THE F-CORONA AND THE CIRCUM-SOLAR DUST EVIDENCES AND PROPERTIES [G. NIKOLSKY MEMORIAL LECTURE]

S. KOUTCHMY
Institut d'Astrophysique,
Paris
P.L. LAMY
Laboratoire d'Astronomie Spatiale,
Marseille

ABSTRACT. This review deals with the main properties of the F-corona. Analysis of its morphology and photometry allows to derive a new axisymmetric, non-spherical model. Polarization, color and infra-red properties are further considered. We suggest the existence of a variable "local" component surperimposed on a quasi-stationnary "far" component.

INTRODUCTION

Originally the Fraunhofer corona, the F-corona together with the K-corona forms the solar corona conspicuously seen during total solar eclipses. The dominating K-corona (more than 90 % of the coronal brightness) is produced by solar light scattered by free electrons; it is characterized by the absence of Fraunhofer lines of the solar spectrum which are completely smeared out by the large Doppler shifts of the high velocity electrons ($T \sim 2 \times 10^6$K) of the corona. The F-corona is the component of the corona light which does exhibit solar Fraunhofer lines which enabled to recognize it as the inner Zodiacal Light caused by light scattering off interplanetary dust grains. In the polar regions, these spectral lines are observed as close as 1.1 $R_\odot$ (see Koutchmy and Magnan, 1973).

This lecture will review the main properties of the F-corona and present a new axisymmetric, non-spherical model. We shall further examine if those properties allow to delineate two components in the F-corona:

i) the "far" F-corona resulting from light diffracted (forward scattering) by interplanetary grains of the Zodiacal cloud which is essentially unpolarized, has approximately spherical symmetric and which dominates in the visible wavelengths

ii) the "local" F-corona resulting from light scattering by circum-solar dust grains which is probably polarized, highly non-spherical symmetric (equatorial enhancements) and which dominates in the infra-red wavelengths.

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1. PHOTOMETRIC AND POLARIMETRIC ANALYSIS OF THE F-CORONA

1.1. Recent progress

The ground-based observations of Allen (1973) and Nikolsky (1975) and the aircraft (windowless) observations of Blackwell (1955) and Michard (1956) performed during the 1940-1970 period are now considered classical; they culminated in the synthesis of axially symmetric models of Van de Hulst (1953) and Saito (1970). Since 1970, considerable progress have been achieved on several fronts: instrumentation, technological means, methods, reduction procedure. Let us give a few examples:

- observations carried aboard high-altitude subsonic and supersonic aircrafts, balloons and rockets during total eclipses;
- coronographic observations carried aboard satellites (Skylab, Solwind, SMM,...) outside total eclipses;
- near-infrared imaging with IR emulsions and IR vidicons;
- infrared scannings (up to 12μm) and infra-red spectroscopy;
- the use of sophistical masks, such as neutral radial filters, avoiding over-exposition and therefore improving the spatial resolution;
- an improved understanding and modeling of the parasitic effects (coronal aureola, variation of the sky luminance) further checked by controlling the lunar background (Earthshine);
- two-dimensional photometry with fast microdensitometers and computers;
- sophisticated image processing such as numerical neutral filtering;
- improved absolute calibrations using stars in the field.

This, by no means, imply that all pre-1970 observations are superseded; several of them which benefited from exceptional conditions (such as the windowless aircraft observations which have never been repeated since) and which were carefully reduced are still extremely valuable as we shall see below.

1.2. Analysis of the flattening of the F-corona

Although the flattened aspect of both K and F coronae was perceived quite early, only the non-sphericity of the K-corona as demonstrated by large coronal streamers and transient events has been thoroughfully analyzed in connection with solar activity as defined by the Wolf number (sunspots). The ellipticity of the F-corona was always neglected leading to classical spherical models (e.g., Saito, 1970) although its natural extension, the Zodiacal Light, is known to be highly flattened. Quantitative equator / pole differences have been reported since 1975 (e.g. , Keller et al., 1975; Saito et al., 1977; Dürst, 1982). The analysis of the flattering of the F- corona faces two major problems:

i) the distortion introduced by the K-corona whose ellipticity varies further with time. In this context, it is interesting to point out that the equatorial F-corona is best observed during the period of <u>maximum</u> solar activity since the almost spherical K-corona tends to concentrate in the polar sectors (negative ellipticity). Conversely, the polar F-corona is best observed during the <u>minimum</u> of solar activity since

