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ASPIICS: A GIANT, WHITE LIGHT AND EMISSION LINE CORONAGRAPH FOR THE ESA PROBA-3 FORMATION FLIGHT MISSION

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INTRODUCTION

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 useful observations of the white light corona inside typically 2-2.5 solar radii (R_{sun}). Formation flying offers an elegant solution to these limitations and allows conceiving 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 at a distance of hundred meters [1, 2]. Such an instrument ASPIICS (Association de Satellites Pour l'Imagerie et l'Interférométrie de la Couronne Solaire) has been selected by the European Space Agency (ESA) to fly on its PROBA-3 mission of formation flying demonstration which is presently in phase B (Fig. 1). The classical design of an externally-occulted coronagraph is adapted to the formation flying configuration allowing the detection of the very inner corona as close as ~ 0.04 solar radii from the solar limb. By tuning the position of the occulter spacecraft, it may even be possible to reach the chromosphere and the upper part of the spicules [3]. ASPIICS will perform (i) high spatial resolution imaging of the continuum K+F corona in photometric and polarimetric modes, (ii) high spatial resolution imaging of the E-corona in two coronal emission lines (CEL): Fe XIV and He I D₃, and (iii) two-dimensional spectrophotometry of the Fe XIV emission line. ASPIICS will address the question of the coronal heating and the role of waves by characterizing propagating fluctuations (waves and turbulence) in the solar wind acceleration region and by looking for oscillations in the intensity and Doppler shift of spectral lines. The combined imaging and spectral diagnostics capabilities available with ASPIICS will allow mapping the velocity field of the corona both in the sky plane (directly on the images) and along the line-of-sight by measuring the Doppler shifts of emission lines in an effort to determine how the different components of the solar wind, slow and fast are accelerated. With a possible launch in 2014, ASPIICS will observe the corona during the maximum of solar activity, insuring the detection of many Coronal Mass Ejections (CMEs). By rapidly alternating high-resolution imaging and spectroscopy, CMEs will be thoroughly characterized.

SCIENTIFIC OBJECTIVES

The rare minutes of total eclipses of the Sun currently present the only opportunities for a seamless view of the corona. This does not allow studying the coronal dynamics and eruptive phenomena nor the corona during a sufficient time to analyze its 3D magnetic structure, including the ubiquitous process of dissipation of the free

magnetic energy. Space-borne coronagraphs were designed and flown to provide a continuous coverage of the external parts of the corona but their over-occluding system did not permit to analyze the part of the white-light (W-L) corona where the main coronal mass is concentrated. ASPIICS with its novel design will thus be the first space coronagraph to cover the range of radial distances between 1.04 and 3 solar radii (from the solar center) where the magnetic field plays a crucial role in the coronal dynamics, thus providing continuous observational conditions very close to those during a total solar eclipse, but without the effects of the Earth's atmosphere. The ASPIICS unprecedented field-of-view makes it uniquely suited for studies of the solar corona, as it will fill the crucial observational gap between the fields of view of low-corona EUV imagers and conventional space coronagraphs. Our investigation is focused on and addresses a large set of key science questions in synergy with other space missions, prominently SDO (Solar Dynamic Observer) whose disk imagers will provide the on-disk information for the ASPIICS coronal observations. In particular, ASPIICS will have the capability to:

- characterize the morphology, dynamics and mass distribution of coronal structures, and their relation to the coronal magnetic field;
- identify the source(s) of the slow wind via extensive high resolution observations, in space and time, of active region expansion, streamer formation and evolution;
- identify and characterize the waves that contribute most to the heating of the corona;
- study the velocity fields, temperature and composition of the solar atmospheric plasma at unprecedented high spatial and temporal resolution in order to eventually resolve the nature of the processes of energy deposition and dissipation;
- determine the connection of coronal mass ejections (CMEs) with their low corona manifestations and establish their kinematics properties (e.g., impulsive acceleration);
- study how and where coronal shocks form.

