SCIENTIFIC OBJECTIVES OF THE NOVEL FORMATION FLYING MISSION ASPICS

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ABSTRACT

Formation flyers open new perspectives and allow to conceive giant, externally-occluded coronagraphs using a two-component space system with the external occulter on one spacecraft and the optical instrument on the other spacecraft at approximately 100-150 m from the first one. ASPICS (Association de Satellites Pour l’Imagerie et l’Interferométrie de la Couronne Solaire) is a mission proposed to ESA in the framework of the PROBA-3 demonstration program of formation flying (presently in phase A). ASPICS 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 from the coronal base out to 3 R⊙. ASPICS 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 ASPICS will allow to map 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. ASPICS will thus attempt to determine how the different components of the solar wind, slow and fast are accelerated. ASPICS will observe the corona during the maximum of solar activity, insuring the characterization of many Coronal Mass Ejections by rapidly alternating high resolution imaging and spectroscopy. In addition, ASPICS will attempt to characterize the topology of the magnetic field in the corona.

Key words: Coronagraph; Solar Corona; formation flying; visible; Fabry-Perot; etalon.

1. FORMATION FLYING APPLIED TO SOLAR CORONOGRAPHY

After 40 years of space coronagraphy, the lower corona (defined here as extending from the solar limb to a radius of approximately 2.5 R⊙, where R⊙ represents the solar radius) remains practically unobserved. The only available images are those obtained with the SOHO/LASCO-C1 (1) coronagraph 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 on instrumental stray light. It will be interesting to see in the coming months how the internally occulted SECCHI-COR-1 coronagraphs aboard the STEREO spacecrafts will perform. 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. For completeness, we mention the images taken on the occasions of (rare) total solar eclipses whose quality remains unsurpassed. The internally-occulted coronagraph SOHO/LASCO-C1 has pointed to the difficulty of reducing the instrumental level of stray light in such a coronagraphic configuration. 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 vignette from the pupil which degrades the spatial resolution prevent observing the inner corona inside typically 2-2.5 R⊙.

Formation flying opens the possibility to conceive and deploy giant coronagraphs in space that are not affected by the above limitations. Basically, the "formation" will act as a single virtual giant instrument impossible to conceive with the launcher limitations. The PROBA-3/ASPIICS (standing for "Association de Satellites Pour l’Imagerie et l’Interferométrie de la Couronne Solaire") mission is composed of two spacecrafts separated by about 100-150 m and forming a giant coronagraph: the external occulter is supported by one satellite while the second satellite hosts the optical system (Fig. 1).

ASPIICS is an externally occulted coronagraph entirely protected from direct sunlight by remaining in the shadow of the external occulter. The classical design is adapted to both the detection of the very inner corona as close as 1.02 R⊙ from the Sun centre with high spatial resolution (5 arcsec), and the addition of a solid "étalon" Fabry-Perot interferometer. Using such a concept, ASPICS will perform high spatial resolution imaging of the corona as well as 2-dimensional spectroscopy of several
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 100-150 m from the first one. Formation flying configuration studied by CNES/PASO (4).

emission lines from the coronal base (1.02 R\(_{\odot}\)) out to 3 R\(_{\odot}\).

The ASPIICS payload (2) proposed on PROBA-3 is an evolution of ASPIICS (3) previously proposed in 2004 to CNES in the framework of their demonstration program of formation flying. ASPIICS incorporated a set instruments (coronagraphs and disk imagers) implemented on both spacecrafts. The limited resources on PROBA-3 led us to address new scientific objectives using a new simplified payload most adapted to the PROBA-3 constraints.

2. SCIENCE OBJECTIVES

The energy that heats the corona and accelerates the solar wind and coronal mass ejections (CMEs) originates in subphotospheric convective motions. The physical processes that transport this energy to the corona and convert it into thermal, kinetic, and magnetic energy are not fully understood. The Solar and Heliospheric Observatory (SOHO) has greatly advanced our knowledge about coronal heating, solar wind acceleration, and CMEs, but many key questions remain unanswered. For instance, UVCS found evidence that the highspeed solar wind is dominated by proton pressure and that heavy ions in coronal holes are heated and accelerated by ion cyclotron wave dissipation (5), but the processes that accelerate the primary proton-electron plasma are still not identified. An understanding of physical processes in the corona is important not only for explaining the origins of space weather, but also for establishing a baseline of knowledge in plasma physics that is directly relevant to the Sun, other stars, and astrophysical systems ranging from the interstellar medium to black hole accretion disks.

Different physical mechanisms for heating the corona probably govern closed magnetic loops, active regions, and the open field lines that give rise to the solar wind (6).