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the K-corona flattens in the equatorial direction and becomes quite faint in the polar regions (coronal holes).

ii) parasitic effects introduced by variations of the sky background (ground-based observations) or of the instrumental background (space coronographs). It is imperative that these backgrounds be very low but they must anyway be modelled and substracted for a correct analysis (see Michart and Sotirovsky, 1965; Koutchmy and Koutchmy, 1974; Dürst, 1982). The flattening index $\varepsilon_F = R_{eq}/R_{pol} - 1$ may now be studied as a function of R_{eq} in the following way: on a given isophote corrected for the sky background, R_{eq} and R_{pol} are measured; they are not however strictly recorded along the equatorial and polar directions but averaged over sectors of ±22.5° centered along those directions. The result for the 1983 eclipse (Koutchmy and Nitschelm, 1984) is shown in Fig. 1. The classical separation into three regions, $1<R<2\ R_\odot$ where the K-corona dominates, $R>4\ R_\odot$ where the F-corona dominates and $2<R<4\ R_\odot$ where both coronae are mixed is dramatically illustrated. One sees that starting from asymptotic sphericity as $R \rightarrow 1\ R_\odot$, the flattening index rapidly increases with R_{eq}. A set of carefully selected measurements on the basis of low sky backgrounds and high-quality photometry are regrouped in Fig. 2. Here, we explicitly assume that the F-corona is stationary and that the dispersion of the data points result only from errors of measurements. There is a good agreement with the result coming from photometric profiles (next section) and a smooth continuity with the ellipticity of the Zodiacal Light as determined by Dumont and Sanchez (1976). It should be kept in mind that this method is a first approximation since it allows to compare average equatorial and polar brightness and gives no information in the other directions.

1.3. Photometry of the F-corona

Once the luminance of K+F has been obtained as a function of solar distance after proper corrections for sky and instrumental backgrounds and the aureola effect, the separation between the K and F components requires further information either spectroscopic or polarimetric (e.g., Koutchmy and Magnant, 1973). We shall make use here of the polarization P_{K+F} which may be written:

$$P_{K+F} = \frac{K}{K+F} P_K + \frac{F}{K+F} P_K$$

Now $P_K(r)$ can be theoretically calculated assuming an homogeneous spherically symmetric model and can be shown to be rather insensitive to the adopted model and to rapidly converge toward the asymptotic value $P_K = 0.64$ at $5\ R_\odot$ (Saito, 1970). The classical condition $P_F=0$ valid up to $\sim 4\ R_\odot$ then allows to obtain an intensity profile of the F-corona. Beyond $4\ R_\odot$, the model can be extended on the basis of the variation of the density of electrons assuming it is a monotonically decreasing function of r. This is not too critical as K becomes rapidly quite faint. To the classical result of Blackwell et al. (1967) and to the classical models of Saito (1970) and Allen (1973) which are in fact averages of various measurements, we added the data of Koutchmy and Magnant (1973)

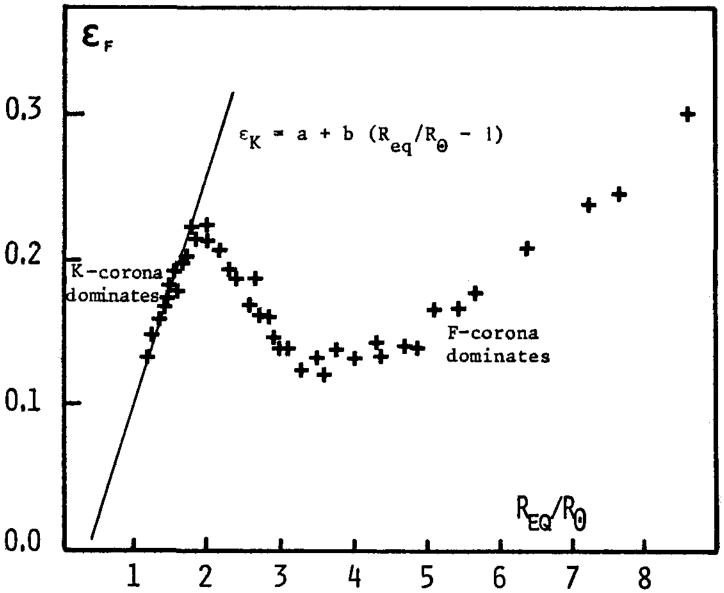

Fig. 1: The flattening index of ε_F the K-corona and of the inner F-corona versus equatorial heliocentric distance.

