DEVELOPMENT OF REFLECTING CORONAGRAPHS

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ABSTRACT Lyot singlet-lens objective coronagraphs are used to observe the emission- and white-light components of the solar corona on a routine basis from high mountain sites. But such conventional coronagraphs cannot meet the observational requirements of many of the current outstanding problems in coronal physics. These problems require fully achromatic coronagraphic systems with high angular resolution and high photon flux. Limitations inherent to the design of Lyot coronagraphs can be substantially overcome. Mirror-objective coronagraphs have previously been proposed that now are a reality due to the recent advances in the development of superpolished mirror technology. Two prototype reflecting coronagraphs are described, of 5-cm and 15-cm aperture, based on off-axis reflection from the primary mirror to an annular field mirror (15-cm instrument) that functions as an inverse occulting disk, reflecting the coronal light to the detection system. The optical design of a third coronagraph of 55 cm aperture has been completed. Based on this design concept, a much larger (2 or more meters aperture) instrument is planned.

Keywords: solar/stellar reflecting coronagraphs, solar corona

1. INTRODUCTION

1.1 Observational Limitations of Existing Instrumentation
Observations of the solar corona in the wavelengths of the visible emission lines, and also the white-light (K) component, are carried out routinely at various high-altitude sites around the world (see, for example, Altrock 1988a). Coronal observations have provided a wealth of data about the short- and long-term morphological characteristics of the corona. Images in the emission lines reveal the typical complex loop structure associated with the photospheric magnetic field. But the structure usually has a rather different form associated with different lines that are characterized by different temperatures. Gross features observed in the K-corona are found also in emission-line images (Koutchmy 1988), which is to be expected if the structures are describing the magnetic-field distribution (Querfeld and Smartt 1984). But lack of high-angular-resolution observations precludes precise comparison and hence considerable

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uncertainties remain. The long-term characteristics of the distribution of the corona around the limb as a function of the solar cycle can be well-studied with existing instrumentation (see, for example, Altrock, 1988b), by recording the brightness of spectra just above the limb, or by using extremely sensitive coronal photometers (Smartt 1982). Photometric measurements usually cannot be obtained beyond a height $\sim 0.5 R_\odot$ above the limb, however. The relationship of hot coronal material with cooler prominence material, and with cool material in general in the coronal environment, has not been well-studied due to the limitations of instrumental sensitivity and angular resolution. Short-time-scale dynamical events such as rapid realignments (Dunn 1971) and oscillations and/or waves have been observed, but mostly such observations have provided only very limited data (Tsubaki 1988). With data from space-based white-light coronagraphs, much has been learned about coronal transients and mass ejections, and their relationship to surface events, although details of the mechanisms involved remain mostly quite speculative. Post-flare loop systems have been well-studied. However, only with improved-quality data has a phenomenon of loop interaction and partial magnetic reconnection become evident (Smartt and Zhang 1987). Extremely faint (relative to the average coronal field) features are occasionally observed at the limit of detection of existing instrumentation, but these data suggest that a whole regime of faint events that possibly occur frequently in the corona are simply never observed.

Spectral observations can provide some information about flow velocities, temperatures and, with white-light observations, densities. Flow velocities associated with coronal holes are of critical importance in solar wind studies. Such measurements are extremely difficult to obtain because of the low light flux and hence extremely noisy signals, requiring long integration times that result in low precision data (Smartt and Zirker 1981). Further, measurements of the magnitude of the magnetic field require much higher light flux (to measure the full spectral profile) and high angular resolution data.

In summary, progress in the field of coronal physics requires substantial improvements in the quality of the observational data, and hence, major advances in the instrumentation.

1.2 Observational Requirements

The above discussion highlights the lack of the availability of advanced instrumentation capable of meeting the current needs of coronal astronomy. Coronal measurements are complicated by the long integration paths inherent in optically thin visible lines and continua. In particular, a much higher angular- and temporal-resolution capability for both images and spectra is required, with the possibility of obtaining simultaneous measurements in different spectral lines. Key to improved understanding of the coronal plasma and its dynamical manifestations is measurement of Doppler velocities and magnetic fields in small-scale structures. Doppler measurements in different temperature regimes are needed to analyze phenomena connected with oscillations, wave propagation, proper motions, etc. High-angular and spectral-resolution analysis should show line profiles composed of many components (multi-component analysis). These components should be followed precisely in time, in order to give a detailed diagnostic of the processes, their evolution and connection with other known phenomena. Up to now, the profile of a coronal line has been described by introducing a "turbulent" velocity, the appropriate value of which is very
uncertain because of the lack of adequate angular resolution (Koutchmy and Smartt 1989). Advances in our understanding require precise determination of line profiles of individual features, in contrast to the smearing that results from overlapping structures. No direct measurements of the magnetic field have yet been obtained, but it is clear that the static magnetic field configuration determines the detailed morphology, while instabilities in the field principally determine the dynamical behavior.

