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APODIZED APERTURES FOR SOLAR CORONAGRAPHY

C. Aime, J. Arnaud, A. Carlotti, M. Faurobert, A. Ferrari, C. Grec and G. Ricort [1]

Abstract. The solar corona cannot be studied without the help of a coronagraph. A telescope with an apodized aperture is, as described by Aime (2007), an alternative to the classical Lyot coronagraph. A spheroidal prolate apodization will modify the PSF of the telescope and optimize the energy concentration in the focal plane. A strong apodization (prolatness parameter $c \approx 10$) would reduce the diffraction halo by a factor 10^5 at a cost of intensity throughput reduced at 10 %. In a site with outstanding daytime seeing, like Dome C, this method should allow to observe the corona extremely close to the solar limb and also, much better than otherwise, the rich chromospheric weak emission spectrum.

1 Introduction

The quest for direct imaging of exoplanets is a major endeavour of modern astronomy. It stimulates many efforts aimed at dimming and shrinking stars images (Cf for instance Aime & Vakili 2006), in a way to allow planets observation at very small angular distances of their stars. A high dynamics imaging technique consists in the association of coronagraphy and apodized entrance aperture (Soummer et al. 2002). Observing the solar corona near to the Sun is also a high-contrast imaging problem. Very recently, Aime (2007) proposed the use of an apodized aperture as an alternative to Lyot type coronagraphs for the observation of the solar corona. We present hereafter this technique and its advantages for studying the solar external atmosphere and we discuss some of the exceptional properties of Dome C, on the Antarctic plateau. It could be the best place on ground to install such an instrumentation.

2 The apodized solar coronagraph

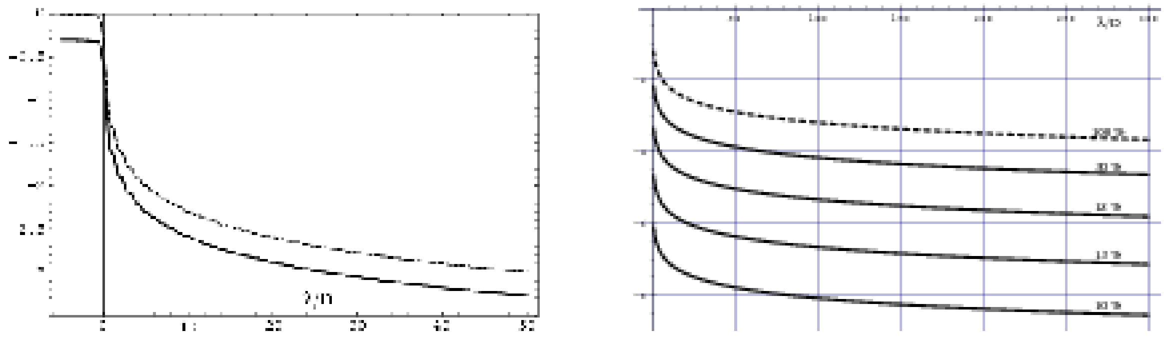

Fig. 1. Fig. 1 Left panel: intensity of the diffraction halo at the edge of the Sun image, for an uniform Sun (upper line) and taking into account the center to limb variation (lower line). The x-axis is in units of λ/D and the y-axis is in logarithmic units of I/I_{Sun}, beeing normalized at 1 at Sun center. Right panel: diffraction intensity for different levels of apodization. The througput of the aperture is indicated in percent.

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[1] Laboratoire Universitaire d'Astrophysique de Nice, Universit de Nice-Sophia Antipolis, CNRS, 28 Avenue Valrose, 06108 Nice, Cedex 2, France