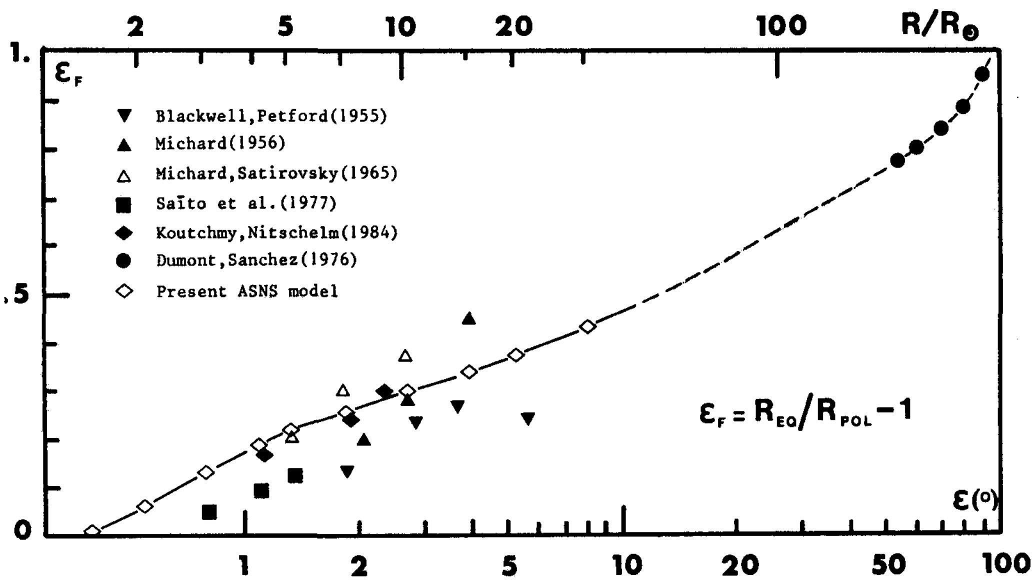

Fig. 2: The flattening index ε_F of the F-corona versus equatorial heliocentric distance in $R_\odot$ (top scale) or elongation in degrees (lower scale).

for the inner corona, of Koutchmy (1973) , of Keller et al. (1975), of Crifot-Magnant and Picat (1980) for a coronal hole and the most recent data of Dürst (1982) to build the axisymmetric non-spherical model ("ASNS") displayed in Fig. 3 valid in the wavelength interval 400-600 nm. Beyond 4 $R_\odot$, the intensity profiles are well represented by the power laws r^{-n} with n = 2.25 along the equator and n = 2.47 along the poles which smoothly connect to the inner Zodiacal Light (Leinert et al., 1976; Dumont and Sanchez, 1976). The ellipticity of the F-corona recalculated from these profiles is given in Fig. 2 and is in good agreement with the data points.

1.4. Polarization

The polarization of the F-corona is of crucial value for the understanding of the Zodiacal cloud as it can yield information on the relative importance of dust particles distributed along the line-of-sight and which diffract mainly non-polarized light and of circumsolar dust particles which scatter polarized light. Let us first consider the measurements of P_{K+F} which have been regrouped in Fig. 4 and which pertain to visible wavelengths. The situation is quite complex as P_{K+F} along the polar direction depends strongly on solar activity. We have therefore indicated this information. However, the reality of two diverging behaviors beyond 8 $R_\odot$ is conspiucous between windowless aircraft measurements of Blackwell (1955) and Michard (1956) later confirmed by the ground-based measurements of Michard and Sotirovsky (1965) and aircraft but through window measurements of Pepin (1970), Keller (1971) and Mutschecner et al. (1975). A possible "window" effect cannot be excluded and, as a matter of fact was noticed by one of the author during the supersonic aircraft (Concorde) observation of the 1973 eclipse. It must be further pointed out that the latter group of authors have attributed their high polarization to the K-corona (clouds of electrons) and not to the F-corona. We attempted to extract P_K using the theoretical result P_K ($r \gtrsim 5 R_\odot$) = 0.64 and obtained:

