NEAR-IR SOLAR CORONAL OBSERVATIONS WITH NEW-TECHNOLOGY REFLECTING CORONOGRAPHS

RAYMOND N. SMARTT

National Solar Observatory/Sacramento Peak, National Optical Astronomy Observatories, Sunspot, New Mexico 88349, U.S.A.*

SERGE KOUTCHMY

Institut d'Astrophysique, CNRS, 98 bis, Boulevard Arago, F-75014 Paris, France

and

JACQUES-CLAIR NOËNS

Observatoires du Pic-du-midi et de Toulouse, 65200 Bagnères-de-Bigorre, France

Abstract. Emission-line and K-coronal observations in the IR have the significant advantage of reduced sky brightness compared with the visible, while the effects of seeing are also reduced. Moreover, strong lines are available in the near-IR. Examples of the current capabilities of IR coronal observations using conventional Lyot coronagraphs are discussed briefly. Photometric measurements using the two IR lines of Fe XIII (10,747 Å and 10,798 Å), together with the Fe XIII 3,388 Å line, have provided a valuable electron-density diagnostic, but with low-angular-resolution. The 10,747 Å line has high intrinsic polarization. It has been used for extensive coronal magnetic field measurements, but only the direction of the field, and that with modest angular resolution, has been achieved due basically to flux limitations. Such studies suffer from the lack of high angular resolution and high photon flux. Moreover, the chromatic properties of a singlet objective lens preclude simultaneous observations at widely-differing wavelengths of the important inner coronal region. A coronagraph based on a mirror objective avoids such problems. Further, comparatively high-resolution and high-sensitivity arrays are now available with quantum efficiencies up to 90%. Reflecting coronagraphs with advanced arrays then provide the possibility of obtaining high-resolution images in the infrared to carry out a wide variety of studies crucial to many of the outstanding problems in coronal physics. A program for the development of reflecting coronagraphs is described briefly, with an emphasis on applications to IR coronal studies.

Key words: infrared: stars – Sun: corona – telescopes

1. Introduction

Observations with emission-line and white-light ground-based coronagraphs have allowed extensive studies of the morphology of the inner coronal region. Such observations, usually with only modest angular resolution, have established the overall structural characteristics of the corona as well as typical changes that occur over time scales of minutes to hours to days, as well as over time scales of the order of a solar cycle (see, *e.g.*, Altrock 1988). Details have been investigated of localized coronal features such as loop oscillations (see, *e.g.*, Antonucci *et al.* 1984), the interaction of post-flare loops (Smartt and Zhang 1987) and unusual transient events that propagate through the coronal environment (Dunn 1971).

Space-based, white-light coronagraphs (MacQueen *et al.* 1974; Sheeley *et al.* 1980) have provided a large database of coronal transients, especially coronal mass ejections, but the important inner corona is not accessible, due to the vignetting

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characteristics of externally-occulted coronagraphs and to the overall design constraints that must allow for the imprecision of the pointing system. Recent X-ray coronal observations from Yohkoh (Ogawara 1991) constitute a rich source of data that directly links the structure of surface-activity patterns with that of the more extended corona. Nevertheless, the angular resolution is necessarily limited, due to upper limits on the instrument dimensions. In general, space coronagraphs have the advantage of no sky background, of possible extended temporal coverage, and of access to wavelength regimes not observable from the ground.

Ground-based coronagraphs can be designed to observe the extreme inner corona down to a few arcsec above the limb, the limit determined by residual tracking errors and image displacements caused by seeing. Large-aperture systems are possible, together with high-spectral-resolution spectrographs and high-precision polarimeters. In principle, such large systems could be deployed in space; extremely high-precision tracking could realistically be achieved with a lunar-based coronagraph (see, *e.g.*, Smartt 1992). However, large space-based systems would be extraordinarily expensive and probably would not be realized for at least several decades, since none are currently planned.

2. Infrared Coronal Observations

2.1. Instrumental Performance Advantages

The power of ground-based coronagraphs can be expanded significantly by carrying out observations in the near-infrared. In particular, the sky brightness decreases as a function of wavelength. Rayleigh scattering is approximately $\propto \lambda^{-4}$; hence, at a wavelength of 2.0 μm, the sky brightness due to Rayleigh scattering is $\sim$ 0.004 of the brightness at 0.5 μm.