2. EXISTING CORONAGRAPH INSTRUMENTATION

2.1 Solar Applications
Ground-based emission-line and white-light coronagraphs use a singlet, primary objective to minimize scattered light, consistent with the original Lyot design. Examples are the Sacramento Peak general purpose 40-cm-aperture emission-line coronagraph and the 20-cm-aperture patrol emission-line coronagraph (Smartt et al. 1981), the white-light Mk III K-Coronameter operated by the High Altitude Observatory in Hawaii (Fisher et al. 1981), and the eight 52-cm-aperture coronagraphs of the Soviet Union, Poland and Czechoslovakia. A primary limitation of these coronagraphs arises from the color curve of a singlet-objective lens. The secondary optical system can correct this color over a wide range of wavelengths and over a relatively large field. By use of a Mangin mirror, the total system can be made achromatic over the wavelength range transmitted by the glass. However, while the solar image is color-free, the image of the occulting disk has an enormous amount of color, with magnification a function of wavelength. This property precludes simultaneous observations at widely differing wavelengths, while observations close to the limb require a variable diameter occulting disk whose position along the optical axis is a function of wavelength. Overall, Lyot-type coronagraphs suffer from a) the chromatic properties of the primary objective; b) aperture limitations of a singlet lens, with a realistic limit probably \(< 1 \, m\), limiting resolution and light flux; c) long- and short-wavelength limits as determined by the glass spectral transmittance; d) internal seeing due to heat flux of the solar image. Despite such limitations, many outstanding observations have been obtained with these instruments. The use of high-resolution image intensifiers and CCD recording has greatly improved the capability of these coronagraphs (Smartt et al. 1987). Nevertheless, the principal requirements as outlined in Section 1.2 cannot be met with existing instrumentation.

2.2 Nighttime Applications
There is considerable interest in obtaining observations of faint emission associated with different types of astronomical objects. Such observations demand coronagraph-quality instrumentation where the faint emission is angularly close to a much brighter source. Examples are the study of reflectance spectra of solar system objects such as planetary rings and outer satellites, white-dwarf companions of binary systems, searches for protoplanetary disks around stars, and the study of other faint emissions associated with some stellar, galactic and extragalactic objects. Coronagraph-like instruments have been designed for stellar studies. These are optical systems that incorporate the essential features of the Lyot coronagraph, that is an occulting mask at the primary
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image plane, and one or more apertures (equivalent to a Lyot stop) to block diffracted light from the secondary-mirror support and apertures of the telescope itself. Successful observations of Sirius B have been obtained with such a device operating on the DuPont 2.5-m telescope, Las Campanas, Chile (Vilas and Smith 1987). A similar device has been proposed for the Hubble Space Telescope (Breckinridge et al. 1984). Limitations result from the use of telescopes with pupil obscuration, diffracted light arising from different components, and hence different planes, in the telescope, and scattered light contributions from more than one optical surface.

2.3 Comparative Requirements
While the basic principles involved in designing coronagraphs for solar applications and for nighttime applications are the same, performance requirements for representative observations are somewhat different. The visible solar emission corona has a spectral brightness typically in the range of $10^{-4}$ (at some locations close to the solar limb around the period of solar maximum) to $10^{-6}$ (or less) of the photospheric spectral brightness of the extended solar surface. The average brightness of the brightest visible coronal line (5303Å; Fe XIV) at 1.4$R_\odot$ from the disk center ($\sim$ 400 arcsec from the limb) is $\sim 10^{-6} \ B_\odot$, while the spectral brightness of the K-corona is little more than $10^{-6} \ B_\odot$ at the limb (Koutchmy et al. 1990). The observational requirement to observe the solar emission corona at a field angle of, say, 400 arcsec from the solar limb is very different from observations of, for example, the white dwarf companion of Sirius, which is $10^{-4}$ times as bright as the major star, with a separation of only a few arcsec (Breckinridge et al. 1984). In the above particular solar example, the requirement is to have an extraordinary low level of instrumentally-scattered light at a relatively large field angle, whereas the stellar example involves smaller differences in brightness, but requires minimization of small-angle scattering. Hence, in the stellar case, macroscopic smoothness of the objective surface is crucially important with regard to small angle scattering, whereas microscopic smoothness (the normal definition of a "superpolished" surface) is probably more important for typical solar coronal studies.

3. REFLECTING CORONAGRAPH

A coronagraph based on a mirror objective avoids the problems inherent in a singlet objective design, since the primary image is achromatic, and for an all-mirror design, infrared and ultraviolet observations are limited only by the transmittance of the earth's atmosphere. Further, large apertures are, at least in principle, possible. The idea of using mirrors as coronagraph objectives has been proposed previously (Newkirk and Bohlin 1963; Zirin and Newkirk 1963) and successfully applied to small externally-occulted rocket- and balloon-borne coronagraphs (see, for example, Kohl et al. 1978). But it is only recently that superpolished mirrors of requisite quality have become available to allow the practical reality of internally-occulted, reflecting coronographs. The amount of scattered light from a polished surface depends on the residual micro-roughness of the surface, apart from that due to surface defects, dust particles and other contaminants. Now surfaces can be polished with an rms roughness of only a few Angstroms, and, for small surfaces, even at the sub-Angstrom level. Moreover,
several methods have been developed for cleaning mirrors without damaging the surfaces. The problem is minimized by using special mountings for the objective and protective covers when the coronagraph is not in use.