$R/R_\odot$	5	6	7	10	15
P_F	3×10^{-4}	0.007	0.016	0.021	0.020

2. COLORIMETRIC AND INFRA-RED ANALYSIS

Likewise the polarimetric data, the colorimetric and infra-red data offers the possibility to trace and characterize the circumsolar dust grains (so-called, "local" F-corona).

2.1. The color of the F-corona

The determination of the color of the F-corona is exceedingly difficult since it requires highly accurate photometry and calibrations in different spectral regions. To alleviate the calibration problem, it is assumed that the K-corona is solar-color (i.e., "white") so that the measure-

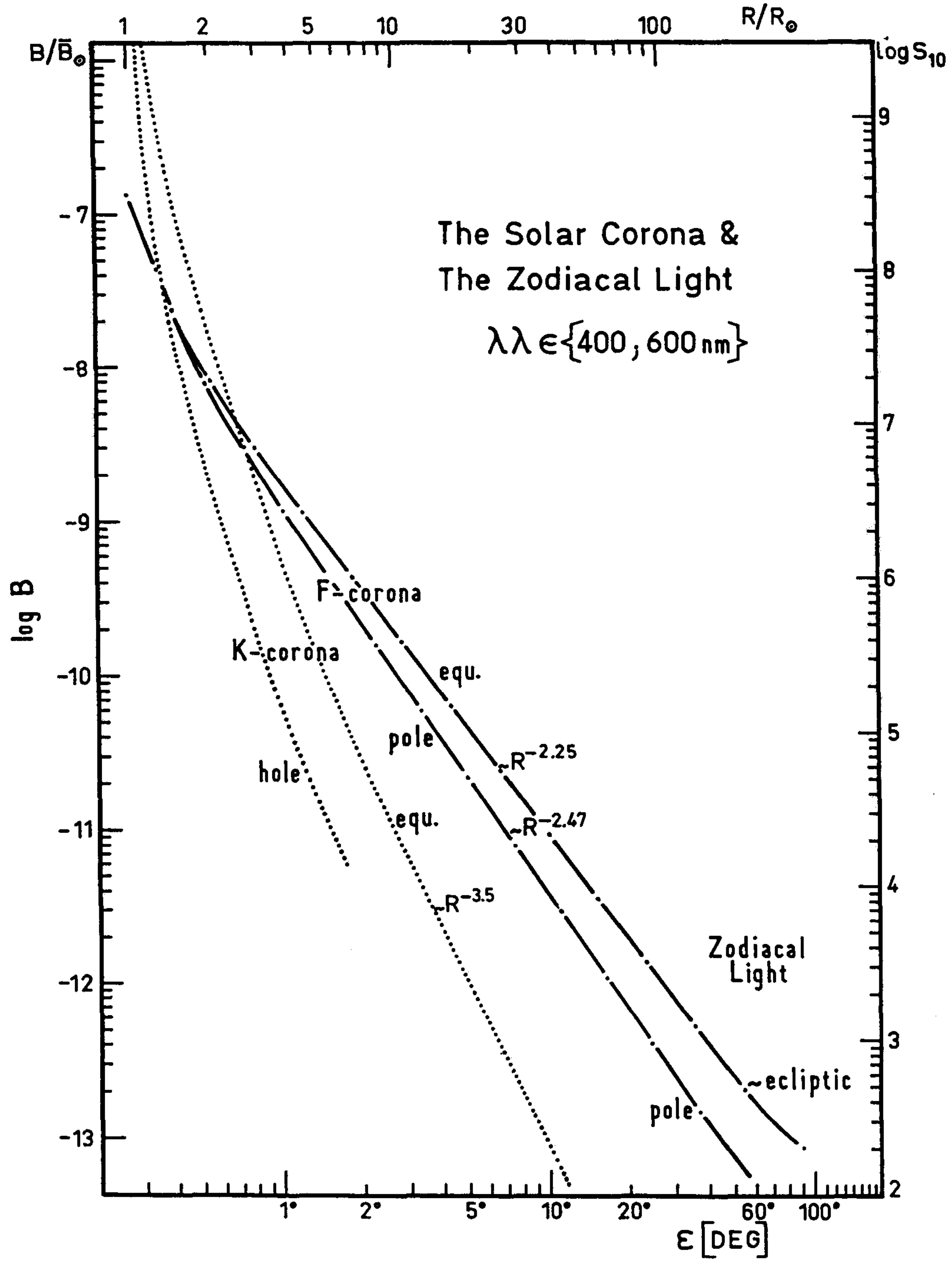