For a circular aperture, the PSF decreases as ρ^{-3}, ρ beeing the distance from the center of the PSF. The diffraction pattern of the solar image is given by the convolution of the PSF and the geometric image. This can be done using a 2D integration (Aime 2007). For this reason, a good approximation of the decrease of the diffraction halo outside the edge of the geometric image is a simple formula where the intensity decreases proportionally to ρ^{-1}, ρ beeing here the distance to the solar limb. Fig. 1 displays the slow decrease of this halo. Its intensity remains above 10^{-4} of disk intensity up to 600 λ/D and reduces to 10^{-5} of disk intensity only at $6.10^3\,\lambda/D$. For a 50 cm diameter coronagraph observing the green line ($\lambda = 503$ nm), $\lambda/D = 1.10^{-6}$ corresponds to 0.2 arc second. Here, the diffraction halo brightness stays above $10^{-4} I_{Sun}$ up to 2 arc minutes above limb and remains above $10^{-5} I_{Sun}$ up to 20 arc minutes above limb. This jeopardizes inner corona observations as, in a good coronal site, the sky background is about $10^{-5} I_{Sun}$, while the corona brightness is only of the order of $10^{-6} I_{Sun}$.

The intensity of the diffraction halo needs to be strongly reduced to provide good coronal observations conditions. In the case of the Lyot coronagraph (Lyot 1939) this is obtained by diaphragming a reimaged pupil (the so-called Lyot stop), after occulting the solar image at prime focus.

Aime (2007) proposes the use of a generalized apodized prolate spheroidal function (GPSF) in a way to reduce by several orders of magnitude the diffraction halo around the Sun. Prolate functions are the best apodizers in terms of maximizing the encircled energy. Computing the diffraction level of a solar Lyot coronagraph is a very difficult task which has not, to our knowledge, been fully realized up to now. A. Ferrari is tackling this problem, this will make possible a quantitative comparizon between the classical solar coronagraph and the apodized one in terms of diffraction halo dimming. Fig. 2 presents a sketch of the Lyot coronagraph drawn by Bernard Lyot and of the new design proposed by Aime: a simple telescope with an apodizer in front of its entrance pupil.

The larger is c, the more efficient is the apodization but the more reduced is the transmission. Fig. 4 shows the PSF core and the diffraction pattern at the edge of the Sun image for different values of the parameter c. For c= 10, the diffraction pattern intensity is reduced by a factor of about 10^5, starting from the very edge of the Sun, while the resolution is reduced by only a factor of 1.7, the transmission being reduced by a factor of 10.

Space-based coronagraphs have to be externally occulted in a way to take advantage of a sky several orders of magnitude darker than from ground. This is at the price of occultating the inner corona, at least up to 0.5 R_{Sun} above limb. Very innovative projects of formation flying coronagraphs like ASPIICS (Vives et al. 2005) propose to use as occultor a second satellite, 100 meters or more ahead from the coronagraph, to observe the inner corona from about one arc minute above limb. This is a huge improvment compared to classical space based coronagraphs.

Classical ground-based coronagraphs use a Lyot mask which oversize the Sun by at least 20 to 30 arcsec in radius to occult also the bright inner part of the diffraction halo. Apodized coronagraphs should not need an occulting disk as the apodization takes full care of the diffraction halo. It will be anyway clearly advisable to occult the Sun image in a way to limit scattered light, but the Lyot mask does not need in this case to be oversized, it may actually be slightly smaller than the Sun image, to permit observations with a reduced background from the very limb.

3 The apodized solar coronagraph

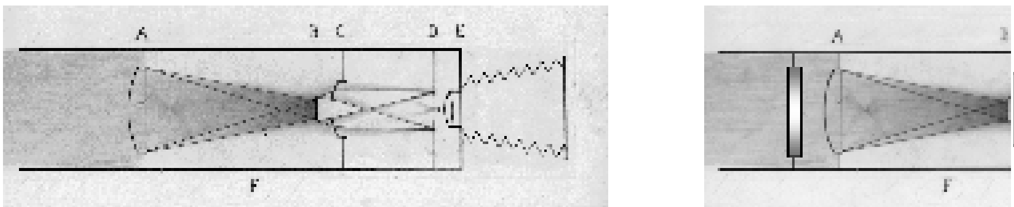

Fig. 2. Left: a sketch of the Lyot coronagraph drawn by B. Lyot (©Observatoire de Paris - Patrimoine scientific heritage). Right: Lyot sketch modified in an apodized coronagraph.