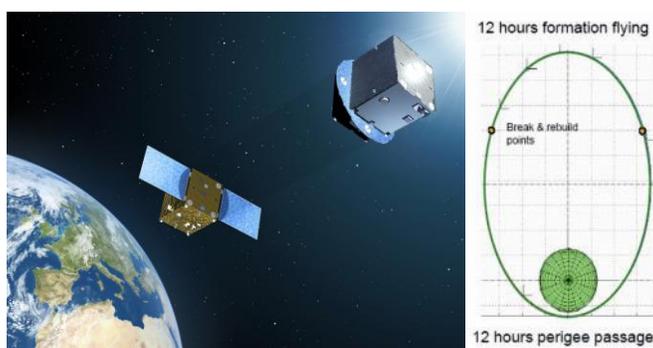


Figure 1. ASPIICS/PROBA-3 is a two-component space system with the external occulter on one spacecraft and the coronagraph instrument on the other spacecraft at 150 m from the first one. The 24 hours elliptical (800 x 70772 km) orbit is divided in two parts. Formation flying will take place over a 12 hours arc centred on apogee allowing a minimum of 6 hours/day of coronal observations. Formation will be broken over the remaining 12 hours as differential gravitational effects would induce too large cold gas consumption. Data transmission will take place during the perigee pass.

I. ASPIICS OVERVIEW

ASPIICS is a visible light, externally occulted coronagraph conceived to perform both high spatial resolution imaging and two-dimensional spectrophotometry of the inner corona. It is distributed on the two PROBA 3 spacecrafts (S/C) separated by 150 m. The coronagraph optical assembly is hosted by the “coronagraph S/C” entirely protected from direct sunlight by remaining in the shadow of the occulting disk hosted by the “occulter S/C”. The ASPIICS optical design follows the general principles of a classical externally occulted Lyot coronagraph but adapted to both the detection of the very inner corona as close as 1.02 R_{sun} from the Sun centre with high spatial resolution (5 arcsec), and the addition of a solid Etalon Fabry–Perot (F-P) interferometer. The design of the front optics is critical because a high level of aberrations and scattered light would prevent observing the very inner corona. An unobstructed three-mirror anastigmat (TMA) solution is

selected to limit the optical aberrations within a reduced volume while minimizing instrument stray light. Two dioptric objectives create a collimated beam for proper operation of the Fabry-Perot interferometer and the narrow band filters and finally image the corona onto a cooled, 2k x 2k CCD detector. There are four mechanisms, a front door, a shutter, a filter wheel (hosting filters and polarizers) and a tilting/retracting mechanism for the Fabry-Pérot. Its data acquisition system is further conceived to reach a high temporal cadence, as high as 1 sec for partial frames in imaging mode. ASPIICS further has the capability to independently control the pointing and alignment of the two satellites and to provide the initial and regular calibrations of the formation control system of the satellites, thanks to its Shadow Position Sensor (SPS) and Occulter Position Sensor (OPS). The adopted methodology optimizes the tradeoffs among the science objectives, the intrinsic properties of the corona, the latest available space technologies and the ultimate instrument performances of a “giant” coronagraph in flight formation within the allocated resources. Table 1 summarizes the current specifications of the instrument.

II. ASPIICS OPTICAL DESIGN

A classical dioptric on-axis solution was first investigated since it benefits from past heritages (i.e. SOHO/LASCO-C2 and C3, STEREO/SECCHI-COR2) and results in low instrumental polarisation. However, we prefer a reflective solution since this design offers major advantages such as a natural front baffle, protection of the first optics against contamination and thermal variations, and straightforward folding (reducing the overall length). Furthermore, this solution achieves a better optical quality at the internal occulter (required to limit the over-occultation and in turn, to observe the very inner corona). The present optical design is illustrated in Fig. 2.

Table 1: Specifications of the ASPIICS coronagraph

Optical specifications	Telescope (TMA) focal length: 1200 mm Entrance aperture diameter: 100 mm Stray light/Sun disk light rejection: 5×10^8 FoV: 1.02 Rs \pm 2.7/3.3 Rs Spatial scale: 2.58 arcsec/pixel
Detector	Size: 2048 x 2048 pixels; 15 μ m pixel Dynamic range: 16 bits Operating temperature < 60 °C
Wavelengths/operational modes	Bandpass 530–590 nm Fe XIV 530.3 nm; He I 587.6 nm Calibration lamp: 546.1 nm (Pen-Ray Mercury line source)
Fabry-Perot	Clear aperture 14 mm Spacer thickness: 300 μ m Finesse: 25; reflection coating: 91 %

