Study of EUV emission of the inner corona and its modeling using PROBA2/SWAP and Hinode/EIS data

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Aim of the Project

The main goal of the project is to investigate EUV emission and properties of a large-scale ray-like structure in the inner corona from PROBA2/SWAP data along with EIS/Hinode and MLSO/Mk4 observations. This work is a continuation of studies of the solar corona based on SWAP data and performed in 2010-2012 in the framework of the Proba2 GI program.

Wide-field EUV telescopes operating in EUV spectral bands often observe extended ray-like coronal structures radially stretching from active regions to distances of 1.5–$2R_{sun}$ and representing the EUV counterparts of white-light streamers. These structures seen in EUV lines at temperatures of about 1 MK are suggestive for being signatures of plasma outflows from active regions.

To study and explain this phenomenon, we investigated properties of a streamer observed on 20-21 October 2010 by the Proba2/SWAP EUV telescope together with the Hinode/EIS instrument and the MLSO/Mk4 white-light coronagraph.

Data preparation and reduction

Planning and execution of the SWAP observations, as well as the standard pre-processing of data to Level 1 SWAP fits-files and data calibration were provided by the SWAP team. The data were processed to correct for dark current, detector bias, flat-field variations, and bad pixels. The solar images were centered, rotated to the top position of the north pole, re-scaled to the square pixel format, and time-normalized, so individual pixel values were expressed in units of DN/s.

We analyzed the SWAP images of the extended EUV streamer observed at the western limb of the Sun on 20-21 October 2010. This structure was originated above the AR 11112, which was located at the disk center on 14 October 2010. Correction of SWAP images for stray light was carried out using the technique and software developed in LPI. The selected images were summarized for each day and transformed to polar coordinates by linear interpolation. In the polar images a strip was selected, which contains the longest and brightest radially directed ray in the center of the structure (Fig. 1a). Its radial brightness distribution was obtained by averaging over the strip width (Fig. 1b and 1c). Application of special observational modes – off-pointing, summation of several dozen high-cadence images and straylight correction – allowed us to obtain the radial distribution of the EUV brightness in the longest coronal ray to a distance of more than $2R_{sun}$ with the acceptable signal to noise ratio.

The observational EIS/Hinode data were obtained in the special coordinated EIS-SWAP session (HOP 165) on 21 October 2010 at 18:28:13 UT, when the active region AR 11112 rotated to the western limb. After standard processing of the initial EIS fits-file, the images in the EIS Fe ion lines were extracted and transformed into polar coordinates. On October 20 the same streamer was observed by the MLSO/Mk4 coronagraph, which measured the polarized brightness in the streamer produced by the Thomson scattering of the photospheric continuous radiation on electrons of the coronal plasma. The corresponding data were taken from the MLSO database.

Preliminary results and discussion

In order to understand the origin of the EUV emission observed by SWAP, two main mechanisms of excitation of the Fe IX–XI ion lines contributing to the flux in the SWAP spectral band were considered: collisional excitation of ions by electrons and resonant scattering of the monochromatic radiation generated in the underlying corona. The incident fluxes in the mentioned spectral lines band were determined from the SWAP and EIT images using segmentation of the structures at the solar disk and calculation of their partial fluxes with the CHIANTI package. An estimation of relative contributions of collisional and resonant components in EUV emission of the corona has shown that for the strongest Fe IX 171.08 A line in the SWAP spectral band (comprising FeIX-FeXI ion lines) collisional excitation dominates up to radial distances $2.5R_{sun}$. Inside this range the characteristic timescale for reaching ionization equilibrium between the Fe IX–XI ions is less than the plasma expansion timescale, which is indicative of thermal equilibrium in the streamer plasma.

The radial distributions of the plasma density and temperature in the streamer and surrounding corona were found by the forward modeling of the coronal emission to best fit the measurements. The streamer ray was modeled as a Gaussian slab with constant angular width, embedded into the spherically symmetric background corona. A fitting of the modeled EUV brightness with the SWAP data gave (Fig. 2 on left) a radial dependence of a product of the emission measure along the line of sight with the temperature-dependent contribution function for the given Fe ion lines. The effective angular width of the slab in EUV as well as the plasma parameters in the corona below $1.2R_{sun}$ were evaluated using the EIS spectroscopic data.