Fig. 3 : The axi-symmetric non-pherical model of the F-corona and its extension to the Zodiacal Light.

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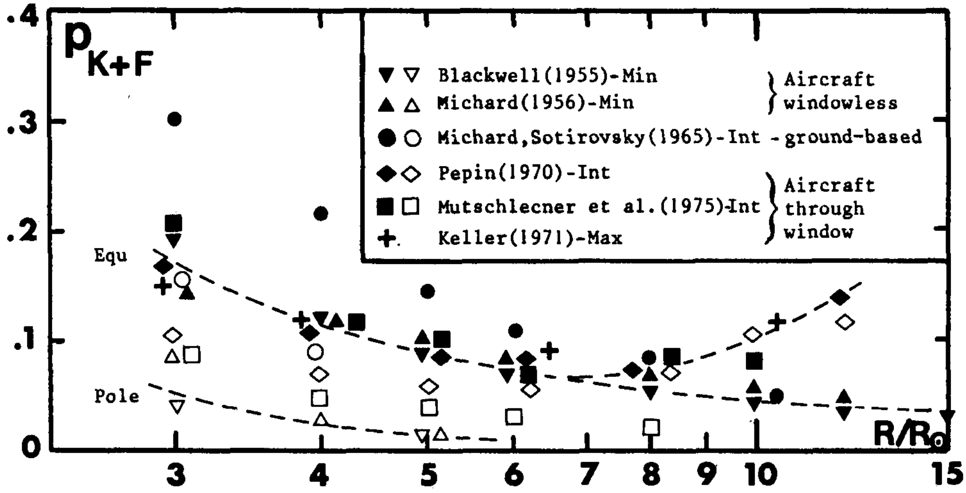

Fig. 4: The polarization of the total K+F corona versus heliocentric distance. The filled symbols pertain to the equatorial direction while the open symbols to the polar direction. The solar activity at the time of the observations is indicated by "Min", "Max" and "Int" for intermediate. The turnover beyond 8 $R_{\odot}$ may well reflect a window effect.

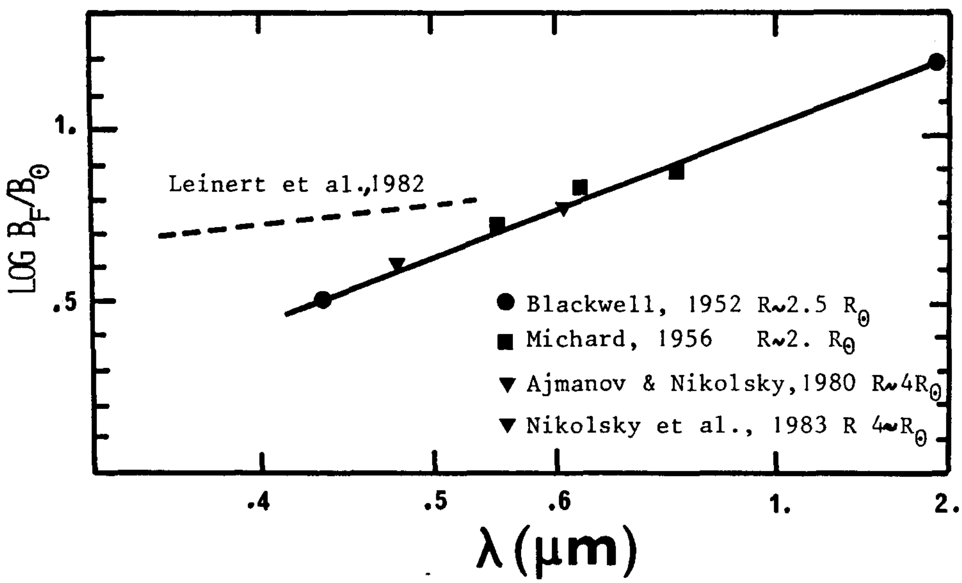

Fig. 5: The color index of the F-corona (see definition in the text) and of the inner Zodiacal Light (Leinert et al., 1982).

