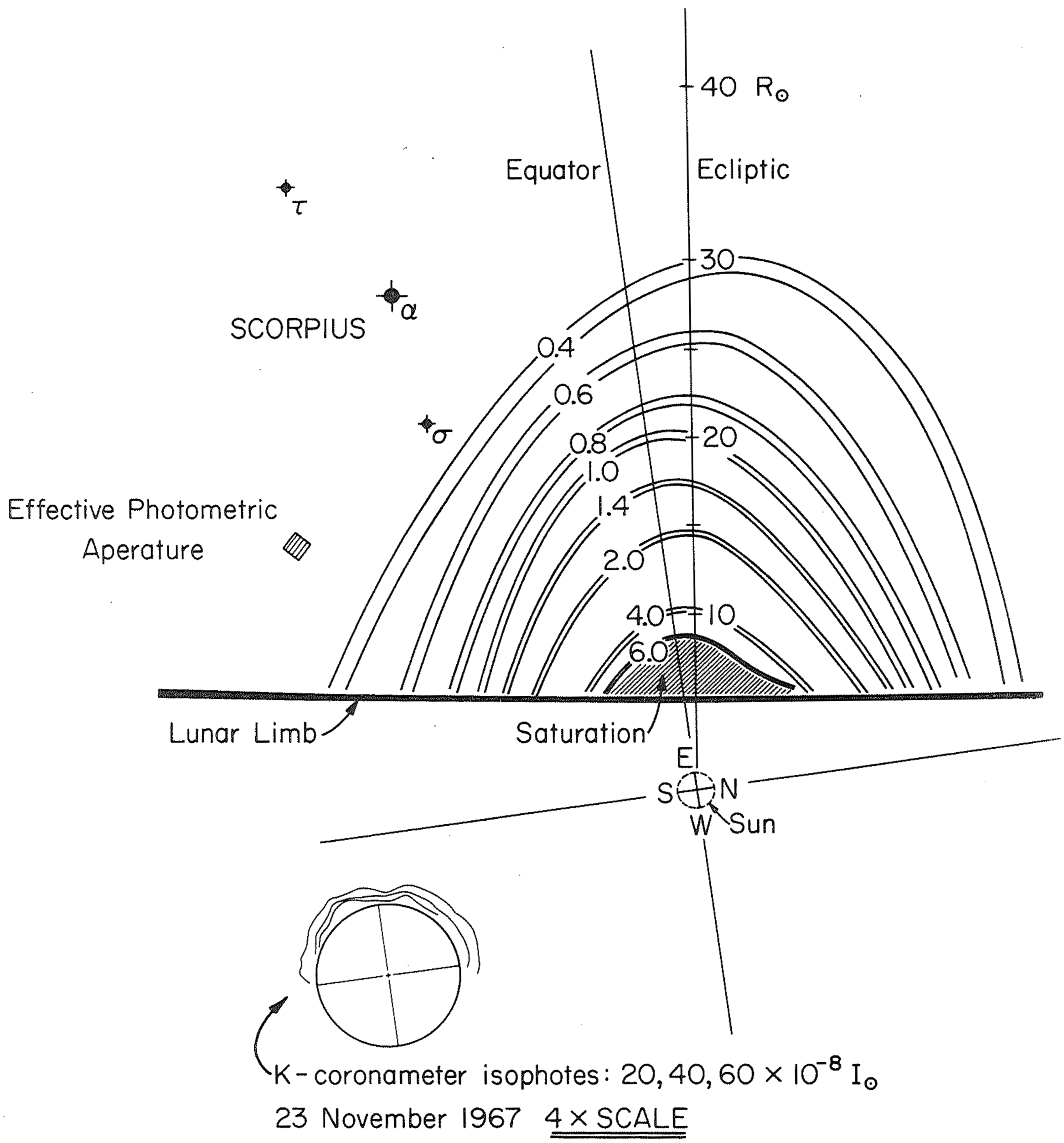