For space-based coronographs, contamination of the primary-objective mirror surface is not likely to be a problem, but experience with other space optical systems suggests that gradual degrading of the reflectance of the objective could occur, especially for a solar coronagraph. A small reflecting coronagraph has been designed and constructed as one of three coronographs that together form the cluster, "LASCO", for the SOHO Mission. The objective is a superpolished uncoated, silicon mirror. An Earth-orbital true coronographic telescope of 1.5-m aperture has been proposed to allow direct detection of a Jupiter-size planet around a solar type star out to a distance of about 10 parsecs (Terrile et al. 1987).

3.1 Prototype Instruments

We review here briefly features of an ongoing program at NSO/SP to develop the technology of reflecting coronographs. The first prototype Mirror Advanced Coronagraph (MAC I) constructed in this program is based on a 5-cm-aperture superpolished silicon objective mirror with a 1-m focal length, operating in an off-axis configuration. The secondary optical system is a conventional design consisting of an occulting disk at the primary image plane to block the image of the solar disk, followed by a field lens, Lyot stop, filter and detection system (Koutchmy and Smartt 1989). As mentioned above, contaminants (such as dust) on the surface of the primary objective could severely impair the coronagraph performance. However, even though this design did not include special means to prevent dust accumulation, experience with this instrument has indicated that the problem is not severe. Only occasional cleaning was necessary, presumably a result of the basic form of the optical system of a reflecting coronagraph in which the objective is protected deep within the instrument. Images have been obtained with MAC I of the emission-corona (5303Å; Fe XIV), the first such images ever obtained with a ground-based coronagraph that uses a mirror as the primary objective. This coronagraph design serves as an excellent prominence monitor and is being converted for this purpose, with CCD detection.

A second prototype instrument (MAC II) is under development that uses a 15-cm aperture, spherical, superpolished objective mirror made of fused silica coated with aluminum, with a focal length of 2.25-m. This mirror, and its active mount, were constructed at Institut d'Astrophysique de Paris under a joint program between IAP and NSO/SP. The secondary optical system features a metal field mirror, annular-shaped, that has a concave radius of curvature. It reflects only the coronal field, while the solar image passes through the central hole to an inclined plane mirror that reflects this light to a second plane mirror and then out of the system. A Lyot stop is located at a pupil image to occult diffracted light from the primary mirror aperture, followed by a filter and detection system. While this is not an all-reflecting system, it offers the possibility of obtaining simultaneous coronal images at widely differing wavelengths, including the near-infrared emission lines. Both the MAC I and MAC II are mounted on the spar of the NSO/SP Hilltop Facility.

A research-quality reflecting coronagraph (MAC III) with an aperture of 55-cm and focal length of 4.5 m is in the design phase. The small field mirror reflects only a limited part of the coronal field (10 x 10 arcmin²) and is rotated around...
the solar disk image to select different regions of the corona. This is an all-
reflecting design (four mirrors) that achieves a diffraction-limited correction over
the above field of view. The design allows the incorporation of a spectrograph as
an alternative to direct imaging to the final focal plane. Experience with the two
smaller prototype instruments has provided key ideas that will be incorporated
in this more advanced instrument. It is anticipated that this coronagraph will
be used also for low-scattered-light observations of the solar disk. This would
be accomplished simply by tilting the primary mirror such that the field mirror
reflects the solar disk image along the secondary optical axis. MAC III will
be mounted on the spar of the NSO/SP John W. Evans Solar Facility. A
much larger reflecting coronagraph of the same basic design, with an aperture
of two or more meters, is also planned. Such a major instrument would be used
for both solar and nighttime studies. For the reasons pointed out above, the
surface of the primary objective would need to have a finish such that both low-
angle and higher-angle scatter is minimized, appropriate for the dual purpose
application of this telescope. Such a quality of polish is in principle possible,
but considerable development and testing work would be required to establish
a satisfactory polishing technology.

4. CONCLUSION

It has been established that advances in the field of coronal physics demand
major improvements in the quality of the observations. Further, independent
work points to the need for low-scattered-light coronagraphic-type telescopes
for many planetary, stellar, galactic and extragalactic studies. Both of these
requirements can be met by the development of reflecting coronagraphs. A
miniature reflecting coronagraph (MAC I) developed at NSO/SP has been
used to obtain images of the solar emission corona in the green-line, thus
establishing the validity of this reflecting coronagraph technology for ground-
based applications. The development of a second prototype instrument and the
design of a third, research-quality instrument are viewed as prerequisites for the
eventual development of a much larger instrument suitable for both solar and
nighttime studies.

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