THE COLOUR OF THE SOLAR CORONA AND DUST GRAINS IN IT

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Abstract. The photometry of coronal colour negatives is carried out. The films were obtained at the March 7, 1970 and July 10, 1972 eclipses. A distribution of the coronal brightness in the red (635 nm), green (545 nm), and blue (455 nm) wavelength intervals up to distances of (6–7)$R_\odot$ is deduced (Figure 1). Colour indexes of the corona (the emission ratio red/blue – C_{rb} and green/blue – C_{gb}) have been obtained. We assume $C_{rb} = C_{gb} = 1$ in the inner corona ($\leq 2R_\odot$). The maximum of colour indexes of the 1970 corona are at the distances of about $4R_\odot$ ($C_{rb} \leq 1.9$ and $C_{gb} \leq 1.7$). A slight reddening within the limits of the errors was found in the 1972 corona.

There is a correlation between colour indexes and diffuse external reinforcements (RED) brightness. The analysis of the results leads to the conclusion that RED consists of dust grains with radii ≥ 1 μm. RED brightness is evaluated to be $4 \times 10^{-10}\,\bar{B}_\odot$. There is 1 grain of dust in the elementary volume with cross section of 1 cm^2 along the line of sight. The intensity of dust emission in wavelength interval 10 μm deduced by the authors is approximately 1 μW cm^{-2} s m^{-1}. That is in agreement with Mankin *et al.* (1974) and Léna *et al.* (1974) observations. The whole dust mass of RED is $\leq 1\%$ of the coronal gas mass contained within RED region. The dust grain number density is about 10^{-11} cm^{-3}.

Determinations of the colour of the solar corona have been made by a number of scientists (Tikhov, 1940, 1957; Allen, 1946; Blackwell, 1952; Michard, 1956; Sharonov, 1958; Nay *et al.*, 1961). The corona colour was found to be somewhat redder than the Sun's. However this question is not finally settled to date.

1. Observations

Colour negatives of the corona have been taken by the members of the Solar-Activity Laboratory (Izmiran) expeditions, during the solar eclipses of March 7, 1970 and July 10, 1972. An objective ($F = 300$ mm, 1:4.5) was fed by a coelostat mirror. The films of the 1970 corona have been obtained by A. A. Sazanov on 35-mm Agfa Colour Negative film CNS (the vicinity of Miauatlan, Mexico) and those of the 1972 by Ju. D. Zhugzhda on 35-mm LN-7 film (the Russkaja Koshka bar, Chukotsk).

2. Photometry

Colour photography has the merit that the coronal images in blue, green, and red wavelength intervals can be taken simultaneously. The photometry of the colour coronal films through blue, green and red filters, enables us to obtain densities suitable for three colours.

The corona photographs (1970, exposures 1/30, 1 and 3 s; 1972, exposures 1/30, 1/5 and 1 s) taken at the midtotality have been chosen for photometry. The photometry was carried out in different position directions through the narrow band

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(20 nm) blue, green and red filters using a recording microphotometer. The characteristic curves were plotted by comparison of photographic densities and brightness distribution known in the inner corona ($r \leq 2R_\odot$) according to Hata and Tojo (1972, the 1970 corona) and Koutchmy *et al.* (1974, the 1972 corona) data.

Prints on a contrast fine grain film were obtained with different exposure times through the same filters that were used for the photometry. The equidensities have been obtained mainly according to Högner (1969). Isophotes areas were used to obtain an average brightness distribution of the corona (Grotrian, 1934). At $r \geq 5R_\odot$ the 1970 corona brightness (west regions) is reduced by vignetting due to nonsymmetrical location of the coelostat mirror relative to the objective. Therefore the average brightness distribution was plotted for the east corona only. The objective vignetting had been taken into account.

