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Solar Drivers of Interplanetary and Terrestrial Disturbances
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White-Light Reflecting Coronagraph for the SWATH Mission

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Abstract. Much has been learned about the morphology of coronal transients from earlier space observations. Nevertheless, particular circumstances on the solar surface that lead to coronal mass ejections (CMEs) remain unclear, while many aspects of CMEs themselves and their impact on interplanetary space and the Earth's environment are poorly understood. The great need for more data on CMEs and other coronal transients, especially observations with improved sensitivity and angular resolution, is reflected in the decision to include three coronagraphs, C1, C2, C3 (LASCO module) on the SOHO spacecraft. C1 is an internally-occulted coronagraph that uses an off-axis parabolic objective mirror. The SWATH (Space Weather and Terrestrial Hazards) coronagraph described here also has a mirror objective, but is externally occulted. It is an on-axis design that uses a 100-mm aperture, super-polished spherical objective mirror, the white-light image recorded with a 2048 x 3072 CCD detector. A special external occulter, and a ring reflector used to reject the direct solar light, are further novel aspects of the design of this coronagraph. It will be used to detect coronal transients, explore the feasibility of detecting space debris by coronagraphic techniques, as well as to record the white-light corona with improved angular resolution for studies of the detailed morphology and evolution of coronal structures.

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1. Introduction

A large observational record of coronal mass ejections (CMEs) and other coronal transients has been obtained with white-light space coronagraphs, starting with data from the NRL coronagraph on OSO-7 (Tousey 1973), from the HAO coronagraph on Skylab (MacQueen 1980), from the NRL SOLWIND coronagraph (Sheeley et al. 1982), and from the HAO SMM coronagraph (Hundhausen 1994). Such observations have been supplemented with ground-based K-coronameter data (Fisher and Munro, 1984) that cover more of the critical inner coronal region than has been available from the space instruments. The state of the art in space-borne coronagraphy before the SOHO epoch has been reviewed by Koutchmy (1988).

While detailed studies of CMEs have provided a wealth of statistical information (see, for example, Hundhausen 1994), many fundamental aspects of CMEs remain unclear, such as the particular conditions that give rise to a CME and trigger its release, how the initiation of a CME relates to other surface events, and the detailed morphology, including the apparent shock front that leads and the more dense material that follows. The critical need for more data on CMEs, especially observations with improved sensitivity and angular resolution, is reflected in the decision to include three coronagraphs, C1, C2, C3 (LASCO module) on the SOHO spacecraft, the three coronagraphs together spanning a field of 1.1 R_o to 30 R_o (Brueckner et al. 1995). C1 is a relatively high-angular-resolution, internally occulted coronagraph that uses an off-axis parabolic objective mirror, covering a field of 1.1 R_o to 3 R_o, and recording both coronal-line emission and the K-corona. C2 and C3 are white-light coronagraphs. It is noted that CMEs directed towards (or away from) the Earth have apparently been identified, as evidenced by enhancements that develop around the entire edge of the occulting disk (Schwenn 1986). Improved coronagraphic performance should increase the probability of such detections, which could provide extraordinarily valuable data from ionospheric forecasting purposes. Apart from CMEs, other types of dynamical events, such as rapid realignments (perhaps revealing reconnection) and loop interactions, are observed in coronal emission-line studies (Dunn 1971; Smartt et al. 1993; Shimizu et al. 1994). Gross features observed in the K-corona have been found also in emission-line images (Koutchmy et al. 1988). Because of the controlling influence of the magnetic field distribution, this is to be expected, although intensity distributions around and within specific features are likely to be different, given the different electron density dependence (line emission is nearly a quadratic function of the Ne distribution, while the white-light intensities are a linear function). But such studies have been necessarily limited and conclusions correspondingly uncertain through a lack of higher resolution white-light coronal observations than has previously been obtained from space coronagraphs. Certainly, high-quality total eclipse observations have revealed fine structure in the white-light corona at the arcsec level (Koutchmy et al. 1993; November & Koutchmy 1995), and *Yohkoh* movies reveal graphically the dynamical nature of the corona, at least as observed in soft x-rays (Shimizu et al. 1994). Given the above perspective, it is abundantly clear that significant progress in the field of coronal dynamics requires coronal observations with considerably improved angular resolution and sensitivity over that previously achieved. The LASCO instrument of SOHO (Brueckner et al. 1995) is aimed at fulfilling this need. The SWATH (Space Weather and Terrestrial Hazards) coronagraph described here, a "new technology" design, has a similar thrust, with the additional aim of exploring the feasibility of detecting space debris.

