Chromospheric and Prominence Physics with the ASPIICS Formation Flying Coronagraph

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Abstract. Classical externally-occulted coronagraphs are presently limited in their performances by the distance between the external occulter and the front objective. The diffraction fringe from the occulter and the vignetted pupil which degrades the spatial resolution prevent observing the inner corona inside typically 2–2.5 solar radii ($R_\odot$). Formation flying opens new perspectives and allow to conceive giant, externally-occulted coronagraphs using a two-component space system with the external occulter on one spacecraft and the optical instrument on the other spacecraft. ASPIICS (Association de Satellites Pour l’Imagerie et l’Interférométrie de la Couronne Solaire) is a mission proposed to ESA in the framework of the PROBA-3 program of formation flying which is presently under study, to exploit this technique for coronal observations. ASPIICS is composed of a single coronagraph which performs high spatial resolution imaging of the corona as well as 2-dimensional spectroscopy of several emission lines (in particular the forbidden line of Fe XIV at 530.285 nm) from the coronal base out to $3R_\odot$. The classical design of an externally occulted coronagraph is adapted to the detection of the very inner corona, and the addition of a Fabry-Pérot interferometer. By tuning the position of the occulter spacecraft, it will be possible to reach the chromosphere and the upper part of the spicules. Filtergrams on the helium D3 line or even better, the hydrogen Hβ line (which is optically thin contrary to Hα) will give access to the “cold corona”, and could allow measuring the chromospheric prolateness.

1. Introduction

After 40 years of space coronagraphy, the lower corona (defined here as extending from the solar limb to a solar elongation of approximately 2.5 $R_\odot$) remains practically unobserved. The only available images are those obtained with the SOHO/LASCO-C1 coronagraph (Brueckner et al. 1995) before it failed following the temporary loss of control of the SOHO spacecraft. Although these images were obtained in the bright green line of Fe XIV, their contrast remains rather limited because of the high level of instrumental stray light. Routine images of the lower corona are obtained with ground-based coronagraphs (e.g., Mk III and IV in Hawaii) but their quality is affected by seeing and atmospheric conditions, and their useful fields of view rarely exceed a few tenth of solar radii. The SECCHI suite of instruments aboard the STEREO dual spacecrafts includes a Lyot coronagraph, and it will be interesting to see the expected white light images of the inner corona in the coming months when it will start operating.
Figure 1. ASPIICS on a two-component space system with the external occulter on one spacecraft and the optical instrument on the other spacecraft at 150 m from the first one. Formation flying configuration studied by ESA (2006).

For completeness, we mention the images taken on the occasions of (rare) total solar eclipses whose quality remains unsurpassed.

Formation flying opens the possibility to conceive and deploy giant coronagraphs in space that are not affected by the above limitations. Basically, the idea of “formation flying” is to coordinate a cluster of platforms that acts as a single virtual instrument or as a single mission spacecraft for coordinated observations or in situ measurements. This technique allows to reconcile the demand for increased instrumental performances with spacecraft and launcher limitations. The PROBA-3/ASPIICS (standing for “Association de Satellites Pour l’Imagerie et l’Interférométrie de la Couronne Solaire”) mission is composed of two platforms separated by about 150 m and forming a giant coronagraph: the external occulter is supported by one satellite while the second satellite hosts the optical system (Fig. 1).

2. The ASPIICS Instrument

2.1. Optical concept and design

ASPIICS is an externally occulted coronagraph entirely protected from direct sunlight by remaining in the shadow of the external occulter hosted by another spacecraft. The classical design of an externally occulted coronagraph is adapted to both the detection of the very inner corona as close as 1.02 $R_\odot$ from the Sun center with high spatial resolution (5 arcsec), and the addition of a Fabry-Pérot interferometer. The current optical design (Fig. 2) is a combination of reflective (basically a three-mirror anastigmat) and a refractive optical systems as such solution presents major technical advantages: a natural front baffle, protection of the first optics against contamination and thermal variations, a design naturally folded (reducing the overall length).
Figure 2. Optical layout of the ASPIICS coronagraph.

The external occulter (EO) blocks the light from the solar disk while the coronal light passes through the circular entrance aperture (140 mm diameter). A Three-Mirror Anastigmat (TMA) system forms the image of the EO onto the internal occulter with reduced geometric and chromatic aberrations to provide more efficient inner occultation. The internal occulter blocks the bright diffraction fringe surrounding the EO. The amount of over-occultation results from the compromise between the stability of the formation, the attitude of the spacecraft hosting the coronagraph, and the vignetting which determines the spatial resolution in the inner part of the corona. The second objective (O2) forms a collimated beam and produces a real image of the entrance pupil at the Lyot stop with a magnification of 10. The narrow-bandpass Fabry-Pérot (F-P) interferometer and a set of blocking filters plus polariser plates are mounted on a double wheel located in this collimated beam. Each blocking filter selects a specific emission line spectral interval, and blocks all but a single transmitted interferometer order. A large band filter allows to transmit several orders thus yielding polychromatic images. To improve the signal-to-noise ratio of polychromatic images and their image quality, the F-P could be removed from the beam in that case. The final image is formed by a telephoto lens system on a detector located behind a mechanical shutter. The layout is such that a circular field of view with a radius of $3 R_\odot$ forms an inscribed circle on the $2k \times 2k$ pixels CCD detector where one pixel subtends 2.8 arcsec in the corona.