The angular and spectral scattering characteristics of aerosols depend on the size, shape, internal structure and complex refractive indices of the individual particles, and on their large-scale spatial distribution. Measurements of particles in the upper atmosphere (upper troposphere and stratosphere) indicate diameters typically < 0.2 μm (Bigg 1976). Such particles would likely have irregular shapes, but if hygroscopic, would tend to be spherical. In the limit of $p \equiv 2\pi a/\lambda \ll 1$, where a is the particle radius and λ the incident wavelength, the scattering of a spherical particle with a real refractive index has the same spectral dependence as that of Rayleigh scattering. For $p \gg 1$, the aerosol scattering coefficient can be assumed to be roughly constant with wavelength, and for p in the intermediate range the scattering coefficient can be assumed to be proportional to λ^{-n}, with n usually in the range 0.5 to 1.5. Even though particles of size larger than about 0.5 μm can potentially cause significant scattering for observations in the near infrared ($\sim$1 μm), in practice their number density is extremely small under "normal" conditions at mountain sites, with minimal degradation of clear-sky conditions (Halthore 1992).

Beyond the advantage of the reduced level of sky background, the scattering properties of a coronagraph objective improve as a function of wavelength. The relationship between the roughness of an optical surface and the resultant scattered radiation has been treated extensively in the literature (for a review, see Elson *et* *al.* 1979). In the case of an rms roughness, σ, where $\sigma \ll \lambda$, for radiation of wavelength, λ, and with a Gaussian distribution of roughness, the scattered component of reflectance at normal incidence, R_s, can be characterized by, $R_s \sim R_o(2k\sigma)^2$, where R_o is the reflectance of a completely smooth surface, and $k = 2\pi/\lambda$. Further, strong emission-lines are available in the near infrared, and with the availability of high-quantum-efficiency IR detector arrays, high-resolution imaging can be expected, especially since the seeing characteristics of the atmosphere also improve with wavelength – Fried's seeing parameter varies as $\lambda^{6/5}$. Hence, on this basis, an adaptive optics system operating in the infrared would require substantially fewer correcting elements, for a given telescope aperture, than one operating at much shorter wavelengths (the required number of elements is then approximately proportional to the ratio of the area of a seeing cell to that of the telescope aperture), and the bandwidth requirements would be less stringent.

2.2. Observational Advantages

Observations of coronal emission lines in the near-IR also have some advantages over those at visible wavelengths. The two infrared lines, 10,747 Å and 10,798 Å, as well as the 3,388 Å line, all Fe XIII transitions, together provide a useful coronal density diagnostic. The line intensity ratios, $I(10,747)/I(10,798)$ and $I(3,388)/I(10,747)$, are functions of the electron density that are independent of the temperature in the equilibrium range of the Fe XIII line. The upper levels are excited by electron collisions (as well as by radiation); hence the populations for the two lines will be dependent on the electron density. Further, the radiative de-excitation coefficient is known. Significant uncertainties in the measurements are present when the density is relatively high. However, it has been established that this technique is useful as an electron density diagnostic in the corona provided that sufficient accuracy in the line intensity measurements can be achieved (Noëns *et al.* 1984).

Studies of the coronal magnetic field are, in general, more easily carried out in the infrared than the visible, with increased Zeeman sensitivity and increased linear-polarization sensitivity. For example, coronal-line emission is characterized by a linearly-polarized component, due predominantly to the mechanism of resonance fluorescence occurring in the presence of the anisotropic photospheric radiation field (House 1972). The strong 10,747 Å line of Fe XIII has high intrinsic polarization, since its transition ends in only one magnetic quantum sublevel. Neglecting collisions, the linear polarization value approaches unity towards the limit of radiation anisotropy, and is already 0.9 at a height of two solar radii (House 1977). By comparison, the corresponding value for the 5,303 Å line of Fe XIV is only 0.05. Therefore, the 10,747 Å line has an enormous advantage for magnetic field measurements as compared with the 5,303 Å line, given detectors of equal efficiency in these two spectral regions. Such observations have been carried out (Querfeld and Smartt 1984) using an infrared coronal emission-line polarimeter (Querfeld 1977). In this instrument, the analyzer consists of a chopper that modulates the intensity of the incoming light, followed by a linear-polarization sensor and a Wollaston prism. The result of the modulation is to produce 25-Hz intensity- and 100-Hz polarization-signals. The detectors (Querfeld 1982) are cooled (194 K) GaAsSb heterojunction photo-diodes that have a quantum efficiency of 0.9. The polarimeter has been used at the NSO/SP 40-cm aperture coronagraph. Measurements were made typically with a 5 s integration time, and a 1′ aperture. Except under observing conditions characterized by extremely low sky-brightness and a relatively strong coronal signal, smaller apertures would result in an unacceptable noise level for the polarization measurements. This points to the need for larger-aperture coronagraphs that would allow high-angular-resolution, low-noise, measurements.

Other near-infrared coronal lines are also of interest. For example, the Si X line at 1.4305 μm was measured at the 12 November 1966 eclipse. The values obtained suggest that the intensity of this line might be approximately one order of magnitude greater than that of the 5,303 Å line (Münch *et al.* 1967).