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ments are in fact restricted to the comparison of the color of the F and K coronae. Following the method of Michard (1956), we present the variation of log $B_F/B_\odot$ on an arbitrary scale but versus the wavelength λ (instead of $1/\lambda$). The data given at different wavelengths (at least two) can, in general, be represented by straight lines which have been forced at the same ordinate at 640 nm. To the measurements of Blackwell (1952) and Michard (1956), we add the recent results of Ajmanov and Nikolsky (1980) and Nikolsky et al. (1983) in Fig. 5. It should be noted that they pertain to different locations in the F-corona. However the agreement is excellent considering further the variety of techniques employed and supports a strong reddening, much stronger that extrapolated from the Helios space probe (Leinert et al., 1982) in the limit $\varepsilon \to 0°$. The essentially solar color of the Zodiacal light at large appears to evolve in its inner part with a reddening increasing with decreasing elongations. This reddening may have different origins which need to be clarified. Both scattering and thermal emission should be considered as this effect may well reflect the increasing contribution from the latter process (see below).

2.2. The infra-red corona and thermal emission

The interest in infra-red observations of the F-corona was triggered by the theoretical prediction of Peterson (1963) of thermal emission bumps near 4 $R_\odot$. Near infra-red ground-based observations by Peterson (1967, 1969, 1971) and ground-based and balloon observations by Mac Queen (1968) have confirmed the prediction although an important quantitative disagreement is present (Fig. 6). Then the situation became confused following several negative reports. First, there was the observation at 10 μm carried out aboard the supersonic aircraft "Concorde" by Léna et al. (1974) whose result is plotted in Fig. 6. Then Mampaso et al. (1982) built a dedicated instrument using an externally occulting disk to perform infra-red observations outside solar eclipses benefiting from an improved detectivity. They reported no peak at all and further showed that their instrument could have detected a peak one order of magnitude de fainter than that observed by Peterson. An observation by Mutschlecner, Brownlee and Hall(quoted by Keller, 1981) performed at 0.7 and 2.2 μm at the February 1980 eclipse failed to record the inner part of the corona but indicate an enhancement at 9 $R_\odot$ and no other feature up to 20 $R_\odot$. At the same eclipse, Rao quoted by Zirker (1984) scanned the corona between 2 and 5.5 $R_\odot$ at 2.2 μm and did not detect the bump at 4 $R_\odot$. The most recent observations were performed with a balloon during the June 1983 eclipse by Maihara et al. (this volume): a preliminary analysis reveals an excess on the west side of the Sun only, especially strong at 1.25 and 1.65 μm. In view of this puzzling situation, we would like to make two comments. First, several authors have reported the existence of a (local?) component of the F-corona strongly reinforced in the equatorial regions (Mac Queen, 1968; Koutchmy, 1972) which appears to be distinctly different in its morphology from the classical flattening. Second, the alternance of positive and negative results may possibly result from the existence of transitory events. Nevertheless, it