Both densities and volumetric heating rates decrease rapidly with distance from the photosphere, but the coronal heating rates per particle remain large in the extended corona (7). This, combined with remote and in situ evidence that heating continues in interplanetary space (8), implies that the processes responsible for heating, wind acceleration, and CME ejection are dynamically important well above the coronal base. An empirical description of the primary acceleration region of the wind and CMEs (in the extended corona) is especially crucial to determining how the plasma properties at 1 AU are established.

There is a growing realization that the innermost 0.5 R\(_{\odot}\) of the solar atmosphere is dominated by different physics than the extended corona at larger heliocentric distances. The chromosphere, transition region, and coronal base are strongly collisional and exhibit a complex magnetic topology, whereas the extended corona is a relatively collisionless and uniform expansion of field lines into interplanetary space. Despite these local differences, the extended corona must be driven by energy that has made its way out through the lower layers. The lower solar atmosphere and corona are indeed efficiently coupled by the transport of nonthermal energy from the convection zone, and by downward thermal conduction of heat from the corona. The nature of the outward energy flux is not known, but stressed magnetic fields associated with MHD waves and electric currents are believed to play an important role. Dissipation of this energy heats the coronal plasma, drives the solar wind and propels CMEs. Understanding this complex system requires the characterization of plasma parameters in the acceleration region of the wind.

By performing high spatial resolution imaging of the corona as well as 2-dimensional spectroscopy of several emission lines from the coronal base out to 3 R\(_{\odot}\) ASPIICS will address the following questions.

2.1. How is the corona heated? What is the role of waves?

The origin of the plasma fluctuations (waves, turbulence, and shocks) that are believed to heat the corona and accelerate the ions is not yet entirely clear. The extended corona is thought to be heated by wave dissipation, but there is no direct evidence for such waves in the lower atmosphere (9). Proposed scenarios for still speculative ion cyclotron resonance in the extended corona (10; 11; 12) suggest that low-frequency waves launched by the Sun are transformed at larger distances, either by turbulent cascade or growing plasma instabilities, into higher-frequency waves capable of heating and accelerating the plasma. We do not yet know whether the same heating processes dominate in streamers, coronal holes, and CMEs. Past UVCS observations suggest that the waves in question are generated in the extended corona very near where they are damped (10; 13).

The extended corona is an ideal place for emission line
spectroscopic diagnostics because the plasma is nearly collisionless, allowing the velocity distributions of each species to retain undiluted signatures of the heating process. In order to address the question "how and where do plasma fluctuations drive the preferential ion heating and acceleration, and how are the fluctuations produced and damped?", ASPIRICS will characterize propagating fluctuations (waves and turbulence) in the solar wind acceleration region by extensively mapping the width of several coronal emission lines corresponding to different regimes of the corona throughout its field-of-view, from 1.02 to 3 R\(_e\). Our priority will go to the line of a "heavy" ion, Fe XIV, which is superior to the line of O VI used by UVCs; the Fe XIV ion is four times more massive and is formed at the true coronal temperature \(T = 1.8 \times 10^6\)K instead of O VI formed at \(T = 3.2 \times 10^5\)K. The iron lines are also much more appropriate to resolve the turbulence inside the corona, including the higher corona where the lines are no more collisionally dominated but are radiatively dominated (the radial gradient was measured by J. Arnaud (14), and it is well confirmed by recent eclipse measurements (15).

Another promising method to search for waves is to look for oscillations in the intensity and Doppler shift of spectral lines. Non-magnetic parts of the solar atmosphere exhibit 3-minute oscillations in lines of neutral or singly ionized species (16). By mapping the bright Fe XIV line of selected subframes at high temporal cadence (10 to 20 sec), ASPIRICS may be capable of detecting such oscillations in the intensity, Doppler shift and width of this line.

2.2. How are the different components of the solar wind, slow and fast, accelerated?

We know for a long time that the fast solar wind originates from coronal holes, though the respective roles of plumes and inter-plumes is disputed. The situation is less clear for the slow solar wind. On the one hand, UVCs found anomalously low abundances in the central cores of quiescent streamers (17; 18) and abundances that match those detected in the in situ slow wind in the outer edges of streamers. This would imply that the slow wind originates primarily in open field lines at the boundaries between streamers and coronal holes (19). On the other hand, LASCO has provided direct evidence for non-stationary mass loss in the form of "blobs" (20). Blobs are claimed to come from the streamer cusps but there is no direct evidence since cusps are usually hidden by the LASCO-C2 occulter. The relative contributions of steady and transient phenomena to the slow solar wind are not yet known quantitatively. In fact, in spite of these significant advances, the major roadblock in the way of a comprehensive understanding of the acceleration of the solar wind remains the lack of tight constraints on the plasma properties. In situ measurements cannot yet sample the acceleration region of the wind, and existing remote sensing measurements have been limited severely by photon statistics and resolution. The combined imaging and spectral diagnostics capabilities available with ASPIRICS will allow to map 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 several emission lines. Spatially resolved velocity profiles will be reconstructed and will shed new light on the above questions.