3. Infrared Coronagraphs

A conventional, singlet-lens-objective Lyot coronagraph could be optimized for operation in the near IR, at least up to the spectral cut-off of the glass used for the objective, typically BKR7. But, this would preclude observations beyond about $\lambda = 2.5$ μm, and performance at visible wavelengths would be poor. Since the singlet-lens objective of a conventional coronagraph produces a chromatic image, the appropriate position of the occulting disk along the axis varies with wavelength. And for observations close to the limb, the size of the occulting disk must also be changed as a function of wavelength. The use of mirror-objective coronagraphs overcomes such problems.

3.1. Reflecting Coronagraphs

Mirror objectives have been applied successfully to small externally-occulted rocket- and balloon-borne coronagraphs (Kohl *et al.* 1978; Smartt 1979). Recent developments in the technology of extremely low-scatter mirrors have opened the possibility of using mirrors for internally-occulted coronagraphs. These mirrors rely on modern techniques for producing extremely smooth polished surfaces as measured by the level of residual micro-roughness over spatial scales ~0.01 mm, as well as extremely smooth evaporated reflecting films. A major advantage to using mirrors for coronagraph objectives is that the primary image is then achromatic. Hence a reflecting coronagraph is appropriate for measurements of both coronal-line emission and the K-corona. Although the K-corona brightness decreases with increasing wavelength beyond ~0.5 μm, extremely-low-scatter sky conditions could provide advantages for observing the K-corona in the near infrared. For an all-mirror system, infrared and ultraviolet observations are limited only by the spectral characteristics of the mirror surface, the detector's spectral response, and the spectral transmittance of the earth's atmosphere. The reflectance of an aluminized mirror is ~0.95 at $\lambda \sim 1.0$ μm, and increases uniformly with increasing wavelength, reaching ~0.98 at $\lambda = 10$ μm (Bennett *et al.* 1963). Further, simultaneous multi-wavelength observations can be carried out in the important inner-coronal region, while large apertures are possible. Also, for reasons pointed out above, the scattered radiation from a typical superpolished mirror should decrease with increasing wavelength, as $\sim\lambda^{-2}$.

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A Mirror Advanced Coronagraph (MAC I) has been constructed at NSO/SP, the first of three prototype reflecting coronagraphs currently under development at SP (Smartt *et al.* 1990). The objective mirror in MAC I is a super-polished, spherical silicon mirror produced by Zeiss-FRG, with a focal length of 1 m, and a micro-roughness < 0.3 nm rms. Tests of this mirror at visible wavelengths indicate that its scattering is of the same order as that typical of good-quality coronagraph objective lenses. The optical system is simply off-axis reflection from the primary mirror to a secondary optical system that is a conventional Lyot coronagraph. This consists 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. A second, more advanced prototype instrument (MAC II), based on a 15-cm diameter super-polished, aluminized Zerodur mirror objective of 2.25-m focal length, has also been constructed. In a joint agreement with the Institut d'Astrophysique de Paris (IAP), part of the construction was carried out at IAP. A concave, annular field mirror, located near the primary focal plane, functions as an inverse occulting disk. The solar disk image, which passes through a central hole in the field mirror, is reflected via two plane mirrors externally from the coronagraph. A Lyot stop is located at the image of the objective, formed by the field mirror. This is followed by a collimating lens, a filter system, and a camera lens to form the final image.

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 of $10' \times 10'$, and is rotated around the image of the solar disk to select different regions of the corona. This is an all-mirror design that achieves a diffraction-limited correction in the visible over the above field of view. With the incorporation of a correlation-tracker capability, this instrument should perform extremely well in the near IR. The design allows the incorporation of a spectrograph as an alternative to direct imaging at 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 also be used 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 at 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 have both solar and nighttime applications. Nighttime IR studies would include observations of faint emission associated with planetary and stellar objects, as well as other galactic and extra-galactic objects.

4. Conclusion

There are several important instrumental performance advantages for IR observations of the solar corona as compared with visible wavelengths. The development of high-quantum-efficiency IR detector arrays together with large-aperture IR reflecting coronagraphs provides the possibility of obtaining high angular- and spectral-resolution IR observations of the solar corona. Moreover, there are considerable observational advantages in the IR as well. Strong spectral lines are available in the near-infrared that have high polarization sensitivity, suitable for magnetic field studies and as density diagnostics. In addition it should be possible to observe coronal images to much greater heights in the corona than with visible lines such as 5,303 Å. With the advent of new IR array detectors and the development of reflecting coronagraphs, it is clear that IR studies of the corona offer an extremely fruitful area of solar research. Finally, critical low-scattered-light IR observations of the solar disk as well as special nighttime studies are ideally suited to this new technology.

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