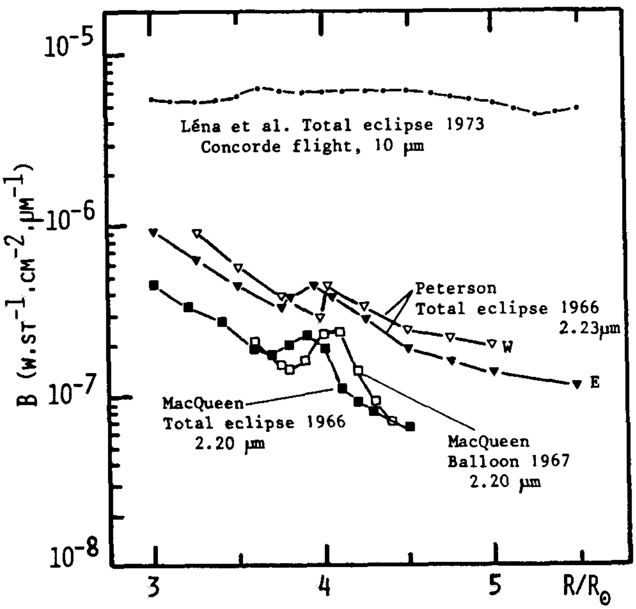

Fig. 6 : The infra-red brightness of the F-corona versus solar elongation showing the thermal feature in the near infra-red near 4 $R_\odot$.

is tempting to regroup all the positive resutls as we did in Fig. 7 with the data of Peterson, Mac Queen and Léna et al. (op. cit.) and of Mankin et al. (1970) for a distance of 4 $R_\odot$ to be compared with a solar color F-corona (white scattered light). In view of the large discrepancy between the above data, it is difficult to conclude although it appears that thermal emission dominates over scattered light beyond 3 µm. The high values observed in the 10 µm spectral domain could indicate the presence of silicates. Finally, it should be mentionned that there has been both predictions and theoretical interpretations of these results, in particular by Lamy (1974), Mukaï and Yamamoto (1979), Mukaï (this volume) and Grimshaw.

CONCLUSION

The properties of the F-corona in the optical domain appears now firmly established -with the possible exception of the polarization- allowing us to obtain a static model with the equatorial-polar asymmetry and having an high accuracy. The situation is far less satisfactory in the infra-red. Overall, it is difficult to assess the relative importance of the supposed two components "far" and "local" F-corona from the available observationnal data. Improved theoretical modeling is certainly required to clarify this question. Following classical observations, new externally occulted coronographs have revealed the permanent dynami-

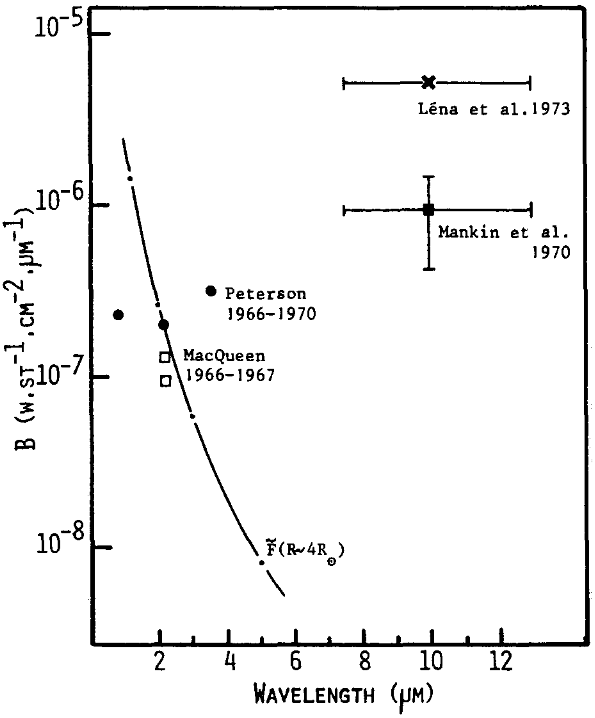

Fig. 7 : The infra-red spectrum of the F-corona near 4 $R_\odot$. The curve $\tilde{F}$ corresponds to a solar color corona.

cal state of the K-corona. Such a behaviour is not excluded for the F-corona as variations may be caused by
i) transitory equatorial enhancements;
ii) dust-free zones changing with the composition of the dust grains;
iii) debris of Sun-grazing comets as observed by Sheeley et al. (1982) and Michels et al. (1982).

In fact, the infra-red bumps at 4 $R_\odot$ may well have been transitory events.

If such ideas receive further support, then the F-corona should be viewed as a superposition of a quasi-stationnary "far" corona and a variable "local" corona, the variability resulting possibly from the interplanetary medium (comets) and from solar phenomenae (transient events, solar wind, solar cycle). Such exciting perspectives call, in our opinion, for infra-red imaging which should be done during solar total eclipses and for a long-life sophisticated space coronameter.

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