2.3. To what degree do coronal inhomogeneities affect the heating and acceleration processes?

An important aspect of solar wind investigations is to determine how the dominant physical processes vary between neighboring flux tubes in the inherently filamentary plasma (21). By measuring plasma properties in and between small scale fine structures in the accelerating wind (e.g., polar plumes and "blobs" in streamers), ASPIRICS can determine how heating and acceleration processes depend on changes in the underlying magnetic field topology and on bulk parameters like density. High-resolution observations can determine the filling factors in different structures. In the extended corona, the integration over the optically thin line of sight is always present, but even the filling factors along the line of sight can be constrained by comparing differently weighted density diagnostics (22; 23). For example, the filamentary nature of coronal holes has typically been interpreted as a two-phase medium (plumes and interplume plasma) but there may be an entire spectrum of density variations rather than just two separate phases. The spatial resolution and wide array of density diagnostics capability available with ASPIRICS will allow this next level of detail to be discerned for the first time.

2.4. How are CMEs accelerated?

LASCO has detected and tracked hundreds of CMEs. Classically, CMEs show a bright leading edge, sometimes including a shock, a dark void behind it, and a core of bright eruptive prominence material; they are propelled outward at speeds from 100 to 2000 km/s. A dozen or so of the LASCO CMEs have also been observed with UVCs showing the potential of combining imaging and spectral diagnostics. Despite these observations, many questions about CME evolution remain unanswered. The most basic questions involve the nature of the interaction between the CME plasma and the magnetic field that drives the eruption. The kinetic energy and thermal heating of the CME plasma are comparable within large uncertainties (24), but the source of heating has not been identified.

With a probable launch in late 2010 or early 2011, ASPIRICS will observe the corona during the maximum of solar activity, insuring the detection of many CMEs. By rapidly alternating high resolution imaging and spectroscopy, CMEs will be thoroughly characterized. Doppler shifts will provide the line of sight velocity component while continuum images will record their propagation in the sky plane, the combination yielding a 3D view of the CME structure and evolution.
2.5. What is the configuration of the magnetic field in the corona?

The importance of obtaining physical measurements of the magnetic field direction in the corona (as contrasted with field directions inferred from the simple appearance of structures) is crucial in a magnetically dominated corona. Of particularly great interest are the following aspects: locating sector boundaries in the solar wind near the Sun, and tracing their spatial and temporal evolution; obtaining magnetic field maps of helmet streamers and searching for neutral sheets; tracking the evolution of the global magnetic field associated with erupting prominences and CMEs; investigating changes in the field near the site of suspected reconnection events. Space observations have completely changed our view of the solar corona but, up to now, the direct investigation of the coronal magnetic fields have been eluded and no mission aimed at changing this situation is yet planned. ASPICS may well be the first instrument to fill this gap as it will map the coronal magnetic structure through polarization measurements in the Fe XIV 530.3 nm line, in fact as it was planned on LASCO-C1.

3. METHODOLOGY

The method consists in analyzing the bi-dimensional distribution of line profiles by a set of quasi concentric fringes generated by the Fabry-Perot etalon interferometer. 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 coronal emission line to a very good accuracy. 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.

Interferograms of the coronal Fe XIV 530.3 nm "green" line with an "etalon" Fabry-Perot interferometer have already been obtained during solar eclipses (25) as illustrated in Fig. 2. In spite of using "old" techniques (photographic film measured with a microdensitometer), intensities, Doppler shifts and line widths have been successfully measured at many points in the corona and the splitting of the line over the poles predicted by models has been observed (Fig. 2, lower panel).

Figure 2. A Fabry-Perot interferogram obtained during the solar eclipse of February 1980 (25) (upper panel). Note that their interferometer was so tilted (center on the solar disk) that only 2/3 of the corona was covered by the fringe network. The fringes at the bottom (south) are not broadened but actually split as predicted by models (lower panel).

4. CONCLUSION

ASPICS will open a new era of high quality, continuous imaging of the inner corona with 2D diagnostic capabilities thanks to:

- the formation flying configuration allowing to conceive an externally occulted coronagraph to observe down to 1.02 R_⊙ with low level of straylight (comparable to eclipses) and high spatial resolution (no vignetting);
- 2D spectroscopy of several coronal emission lines truly representative of different coronal regions;
- mapping of the direction of the magnetic field.

With these unique capabilities with no competitor in the coming ten years, ASPICS should significantly contribute to still unanswered questions of coronal physics.
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REFERENCES