The sky brightness during the eclipse should be taken into account for the middle and outer corona photometry. The sky brightness ($B^s \geq 10^{-9} \bar{B}_\odot$) is equal to those of the corona at $4R$, and it is 4–5 times brighter at $r \approx 8R_\odot$. While estimating the sky brightness, we believe the corona brightness to be low at $r \geq 8R_\odot$, the sky brightness to rise with the decrease of wavelength and the distribution of the corona brightness to follow the power law with the exponent of (2.5–0.2). Taking account of all of the above mentioned factors, the relative error in sky brightness is $(\Delta B^s/B^s) \leq 10\%$. The sky brightness was considered to be independent of the direction. Maximum variations do not exceed 10% (the 1972 corona, the direction along the altitude circle) at $r \approx 6R_\odot$ (Koutchmy and Nikolsky, 1973). The error of (the corona + the sky) the brightness $\Delta\ (B + B^s)$ was estimated by us in 10% for all three wavelength intervals. This value is due to the accuracy of photometry and of the combination of the brightness distribution obtained from the negatives with different exposures.

The inner corona brightness ($r \leq 2R_\odot$) was considered to be the same in blue, green and red colours. At such distances the electron K-corona predominates significantly over the dust F-corona, and the colour of the inner corona may be considered coincident with that of the Sun. The coronal brightness distributions (1970, 1972) are shown in Figures 1a, b for three wavelength intervals. A relative error was estimated from the expression that was just for each wavelength interval

$$\frac{\Delta B}{B} = 0.05 \pm 0.1 \frac{B^s}{B}, \tag{1}$$

where B^s is the sky brightness and B the coronal brightness. The expression (1) can be obtained from the correlation as follows:

$$\Delta B = \tfrac{1}{2}\{|\Delta (B + B^s)| + |\Delta B^s|\},$$

which involves the average of the maximal and minimal errors. The ratios of the coronal brightness for different effective wavelengths ($C_{rb} = B_r/B_b$ and $C_{gb} = B_g/B_b$) were chosen as colour indices. The indexes r, g and b correspond to an effective wavelength in red, green and blue spectral ranges ($\lambda_{\text{eff}} = 635$, 545, and 455 nm). As

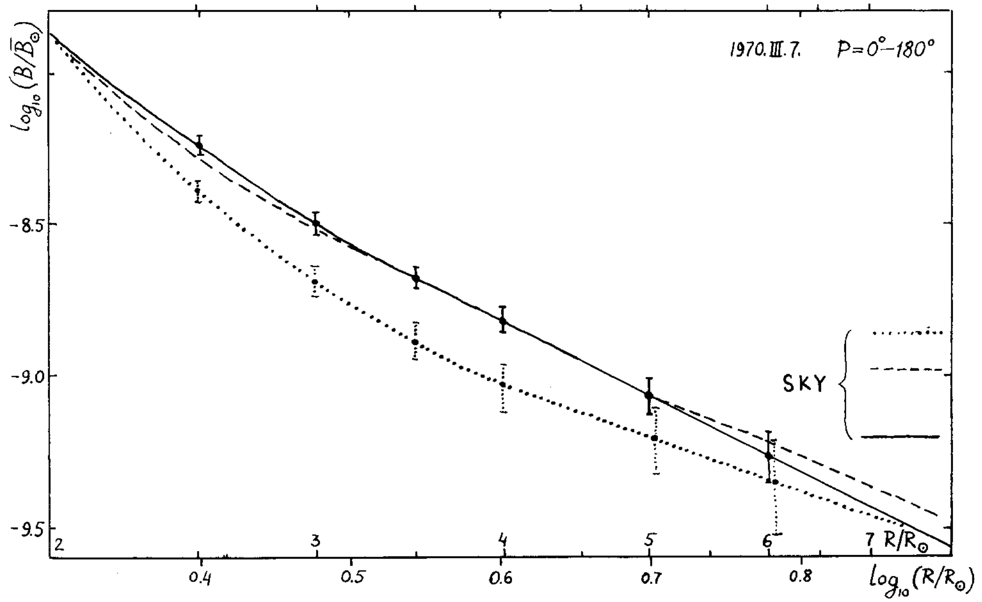

Fig. 1a.