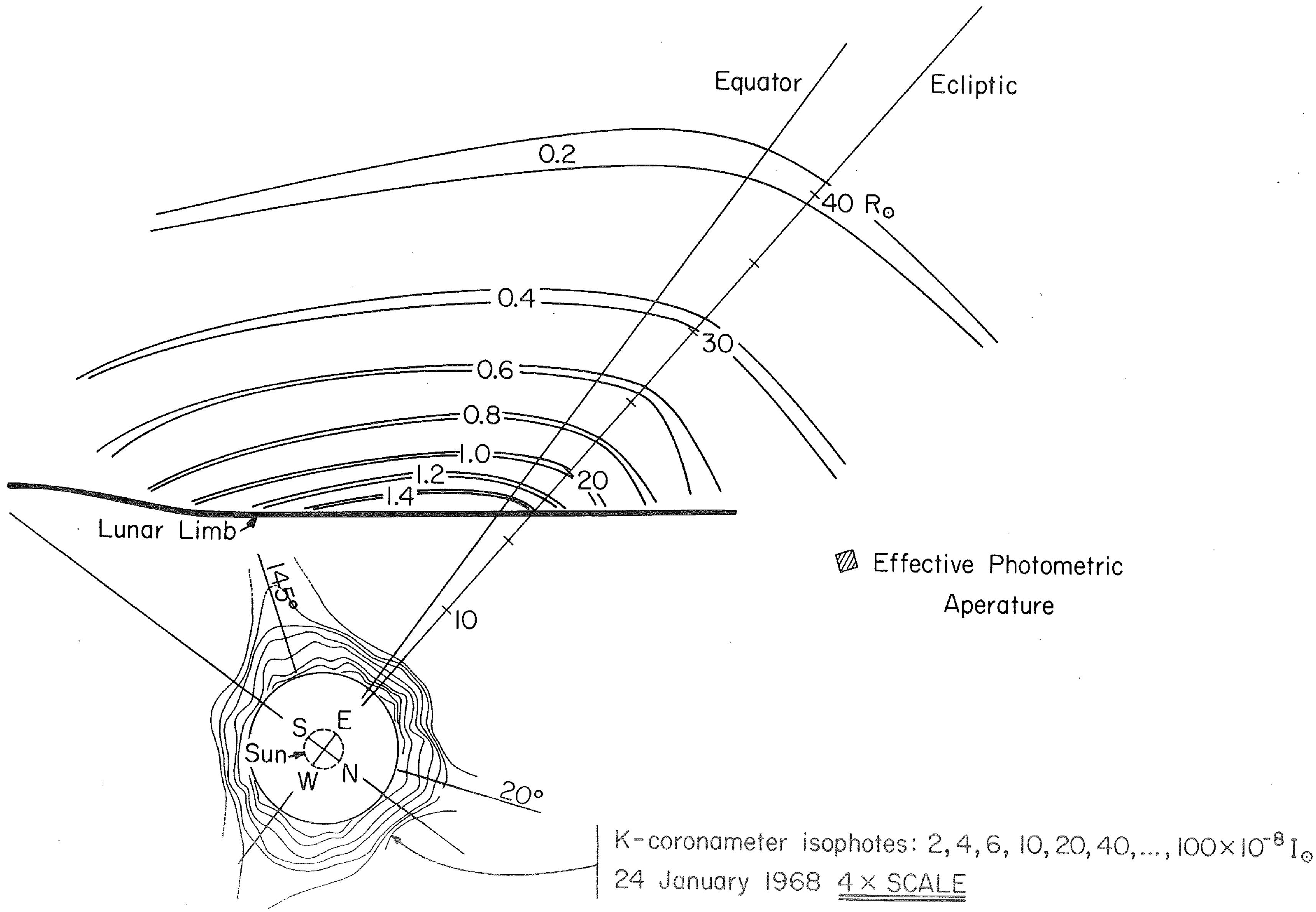