The originally-planned SWATH mission contains four observing instruments – a high-resolution, normal-incidence x-ray solar telescope (6.35nm), two small EUV solar telescopes (19nm) and a white-light coronagraph. The x-ray telescope has a field-of-view of 1000 arcsec, with an angular resolution given by 0.5 arcsec pixel sizes on a 2048 x 3072 CCD detector. The coronagraph and EUV telescopes share a common housing and an identical CCD detector, with observations time-shared between the coronagraph and EUV telescopes. Mission objectives are to study transient disturbances associated with, for example, mass ejections, flares, coronal holes and recurrent storms, and to monitor and study coronal activity. The coronagraph will also be used to explore the feasibility of detecting space debris in the sub-cm range of particle sizes. Coronagraphic observation of space debris in the local spacecraft environment was demonstrated on Skylab, using the SO52 experiment (Schuerman et al. 1977). Analysis of photographic data indicated that the debris consisted of particulates ($\sim$ 10-100μm size) at close range that were apparently generated in the course of the Skylab mission operations. The larger aperture of the SWATH coronagraph would allow detection of more distant objects including, in addition to locally generated particulates, debris in different orbits, provided the angular velocities across the line of sight were not large. Assessment of the SWATH coronagraph's performance would likely lead to the design of larger aperture, internally-occulted space coronagraphs, thus providing the capability for comprehensive study of the debris environment.

The primary SWATH contract is held by the Smithsonian Astrophysical Observatory (Leon Golub, Principal Investigator), the National Solar Observatory/Sacramento Peak (NSO/SP) having a sub-contract to SAO for design, development and construction of the white-light coronagraph, which we describe here. Completion of the full instrument package awaits full funding. While the coronagraph sub-contract has been fully funded, the remaining funds have allowed (at this time) only the acquisition of the critical x-ray telescope objective mirror and the two special CCD detectors.

2. Mirror-Objective Coronagraph Technology

Mirror objectives for coronagraphs have been successfully applied to small externally-occulted rocket- and balloon-borne coronagraphs (Kohl et al. 1978). Recently, extremely low-scatter mirror development has allowed the use of such mirrors as objectives for internally-occulted coronagraphs (Smartt et al. 1990a; Epple & Schwenn 1995) with the advantages of achromaticity, wide spectral coverage and the realistic possibility of large apertures (meter class, or even larger) for ground-based instruments. For internally-occulted designs, an off-axis optical configuration is appropriate since a clear-aperture entrance pupil is required for optimum performance. An inverse occulting system can be used by having an annular field mirror at the primary focal plane - the coronal field is reflected to the secondary optical system while the solar disk image passes through the central hole in the field mirror. Rejection of the solar disk image from the coronagraph then avoids the need to control excessive heating within the instrument.

The amount of scattered light produced by a high-quality optical mirror depends primarily on the residual micro-roughness of the substrate and on the reflective coating, apart from that due to surface defects, dust particles and other contaminants. Measurements of the scattered light of several super-polished mirrors have been carried out at NSO/SP. For a 5-cm diameter, silicon super-polished (0.25nm rms micro-roughness) objective mirror, the measured scattered light level was 10^{-6} B_{source} at an angular distance equivalent to $1.5R_o$ from Sun center. This mirror has obvious imperfections and a higher-level performance is to be expected. This is to be compared with the brightness of the 5303Å (Fe XIV) coronal emission above active regions with typical values $> 10^{-5}$ B_o (solar maximum) to $> 10^{-6}$ B_o (solar minimum) at 1.3 R_o.

A small prototype, emission-line reflecting coronagraph, Mirror Advanced Coronagraph I (MAC I) has been constructed at Sac Peak. The objective is a super-polished, spherical silicon mirror of 5-cm diameter, with a focal length of 1-m, and a micro-roughness < 0.3 nm rms. The optical system is simply off-axis reflection from the primary mirror to the secondary optical system of a conventional Lyot coronagraph. It has been used to produce satisfactory images of the emission corona in the 530.3 nm (Fe XIV) line (Smartt et al. 1990a; Smartt et al. 1989). A second, more advanced, prototype instrument, MAC II, based on a 15-cm diameter super-polished mirror objective has been constructed, jointly with the Institut d'Astrophysique (IAP). The objective mirror has a focal length of 225 cm. A concave annular field mirror, located near the primary focal plane, forms an image of the objective at the position of the Lyot stop, and a collimating lens filter and re-imaging lens before the final image plane comprises the total optical system. The field mirror functions as an inverse occulting disk (unlike MAC I, the coronal field is reflected while the solar image is transmitted through the central hole that is a few percent larger than the solar image itself). The solar disk image passes through this hole to a light trap. This design represents overall the preferred optical system for a ground-based reflecting coronagraph, except that an equivalent all-mirror system would preserve full achromaticity and allow UV and IR observations to the full extent of atmospheric transmittance, mirror reflectance and available detectors.