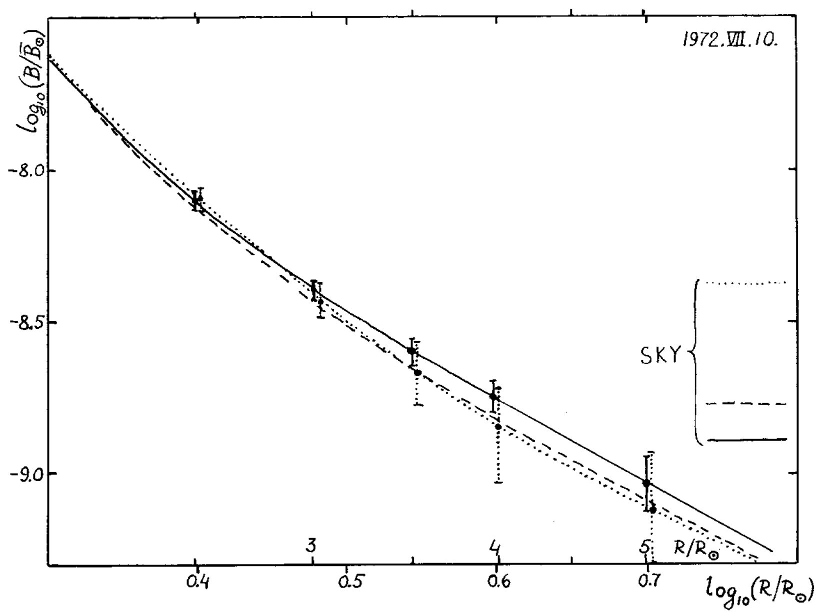

Fig. 1b.

Fig. 1a–b. Distribution of the corona brightness in the red (*solid line*), green (*broken line*), and blue (*dotted line*) spectral ranges. Vertical segments are the errors calculated by formula (1). The sky brightness obtained is shown by a corresponding line. Absolute calibration is made highly approximately according to Hata and Tojo (1972), Koutchmy and Koutchmy (1974), Koutchmy *et al.* (1974) and Koutchmy and Nikolsky (1973) data. (a) The March 7, 1970 corona averaged over the east hemisphere (the position angles 0–180°. (b) The July 10, 1972 corona averaged over all position angles.

$C_{rb} = C_{gb} = 1$ in the inner corona, they characterize the colour of the outer corona relative to the Sun's colour at the distances of $\geqslant 2R_\odot$.

The relative error of the coronal colour index C_{rb} (the same way for C_{gb}) was calculated according to

$$\frac{\Delta C_{rb}}{C_{rb}} = \frac{1}{4}\left[\delta_r + \delta_b + (\delta_r + \delta_r^s)\frac{B_r^s}{B_r} + (\delta_b + \delta_b^s)\frac{B_b^s}{B_b}\right], \tag{2}$$

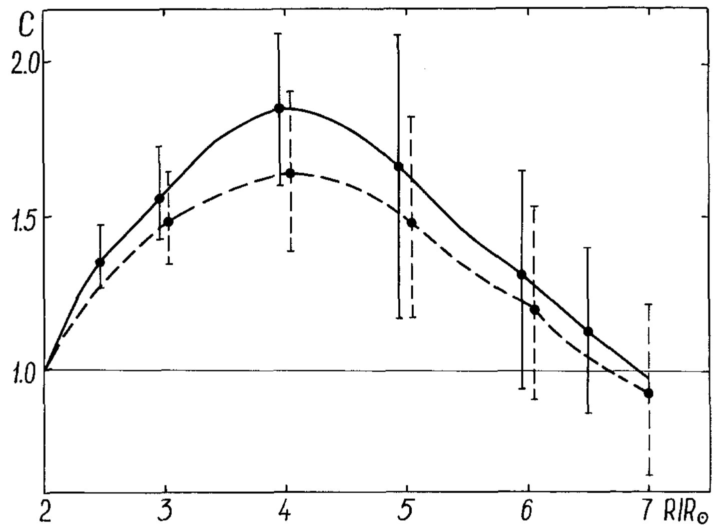

Fig. 2a.