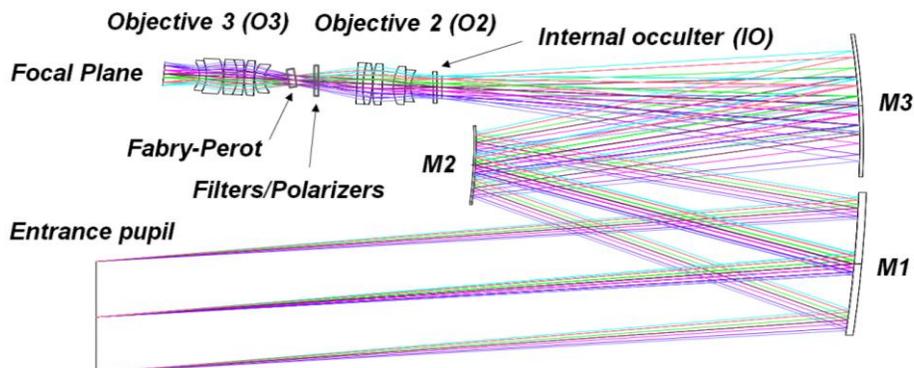


Figure 2: Optical design of the ASPIICS coronagraph with its Three-Mirror Anastigmat telescope (M1, M2 and M3 mirrors).

The external occulter (EO), hosted by the O-S/C, blocks the light from the solar disk while the coronal light passes through the circular entrance aperture (100 mm diameter). The primary mirror of the TMA is located 804 mm behind the entrance pupil. The internal occulter (IO) is located slightly beyond the focal plane of the 3-mirror objective since it is conjugated with the EO. An aspheric plate supports the internal occulter and compensates for the astigmatism introduced by the out-of-focus off-axis design. The dioptic objective (O2) produces a collimated beam where is located the image of the entrance pupil (Lyot stop) with a magnification of 5.5. The collimated beam leaving O2 passes through a narrow-bandpass Fabry-Perot (F-P) interferometer, a set of blocking filters (or a polarizer) mounted on a wheel. Each blocking filter isolates a specific emission line, and blocks all but a single transmitted interferometer order. The broadband filter allows obtaining polychromatic images of the corona (the Fabry-Perot is then removed from the optical path). The final image is formed by a telephoto lens system (O3) onto the CCD detector such that a circular field-of-view with a radius of about 2.7 R_{sun} forms an inscribed circle on the 2k x 2k pixels detector where one pixel subtends 2.58 arcsec on the corona.

The TMA is an off-axis 3-mirror system composed of three off-axis mirrors. It is the most critical optical component as far as stray light is concerned, and therefore all optical surfaces will be superpolished. The TMA was first optimized for infinite conjugate and then after it has been optimized for finite distance object (150 m) only changing three conic constants and the focus. The achieved optical quality at the internal occulter plane over a FoV of 1.5 deg diameter (mean wavefront error of $\lambda/200$ rms) allows minimizing the over-occultation due to optical aberrations. Finally the astigmatism introduced by the re-optimisation for finite object distance is compensated by an aspheric plate located behind the internal occulter. The mean WFE (computed over 1.04 R_{sun} for all wavelengths) is about 0.0051λ . Note that the WFE increases up to 5λ (mainly astigmatism) for infinite distance object. As shown in Fig. 3, the current optical configuration allows achieving high image quality (i.e. diffraction limited) at i) the internal occulter, reducing over-occultation, justifying formation flying and ii) the focal plane, producing sharp images, allowing to exploit the high spatial resolution of the coronagraph.

The aim of the internal occulter is to block most of light from the diffraction fringe surrounding the external occulter by slightly over-occulting its image. In the case of ASPIICS, the fringe is much fainter than in classical coronagraphs, so it will only be attenuated by a factor ≈ 10 to retain access of the inner corona as close as possible to the solar limb. The IO, which is placed very near the first image of the corona, is in fact a radial attenuator filter that will compensate the steep gradient of the radiance of the inner corona and therefore limit its dynamical range in the ASPIICS field-of-view. In classical coronagraphs such as LASCO, this is naturally achieved by the intrinsic vignetting introduced by the EO, this effect be nearly absent in ASPIICS because the EO is such at a large distance (150 m). Radial compensation by a density filter with radially variable transmission is a well proven technique often used during solar eclipses. The proposed radial transmission profile is displayed in Fig. 4.