A much larger, research-quality instrument has also been designed (Smartt & Koutchmy 1995). It is based on a 60-cm diameter objective, the all-mirror design optimized to allow diffraction-limited observations of the corona over a square field-of-view limited to several arcmin on a side. For this, a small field mirror is used that covers only the part of the corona under study. Different parts of the corona are then observed by rotation of this mirror around an axis passing through the center of the solar disk. The current design has an overall length of ~ 7m. Advanced spectral analyzing instruments, including a grating spectrograph, a tunable Fabry-Perot interferometer and a polarimeter, are planned for this instrument.

For an externally-occulted, space-based reflecting coronagraph, as in the SWATH design, a mirror objective has the additional major advantage of compactness (as compared with a conventional lens-objective coronagraph of the same aperture), since the primary image is formed close to the plane of the entrance aperture, and the objective is deep within the instrument, so that the likelihood of dust contamination and radiation damage is then lessened as compared with a lens objective at the entrance aperture.

A moon-based UV (Lα; 121.6nm) reflecting coronagraph of similar design has also been proposed (Smartt et al. 1990b; Vial et al. 1994; Smartt 1992). Operations from a lunar base would have several advantages, as compared with an orbiting instrument, such as extremely precise tracking and absolute pointing, uninterrupted data acquired over a lunar day with the possibility of high data rates, and Lα completely free from any geocoronal background.

3. SWATH Coronagraph Design

For the proposed mission, a novel mirror-lens design, indicated in Fig. 1, has been developed that best meets the spacecraft requirements of mass and size limitations. The on-axis, symmetrical design (by R. B. Dunn) features a relatively-large-aperture objective mirror, a novel external occulter design (by S. Koutchmy and G. Courtes), relatively-high angular resolution, and shared CCD detector with two EUV telescopes.

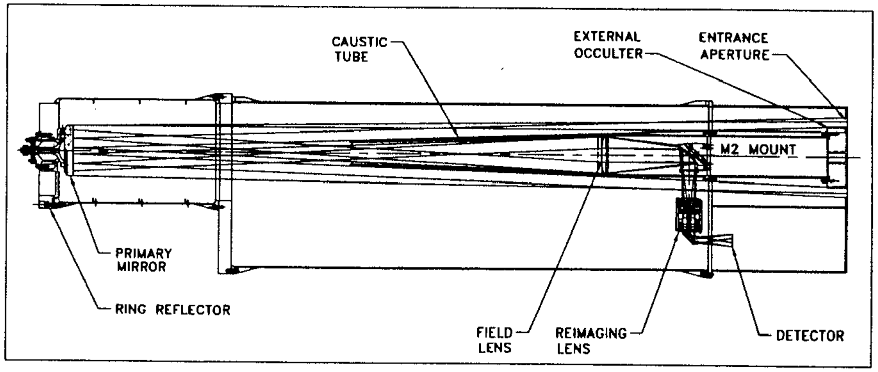

Figure 1. Symmetric objective-mirror lens system for a planned satellite coronagraph.

High optical correction is required, especially for space-debris detection, since although small particles will be unresolved, flux considerations lead to a specification that the image spread of an unresolved particle will be substantially limited to no more than the size of one pixel on the 2048 x 3072 array detector. A solution has been found, using a spherical primary mirror (100 mm diameter; 1035 mm focal length), singlet field lens and a compound relay lens that achieves this level of correction over a wavelength band of approximately 200 nm and a coronal field out to 6 R_o.

The annular entrance aperture is formed by the centered external occulter and a surrounding serrated aperture of 160-mm diameter. Together with the primary mirror at a distance of 1520 mm, this entrance aperture gives a field-of-view of 1.5 - 6.0 R_o, with 100% obscuration at 1.5 R_o, and 30% at 6 R_o. The remainder of the optical system consists of the super-polished primary objective, a singlet lens close to the primary image, and a 6-element re-imaging lens that forms the final image at the detector after reflection from a second plane mirror. The design of the re-imaging lens is complex, especially given the crescent-shaped pupil that varies with field angle and the associated diffraction components. The effective focal length of the entire system is 354 mm with an overall focal ratio of 3.5 and a depth of field of $\sim 25\mu$m. A cut-off filter near the focal plane blocks transmission of wavelengths less than $\sim$ 470 nm. The CCD detector pixels are equivalent to 6 arcsec, with the highest angular resolution $\sim$ 12 arcsec corresponding to the largest field angles. The assembled coronagraph is shown in Fig. 2.