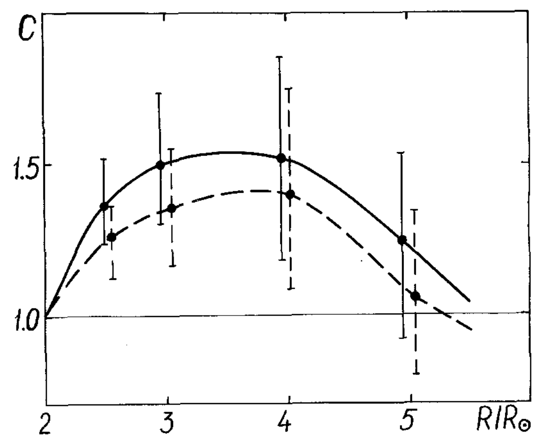

Fig. 2b.

Fig. 2a–d. The dependence of the colour indexes of the corona on the distance. *Solid line*: A brightness ratio in the red spectral range to the blue one (C_{rb}). *Broken line*: A brightness ratio in the green spectral range to the blue one (C_{gb}). *Vertical segments*: The errors estimated by the formula (2). (a) The 1970 corona, position 90°. (b) The 1970 corona, position angle 180°. (c) Mean values for the east hemisphere of the 1970 corona. (d) Mean values over all position angles for the 1972 corona.

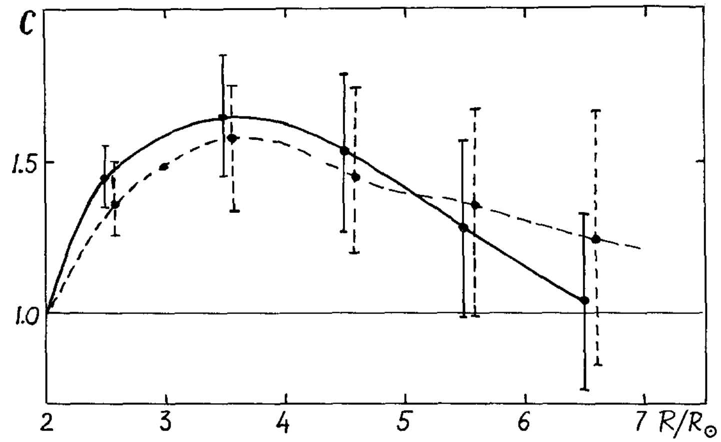

Fig. 2c.

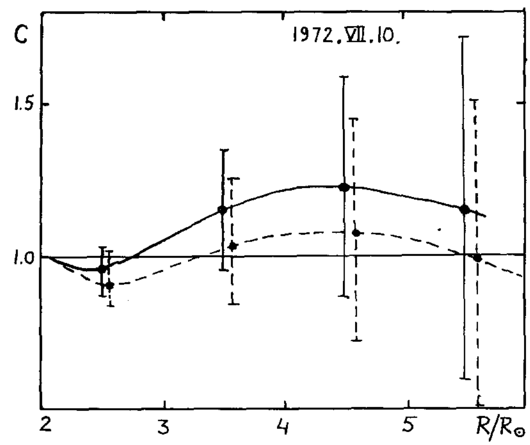

Fig. 2d.

where δ is a relative photometrical error of the brightness determination (the corona + the sky) and δ^s is a relative error due to the choice of the sky brightness B^s.

C_{rb} and C_{gb} for the 1970 corona increase with distance in all 10 position directions studied by us and they run up to maximum at distances of about $4R_\odot$. The most typical distributions of C_{rb} and C_{gb} with distance are shown in different position directions. In Figure 2c the 1970 corona seems to have an appreciable colour excess in green and red spectral ranges as compared with the Sun.

No significant difference between the corona colour and the Sun's colour was found for the 1972 corona in all 10 position directions studies. On the average there is some radiation excess in red wavelength interval. However its value is within the limits of errors (see Figure 2d). Hence it follows that the corona colour depends on the epoch.