The field-of-view (FoV) of ASPIICS is limited by an inner circle defined by the occulter and a square defined by the detector (Fig. 3). The external occulter will have a radius corresponding to 1.015 R_{sun} and the inner occulter will add an additional over occultation bringing the inner limit to 1.02 R_{sun}. The side of the outer square corresponds to a FoV of ± 2.7 R_{sun} while its diagonal corresponds to ± 3.8 R_{sun}. The spatial resolution falls into two different regimes (Fig. 4). Beyond 1.075 R_{sun}, it is pixel limited as the pixel angular extent (IFoV) of 2.58 arcsec exceeds the optical resolution of the telescope. Adopting the standard Nyquist criterion,

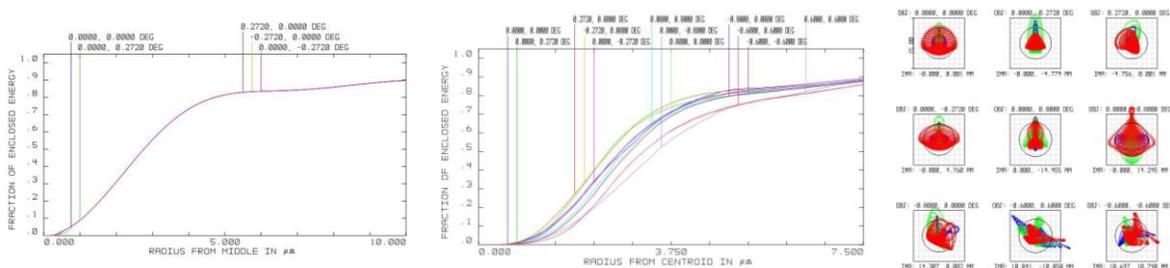


Fig. 3: Encircled energy within $10\mu\text{m}$ at the internal occulter plane for finite conjugate distance (left panel). Encircled energy within 1 pixel ($15\mu\text{m}$) at the detector focal plane central panel). Spot diagrams at the detector focal plane within one pixel (box) for 3 typical wavelengths (540, 560, 580 nm) for 9 field positions. The circle represents the Airy disk at 550 nm (left panel).

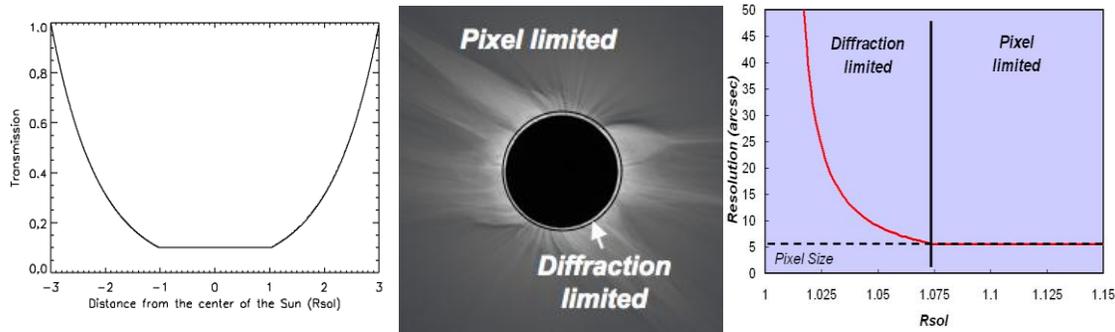


Figure 4: The radial profile of the neutral attenuator forming the internal occulter (left panel), the field-of-view of ASPIICS superimposed on a coronal image obtained by M. Druckmüller and P. Aniol at the 2006 eclipse (central panel) and the two regimes of spatial resolution (right panel).

the (2 pixels) spatial resolution amounts to 5.2 arcsec (to be compared with 24 arcsec for LASCO-C2 [4]). Inside 1.075 R_{sun}, the pupil starts to be vignetted and the resolution becomes a steep function of the FoV, reaching for instance 10 arcsec at 1.04 R_{sun}. This may in fact reflect the practical inner limit of the FoV. Further inside, the resolution degrades rapidly and this annular region will further be affected by the defocused wing of the diffraction fringe surrounding the occulter.