r/R⊙
4 6 8 10 20 40 100
10^-9
10^-10
10^-11
10^-12
B/B⊙
Mean Ecliptic Corona &
Zodiacal Light
Blackwell et al. (1967)
Streamers:
Schmidt (1953)
Saito (1959)
Michard (1954)
Present
Streamer Results
0.1° 1° 10° 100°
Elongation Angle from Sun

Fig. 1



40 R⊙
Equator
Ecliptic
τ
α
SCORPIUS
σ
30
0.4
0.6
0.8
20
1.0
1.4
Effective Photometric
Aperature
2.0
4.0
10
6.0
Lunar Limb
Saturation
E
S
N
W
Sun
K-coronameter isophotes: 20, 40, 60 × 10⁻⁸ I⊙
23 November 1967 4 × SCALE

Fig. 2



Equator
Ecliptic
0.2
40 R⊙
0.4
30
0.6
0.8
1.0
20
1.2
1.4
Lunar Limb
Effective Photometric
Aperature
10
145°
S
E
Sun
W
N
20°
K-coronameter isophotes: 2, 4, 6, 10, 20, 40, ..., 100×10⁻⁸ I⊙
24 January 1968 4 × SCALE

Fig. 3

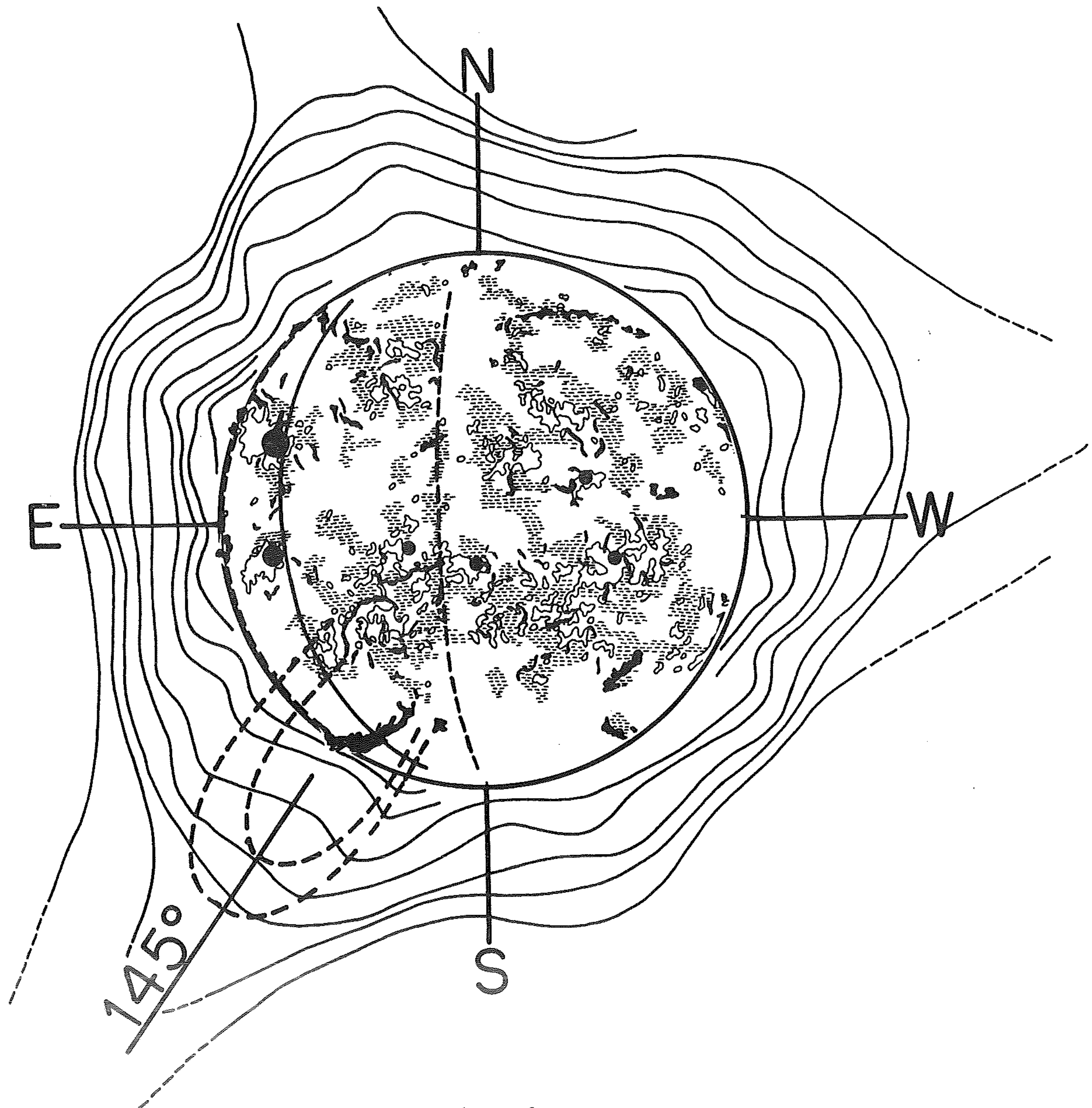


Fig. 4

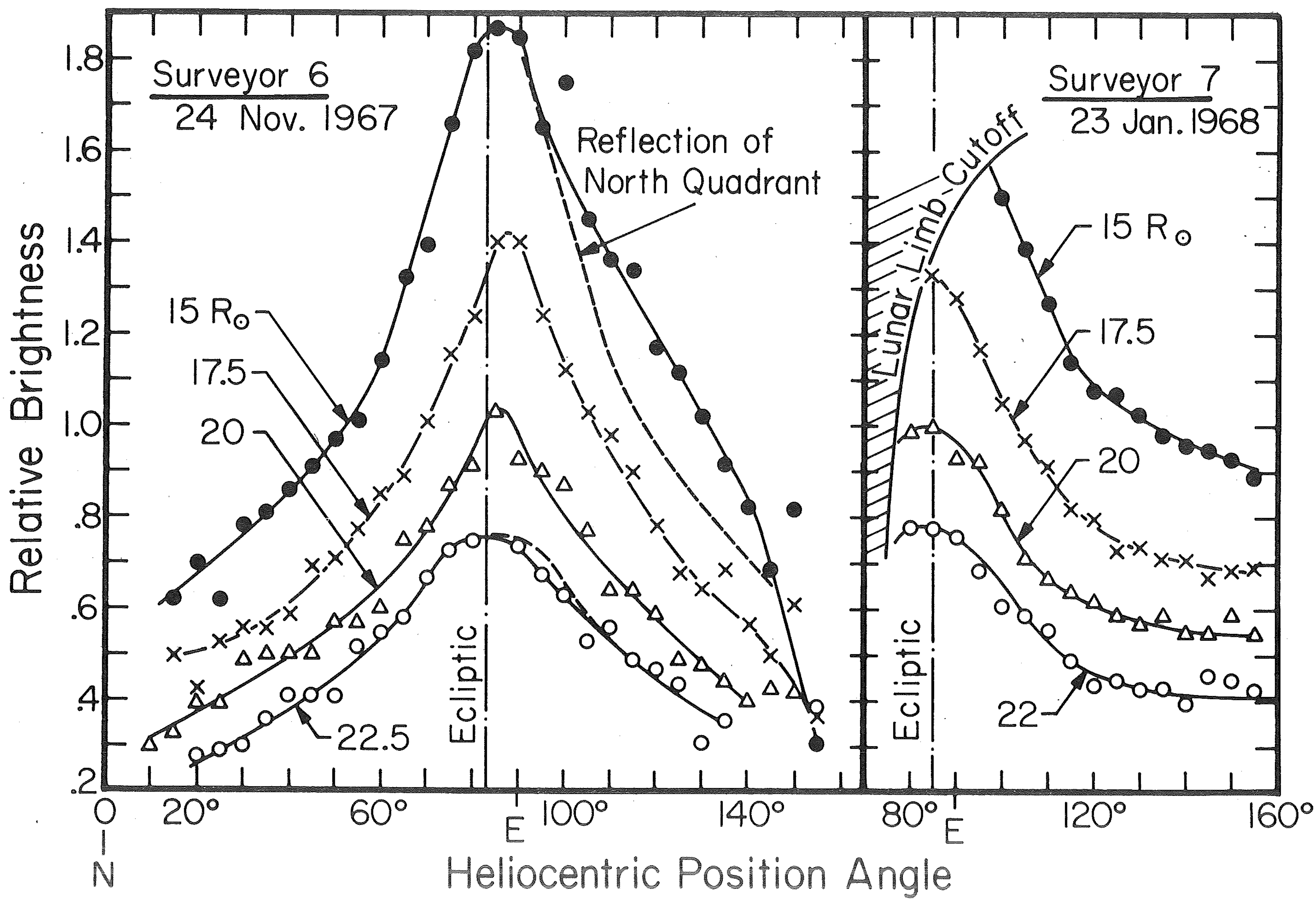

Surveyor 6
24 Nov. 1967
Reflection of
North Quadrant
15 R☉
17.5
20
22.5
Ecliptic
Surveyor 7
23 Jan. 1968
Lunar Limb Cutoff
15 R☉
17.5
20
22
Ecliptic
Relative Brightness
1.8
1.6
1.4
1.2
1.0
.8
.6
.4
.2
0
N
20°
60°
E
100°
140°
80°
E
120°
160°
Heliocentric Position Angle