3. The Corona Colour and Diffuse External Reinforcements at 3–6 $R_\odot$

The maximum of our colour indexes of the March 7, 1970 corona is at about $4R_\odot$. At such distances Koutchmy (1972) has found diffuse external reinforcements ('renforcements externes diffus' or RED) using the 1970 corona photos. RED brightness is different in various position directions and does not correlate with the electron corona brightness.

Coronal colour indexes are compared with RED brightness (Figure 3). We have estimated RED brightness using a five-point scale (0 – RED are absent, 5 – RED have maximal brightness). In spite of the considerable data scattering C values increase with ΔI (RED) brightness). The scattering is large at low ΔI. On the average $C^0_{rb} = 1.60$, $C^0_{gb} = 1.40$ correspond to $\Delta I = 0$ and $C_{rb} = 1.90$, $C_{gb} = 1.65$ correspond to the brightest RED ($\Delta I = 5$).

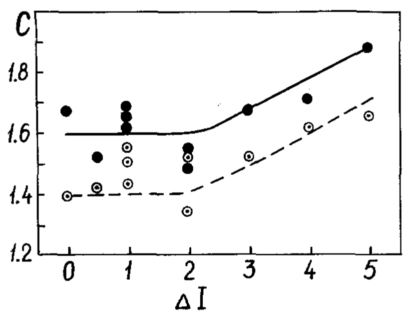

Fig. 3. The relation between colour indexes C_{rb} (*solid circles*) and C_{gb} (*open circles*) with brightness of diffuse external reinforcements (RED) for the 1970 corona.

The increase of C with ΔI indicates that RED has a 'redder' colour than the corona. Hence it follows that RED consists of dust grains rather than of electrons. Thus, the alternative of RED nature considered by Koutchmy (1972) is solved. C^0 values correspond to the F-corona colour because of its dominance at distances $\geq 4R_\odot$ ($F/K \approx 4$). A significant error of C determination ($\approx$15% at distances of about $4R_\odot$) cannot change the character of C (ΔI) dependence, the shift of zero of y-axis may merely be about 15% (Figure 3).

RED brightness may be estimated neglecting $\Delta I_b/B_b$ value in C and C^0 expressions:

$$\frac{B_r + \Delta I_r}{B_b + \Delta I_b} = C_{rb}; \qquad \frac{B_r}{B_b} = C^0_{rb}; \qquad \frac{\Delta I_r}{B_r} \approx \frac{C_{rb}}{C^0_{rb}} - 1 = 0.2. \tag{3}$$

The 1970 corona brightness is about $2 \times 10^{-9}\,\bar{B}_\odot$ at the distances of about $4R_\odot$ (Hata and Tojo, 1972), hence

$$\Delta I_r \approx 4 \times 10^{-10}\,\bar{B}_\odot\,. \tag{4}$$

4. On the Nature of Diffuse External Reinforcements

According to Lamy (1974a, b, 1976) in the vicinity of the Sun there are zones of probable concentration of interplanetary dust. These zones surround the regions of total dust sublimation. From Lamy's calculations it follows that obsidian grains (radius $a \approx 1$ μm) may exist at stable heliocentric orbits ($\approx 4R_{\odot}$) for a long time.

The visible emission of RED is due to the scattering of the solar light at the angles of approximately 90°. That differentiates the RED emission from the F-corona one. The latter is due to the diffraction at the angles close to 0°. Taking into account a scattering indicatrix on the dust grains ($a \approx 1$ μm), we believe the scattering at the angles of 60–90° to be the main contributor to the RED emission. At such angles the efficiency of scattering will increase from blue to red wavelengths for the grains with radius of about 1 μm if the refraction index of dust matter is about 2. The obsidian refraction index is about 1.5. To accord our observation with Lamy's theory it is necessary that the radius of the grains be $a > 1$ μm (≈ 2 μm). To construct the scattering factor $I(\theta)/I_0$ (where I_0 is the intensity of incident light) we made use of Wickramasinghe's (1973) tables. The scattering maximum at $\theta = 90°$, $n = 1.5$ is at $X_m = 2\pi a/\lambda \approx 10$. To increase the scattering of light with wavelength (reddening) it is necessary that $X > X_m$. Hence it follows that $a > X_m\lambda/2\pi \approx 1$ μm.