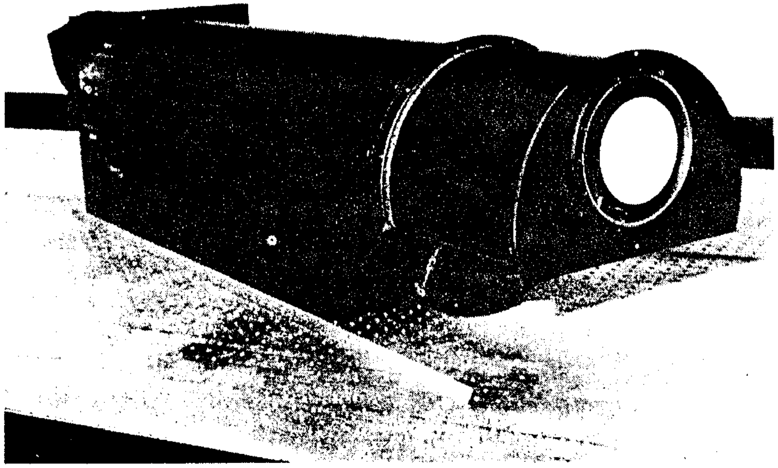

Figure 2. Coronagraph with the front cover removed to show the front of the external occulter and the surrounding serrated external aperture

The principal construction material is aluminum, but titanium is also used for some key parts. The vertical plate at the end of the large tube corresponds to the spacecraft bulkhead interface. The rear tube (on left in Fig. 2) contains the primary objective mirror and ring reflector as an integral unit. Likewise, the front housing contains the external occulter and serrated aperture mounts, the secondary optics and baffles, and the detector, all mounted as an integrated unit. Lyot and other stops are located in different positions along the optical axis to suppress stray-light images. The entire system will be hermetically sealed after cleaning and final assembly.

4. Discussion

Of critical importance in the performance of the coronagraph is the scatter characteristic of the primary mirror, which depends principally on the surface microroughness. The SWATH coronagraph primary objective mirror (produced by Research Electro-Optics, Inc., Boulder, Colorado) has a microroughness, after coating with aluminum and SiO_2, of 0.055 nm rms. This extremely low value, together with external occulting, should assure a high-quality coronagraphic performance, provided that particulate and molecular contamination of the mirror surface remains negligible during the mission. The primary mirror is surrounded by an annular toroidal mirror that rejects the direct solar light by focusing it to a narrow ring at the plane of the entrance aperture. This special mirror, and also the external occulter, are diamond-turned and polished to produce low-scatter reflecting surfaces, also critical for efficient coronagraph performance. The novel external occulter design has been developed at IAP. The underlying principle is to have a continuous compound cylindrical surface that is a further development from an earlier version consisting of a threaded surface that simulated a multiple-disk occulter. Tests indicate that this new system gives a superior performance to other occulter designs in terms of the level of diffracted light from it that falls on the objective aperture. A further advantage is that this new occulter design is far less sensitive to misalignment than the earlier disk designs. The detector will be used also to record images of the Sun produced by two small EUV (19nm) telescopes in a time-sharing mode with the coronagraph. The external occulter, limiting the inner field-of-view to 1.5 R_o, provides a safe margin in the case of unexpected spacecraft pointing errors, while also minimizing scattered-light problems.

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An Update on the FIRE (Solar Probe) Mission

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Abstract. A joint U.S.-Russian mission to the Sun named FIRE is currently being planned. The mission consists of two spacecraft, one U.S. built and the other Russian built. Both spacecraft will be launched from a single vehicle, will be separated after launch, and then travel to Jupiter for a gravity assist that will maneuver the spacecraft into highly elliptical polar orbits about the Sun. The U.S. spacecraft will have a perihelion of 4 solar radii (R_S) and the Russian 10 R_S. A full complement of in-situ fields and particles instruments are planned for both spacecraft to measure acceleration mechanisms and other characteristics of the solar wind. The strawman payloads and expected science return will be discussed.

1. Introduction

The FIRE program was conceived in 1994 to develop a joint U.S. and Russian mission to travel to the vicinity of the Sun. It was planned to use a single launch of a Russian Proton launch vehicle in 2001. The program promises to yield new data about the local environments around the Sun and specifically will reveal new information about the birth and acceleration of the solar wind. Miniaturized instruments will be developed that can be accommodated on small high technology spacecraft from each country. The two small spacecraft will be stacked inside the Proton firing and will be launched to Jupiter for a swing-by that will place them on trajectories with perihelion radii of 4 R_S (U.S.) and 10 R_S (Russian).

2. The Science Context

The FIRE science objectives were defined early in the joint study (ref. 1) and provided the context for the science observational requirements of the mission.

One of the fundamental mysteries in the universe is why ordinary stars like our Sun have extremely hot outer atmospheres (approximately one million