To obtain separately the density and temperature radial distributions determined in combination from the SWAP data, we modeled the white-light brightness of the K-corona along the streamer ray and fitted it with the polarized brightness measured by the Mk4 coronagraph (Fig. 2 on right). As a result, the forward modeling of the EUV and white-light photometric data fitted with the data from the three instruments allowed us to obtain the self-consistent solution which gave the most probable radial distributions of density and temperature in the streamer ray and surrounding background corona. It was found that in the streamer ray the plasma was isothermal with the temperature $T = 1.35 \pm 0.07$ MK and the density varying from $\approx 2\cdot10^9$ cm^{-3} at the limb to $1–2\cdot10^7$ cm^{-3} at $2R_{sun}$. In the background corona the density varied from $2–3\cdot10^8$ to $0.7–1.5\cdot10^6$ cm^{-3} at the same temperature. The density in the streamer was found to be higher than the hydrostatic model predicts (Fig. 3), which suggests the existence of non-thermal outward plasma flow along the streamer.

Taking into account the determined plasma parameters, it was found that in the streamer ray the resonant component constitutes less than 10% of the total flux, whereas in the background corona it may become dominating at the heliocentric distance $>2R_{sun}$. However, at plasma velocities of 40 km/s and more the contribution of the resonant component rapidly decreases due to the Doppler dimming effect. In conclusion, the results obtained testify that the EUV emission of a large-scale streamer at the distances from the limb up to $2R_{sun}$ can be correctly modeled by assuming collisional excitation in the thermal equilibrium plasma.

Conclusion

The photometric analysis of extended large-scale coronal structure on the basis of combined SWAP, EIS and Mk4 observational data, performed in the framework of the Proba2 GI program, allowed us to study properties of a EUV streamer and to determine its physical parameters using spectroscopic diagnostics methods. Mechanisms of formation of EUV emission in the inner corona were investigated and their contribution was evaluated. It was shown that the coronal plasma in the streamer under study in the range of $1.2\text{-}2R_{sun}$ is nearly isothermal with the temperature of about 1.35 MK. At the same time, the hydrostatic temperature determined from the derived density distribution was noticeably higher (≈1.7 MK). This result suggests existence of the outward plasma flow along the streamer. Therefore studying extended coronal EUV structures (coronal rays) may shed light on the nature of local sources of the solar wind. The results of our work are presented in the manuscript “Study of EUV emission and properties of a coronal streamer from PROBA2/SWAP, Hinode/EIS and Mauna Loa Mk4 observations” submitted to Astrophysical journal.

We also hope that the studies of the EUV coronal emission at larger distances will be continued in the forthcoming solar missions projects such as Solar Orbiter and ASPIICS.