Let us evaluate the grains number in RED. The brightness of the solar emission scattered by elementary volume of RED and observed at the Earth distance is

$$\Delta I = \frac{1}{4\pi} N\sigma W B_{\odot}\,, \tag{5}$$

where N is the number of the dust grains along the line of sight, $W \approx \frac{1}{4}r^2 = 0.016$ is the dilution factor at RED distance, and $B_{\odot}$ is the intensity of the solar emission at the Earth's distance. If we believe the efficiency factor to be about 3 (the scattering angles 60–90°, $n = 1.5$), we obtain a scattering cross-section $\sigma \approx 3\pi a^2 \approx 10^{-7}$ cm^2. If we substitute the values of ΔI and σ into expression (5), we get $N \approx 1$ cm^{-2}. RED extention along the line of sight is approximately $1R_{\odot}$. Then the concentration of the dust grains in RED n_d is about 10^{-11} cm^{-3}. This value is at least 1000 times greater than the interplanetary one. The latter is caused by the F-corona and Zodiacal light. The whole dust mass in RED (a dust density $\rho = 3$ g cm^{-3}) is

$$M_d \approx (2\text{–}4)\tfrac{4}{3}\pi a^3 \rho N R_{\odot}^2 \approx (1\text{–}2)\times 10^{11}\ g\,, \tag{6}$$

e.g. about 10^{-7} of interplanetary dust mass or 10^{-6} of the coronal plasma mass. The dust mass is less than 1% of the coronal gas mass that is contained in RED volume. The dust quantity in RED is likely to vary with time (different data on the coronal colour for the 1970 and 1972).

5. Thermal Emission of the Corona and RED

At distances of about $4R_{\odot}$, as Peterson (1963) has predicted theoretically and Peterson (1967, $\lambda = 2.2$ μm and 3.5 μm) and MacQueen (1968, 2.2 μm) have confirmed experimentally, there is a zone of the interplanetary dust sublimation. Ground based observation of thermal emission of March 7, corona in the 10 ranges (Mankin *et al.*, 1974) provide $\Delta I = (0.9 \pm 0.5)$ μW cm^{-2} sr^{-1} μm^{-1} at $\approx 4R_\odot$. This result seems to be unreliable because of sky noise. According to the coronal observations in the 10 range during the June 30, 1973 eclipse on board of Concorde aircraft (Lèna *et al.*, 1974) the intensity of infrared emission at the distance of about $4R_\odot$ is 4 μW cm^{-2} sr^{-1} μm^{-1}.

Let us estimate the thermal emission that may be due to the RED. In accordance with Lamy's calculation obsidian grains ($a \approx 1$ μm) at 1000 K (obsidian grains have such a temperature at the distance of about $4R_\odot$) emit in 10 μm

$$\varepsilon_{\mathrm{IR}} \approx 5 \times 10^4 \ \mu\mathrm{W\,cm^{-2}\,s^{-1}\,\mu m^{-1}}\,. \tag{7}$$

The intensity of RED thermal emission at the Earth's distance is

$$\Delta I_{\mathrm{IR}} = \varepsilon_{\mathrm{IR}} N \left(\frac{1R_\odot}{1\ \mathrm{AU}}\right)^2 \approx 1\ \mu\mathrm{W\,cm^{-2}\,sr^{-1}\,\mu m^{-1}}. \tag{8}$$

This value correlates with Mankin *et al.* (1974) and Lena *et al.* (1974) observations within a low accuracy of our estimations. We believe RED extent in a picture plane to be about $1R_\odot$.

6. Conclusions

The main aim of the present paper is to attract attention to an interesting problem of the corona colour and its relation to the existence of the dust grains in the vicinity of the Sun. In future it will be necessary to carry out a careful determination of the corona colour using aircraft observations to decrease the sky brightness significantly.

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