III. ASPIICS FABRY-PEROT INTERFEROMETER

To perform two-dimensional spectrophotometry of emission lines, no system can compete with the Fabry-Pérot (F-P) interferometer in terms of instrumental compactness. Tuneable F-Ps are very attractive as full two-dimensional imaging spectroscopy over a coronal line profile is achieved by synchronizing a series of exposures with a stepwise spectral scan of the tuneable filter. Such a system based on piezo-electric spacers has been implemented on LASCO-C1 [4] but has turned out difficult to adjust and control (some interesting results have however been obtained). Liquid crystal tuneable F-Ps are very promising but still in their infancy for space applications. They are under studied for the Solar Orbiter mission and are part also of our evaluation program. A further difficulty with the PROBA-3 mission is the high radiation dose that may be a severe problem for liquid crystal devices. Although this option is actively pursued [5], we prefer for the time-being to baseline our system on the other option, the F-P etalon with fixed spacers, a system of utmost simplicity and robustness. The method consists in analyzing the bidimensional distribution of line profiles by a set of quasi concentric fringes generated by the etalon (Fig. 5). The fringes have an instrumental profile of typically 0.02 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 CEL to a very good accuracy. The ASPIICS F-P will be mounted on a simple mechanism with a rotating cam allowing i) slight angular tilts to displace the system of fringes and to increase the spatial coverage of the CEL measurements and ii) complete retraction from the optical beam to operate the pure imaging mode.

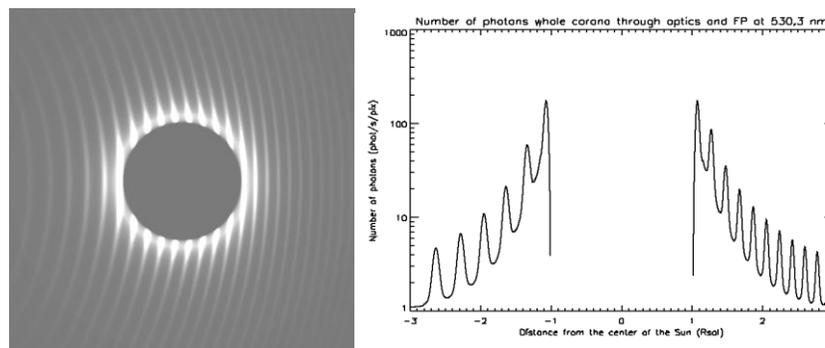


Figure 5: Simulated interferogram (left panel) and expected signal from the Fe XIV emission line for a corona of the minimum type

IV. STRAY LIGHT CONSIDERATIONS

Of prime importance for a coronagraph is its stray light level. This question is being approached by both optical calculations and laboratory tests [6, 7] and is still actively studied. Assuming that a high performance external occulter can be implemented, the total stray light that will enter the 10 cm pupil amounts to 5×10^{-8} Bsun, to be compared with 10^{-6} Bsun that enters the 2.1 cm of LASCO-C2. This reflects well the tremendous impact of increasing the EO-pupil distance. A large fraction of this stray light will be concentrated in the image of the diffraction fringe which itself will be blocked by the inner occulter, and only a small fraction, estimated at 10^{-9} Bsun, (similar to the coronal radiance at 3 Rsun) will appear as a constant background which can be subsequently subtracted. Internal stray light originating from the mirrors, the baffle and other components has been investigated and quantified [8].

V. ASPIICS FORMATION FLIGHT CONTROL

Two subsystems for control of the formation flight are part of ASPIICS to independently insure its correct pointing to the Sun and the alignment of the EO with the optical axis, and to further help calibrating the satellites GNC/flight formation subsystems. The "Shadow Position Sensor" (SPS) checks the safe centering of the entrance pupil of the instrument into the shadow cone of the occulting disc, by balancing the intensity received by four light sensors located around this entrance pupil in the penumbra zone. The "Occulter Position Sensor" (OPS) checks the correct positioning of the occulter in the field-of-view of the coronagraph by imaging a set of LEDs mounted on the rear side of the external occulter. Both systems have now been studied and laboratory demonstrators have shown that they exceed the required specifications [9, 10].

CONCLUSION

The ASPIICS project under the responsibility of the Principal Investigator (PI), Philippe Lamy, assisted by the Instrument Manager (IM), Bernard Repetti involves 12 institutes from 9 different countries, each supported by its national funding agency. The overall science consortium includes 44 Co-Investigators, 41 Associate Scientists, mixing senior and junior scientists, testifying to the vitality of the solar community particularly in Europe, and to the realization that ASPIICS will open a new window in coronal investigation. Indeed, ASPIICS heralds the next generation of coronagraph for solar research, exploiting formation flying to gain access to the inner corona under eclipse-like conditions for long periods of time, the outcome of a long quest since Bernard Lyot invented the coronagraph in 1931. ASPIICS will make a giant step in our knowledge of the solar corona by providing observations that will lead to the insights necessary for understanding key physical processes and for the prediction of space weather in the Sun-Earth system.

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