2.2. The “etalon” Fabry-Pérot interferometer

Various instrumental solutions have been considered to perform spectral measurements in the corona. Conventional slit spectrographs have the disadvantage that they give 1-D information, i.e., along the slit. All or part of the instrument must be rotated to map the corona (e.g., SOHO/UVCS). This requires bulky mechanisms on the one hand, and a fairly long time to perform 2-D observations (several hours in the case of UVCS) on the other hand, both aspects being incompatible with the practical constraints of the contemplated demon-
The method consists in analyzing the bi-dimensional distribution of line profiles by a set of quasi concentric fringes generated by the etalon. This method has already been used by Desai et al. (1982) during the solar eclipse on February 1980 (Fig. 3). The fringes have an instrumental profile of typically 0.05 nm, narrower than the width of the line (0.1 nm for Fe XIV) so that the observed profiles are not significantly affected by the instrumental function and directly give the real profiles of the coronal emission line to a very good accuracy. The free spectral range will be approximately 0.4 nm, a compromise between the
expected shifts and the rejection of the continuum corona, leading to a finesse of about 20. The set of fringes can be centered on the Sun or decentered, even outside the solar disk. In the former case, the analysis is axially symmetric but the F-P works in low orders thus limiting the spatial resolution. In the latter case, it works in high orders producing dense fringes thus resulting in a higher spatial resolution. The etalon will be mechanically tilted to displace the set of fringes and increase the resolution. The interferogram may be viewed as resulting from a multislit spectrograph: all the spectral information is contained in the image, and there is no need to combine several images as in the scanning F-P to reconstruct the spectra.

To perform a precise line profile analysis far enough out in the corona, the strongest emission line available, the forbidden line of Fe XIV at 530.285 nm, is the prime choice. This truly coronal emission line formed at temperature $T = 1.8 \times 10^6$ K is not sensitive to the so-called Doppler dimming effect, such that its profile is directly reflecting line-of-sight velocities inside the corona. In addition, it has been established a long time ago (Allen 1946) that the line is measurable in the corona all along large radial distances (beyond at least 3 $R_\odot$ from the solar center). Furthermore, this line is linearly polarized thus giving access to the direction of the coronal magnetic field. The iron lines are also much more appropriate to resolve the turbulence inside the corona, including the higher corona were the lines are no more collisionally dominated but are radiatively dominated. Additional emission lines will be included to better address different coronal regions, in particular the helium D3 line and the hydrogen H\(\beta\) line (which is optically thin contrary to H\(\alpha\)) will give access to the “cold corona”, and could allow measuring the chromospheric prolateness. Finally, a broad spectral channel will image the white light corona so as to derive electron densities.

3. Formation Flying Requirements

The optimal inter-satellite distance is approximately 150 m (Vivès et al. 2006). This essentially results from a compromise between both the limitation of the vignetting by the external occulter (so as to preserve the spatial resolution as close as possible to the solar limb), and the compensation of the steep gradient of intensity of the inner corona by vignetting the field of view up to 1.1-1.15 $R_\odot$. As an example, for two spacecrafts separated by 150 m, the unvignetted field of view extends from 1.15 $R_\odot$ and the diameter of the occulter is about 1.5 m.

The stability of the formation is directly linked to the high level requirement of keeping the pupil in the shadow of the occulter. As a baseline, the lateral positioning is about $\pm 2.5$ mm while the longitudinal positioning is about $\pm 250$ mm. These specifications allow to observe the corona down to $1.01 \pm 0.0075 R_\odot$. There is a coupling between lateral/longitudinal positionings, and the absolute attitude of the spacecraft hosting the coronagraph ($\pm 20$ arcsec on transverse axes) since the fringe diffracted by the occulting disk has to be blocked by the internal occulter. It is interesting to note that the attitude of the satellite hosting the occulting disk is not strongly constrained by science as a tilt of its axis will result in a slightly ellipsoidal projected shadow. For instance, a tilt of 2 degrees implies a difference of only 0.001 $R_\odot$ between the two axes of the ellipse.
4. Conclusion

Formation flying offers the outstanding opportunity to conceive giant, externally-occulted coronagraphs capable of observing from the very inner corona up to several solar radii with high spatial resolution. This article presents the implementation of such a coronagraph for the formation flying demonstration PROBA-3 of ESA. The ASPIICS coronagraph will perform high spatial resolution imaging of the corona as well as two-dimensional spectroscopy of several emission lines in order to address key questions of coronal physics. By tuning the position of the occulter spacecraft, it will be possible to reach the chromosphere and the upper part of the spicules. Filtergrams on the helium D3 line or even better, the hydrogen Hβ line will give access to the “cold corona”, and could allow measuring the chromospheric prolateness.

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References

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