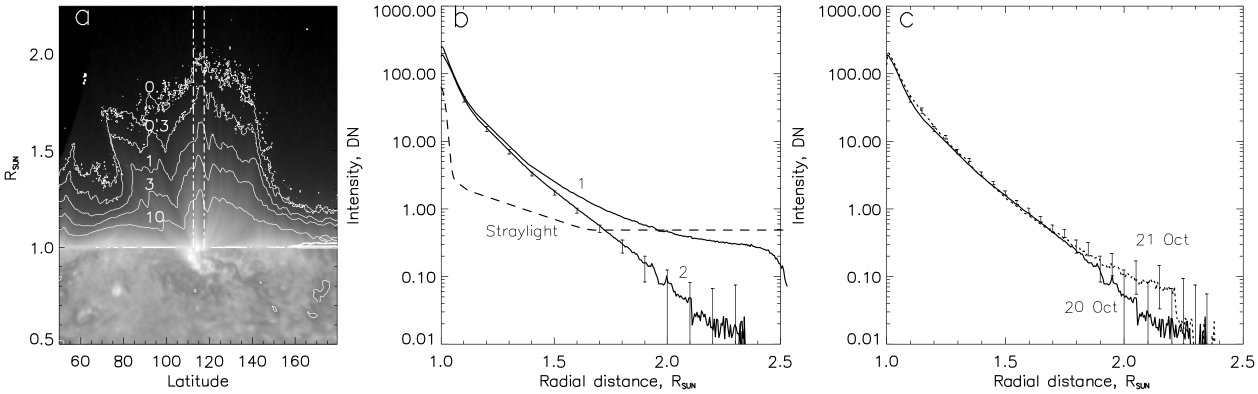

Figure 1. (a) Polar diagram of the coronal structure under study. The contours map the levels of brightness from 10 to 0.1 DN. The chain lines mark out the boundaries of the analyzed coronal ray at the angle of 115±2.5°; (b) the measured radial distributions of brightness in the ray before (curve 1) and after (curve 2) subtraction of the straylight (dashed line); (c) Superposition of brightness distributions in the ray derived from the data on 20 and 21 October 2010.

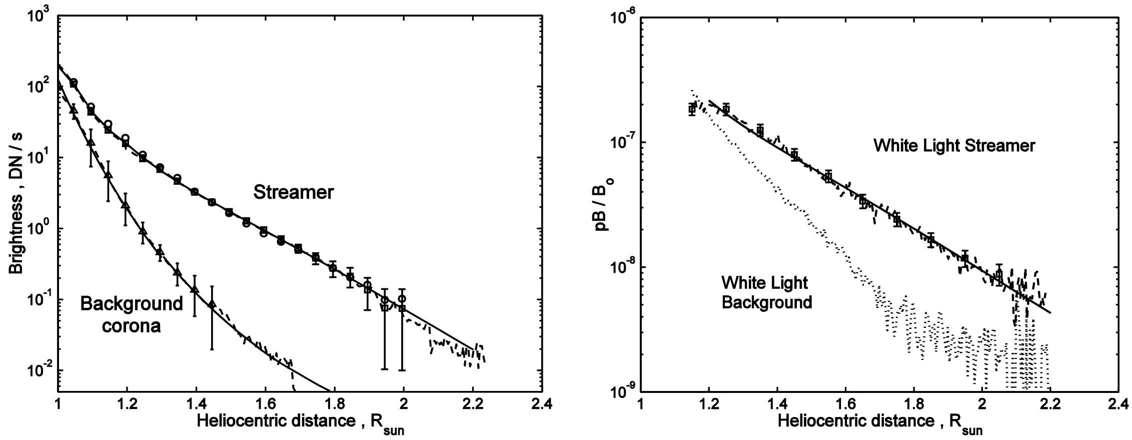

Figure 2. Left: EUV brightness of the streamer and background corona from the SWAP data on 20-21 October 2010 compared with the modeled EUV emission (dashed curves with error bars are observational data; solid curves stand for the modeled brightness distributions). Right: comparison of the model with the MLSO/Mk4 data on 20/10/2010 (dashed line with square error bars is Mk4 data on 20/10/2010; solid curve is the modeled polarized brightness; dotted curve corresponds to the background corona on 14/10/2010).

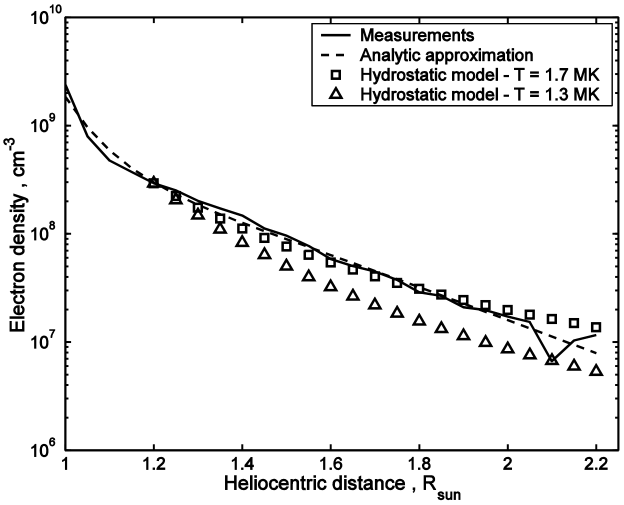

Figure 3. Comparison of the derived density model distribution with hydrostatic density one.