Fig. 5

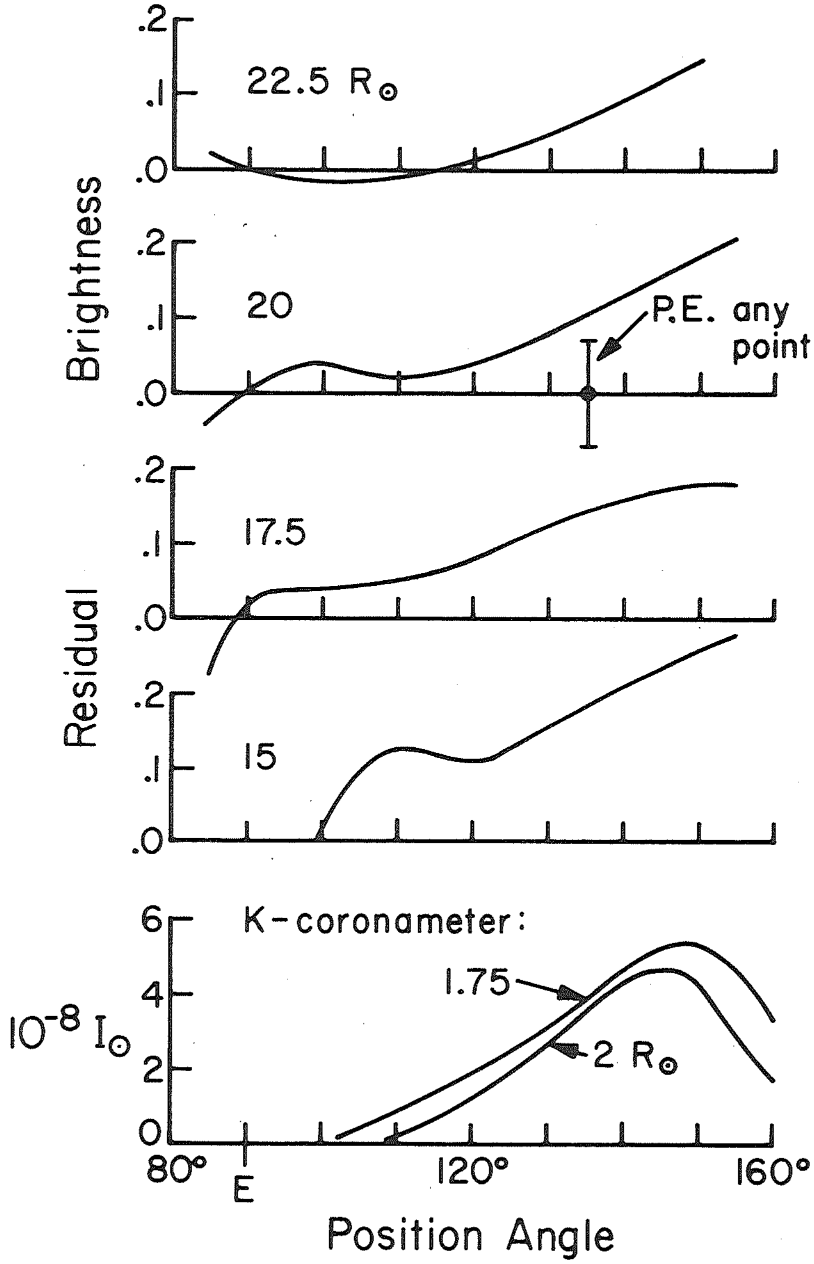

.2
.1
.0
22.5 R⊙
20
P.E. any point
17.5
15
Brightness
Residual
6
4
2
0
K-coronameter:
1.75
2 R⊙
10^{-8} I⊙
80°
E
120°
160°
Position Angle

Fig. 6