This is expected to provide a unique possibilty for studying the innermost corona and, also, the very rich chromospheric emission spectrum (Pierce 1968), without the difficult and inaccurate process of extracting the weak chromospheric lines from a strong diffracted background. Many of those chromospheric lines are only present in the first couple of arcseconds above limb. Observing conditions expected from apodization may open a new avenue for the study of the magnetic field in the very complex chromosphere (Faurobert & Arnaud 2002). Observing the solar corona extremely near to the solar disk is crucial to understand important processes concerning, for instance, the emergence of magnetic field into the corona through the photosphere. Very strong coronal magnetic fields are observed above active regions extremely low in the corona (Brosius et al. 2006). Those fields could be much more easily measured, and with a much higher spatial resolution, using the Zeeman effect in visible or infrared coronal emission lines, than fields existing upper in corona which are several orders of magnitude fainter (Lin et al. 2004).

To take full advantage of the apodization technique excellent seeing conditions are required. Otherwise, the background very near to the Sun is dominated by solar light spread out by image motion and blurring, strongly reducing the apodization benefits. Adaptive Optics (AO) is efficient using the solar limb as a reference, but only in the direction along the solar radius, so image quality is improved only in this direction, inside the small isoplanetic patch. Moreover, adaptive optics can only provide image correction for part of the light (Beckers 1993). What remains of the light, already 20% for a very efficient AO, is not corrected: the spread over of the solar light by seeing is only partly reduced by AO.

To really take advantage of the apodization technique to observe weak emissions extremely near to the solar limb, a site with outstanding daytime seeing is requested. This is also important for scientific reasons: high spatial resolution imaging and polarimetry are needed to improve our understanding of the very mixed chromospheric medium and of the highly structured low corona. Dome C is very likely to provide the requested observation conditions.

4 Concordia Station at Dome C

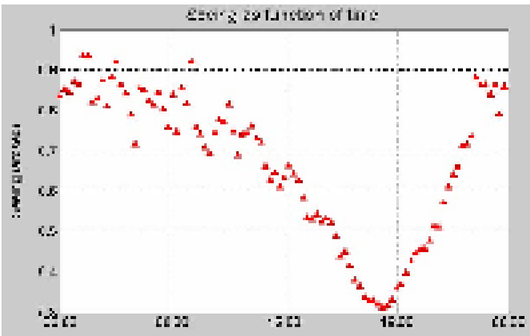

Fig. 3. Characteristic 24 hours daytime seeing pattern at Dome C. The plot is an average of the seeing variations over 24 hours for a summer observing campaign (Aristidi et al. 2005).

Concordia is a french-italian scientific facility installed at Dome C, on the Antarctic plateau. It is situated at 75° South and −123° East, its elevation being of 3220 m. The site is caracterized by very low temperatures (in average −30° C in summer and −60° C in winter), very slow winds (on average 2.8 m/s) and a very low level of precipitations (about 6 cm of snow yearly). Intensive site testing for astronomical observations started a few years ago. Day time seeing, measured at 8.5 meters above ground, is caracterized by a remarkably stable 24 hours pattern (Fig. 3), including outstanding image quality, in the 0.3 - 0.5 arcsec range, for several hours each day (Aristidi et al. 2005). Night time seeing (Agabi et al. 2006), measured at the same high above ground, has an average value of 1.2 arcsec. This is due to the presence during winter time of a 30 meters thick turbulent ground-layer. Above this layer the image quality is excellent: 0.35 arcsec in average.

Mosser & Aristidi (2007) determined that clear sky fraction (portion of the sky free of clouds) is greater than 0.9 for 84% of the time with an average number of consecutive clear days of about 7.

Those characteristics demonstrate that Dome C is an outstanding site for astronomical observations. It has the unique particularity of a much better seeing at ground level during daytime than during nighttime. On classical sites, it is the opposite, the best daytime seeing occurs during early morning when the Sun is very low above horizon as shown by Bradley et al. 2006 for Haleakala, one of the best classical sites for astronomical observations.

Dome C is reported, from naked eye observations, to be of very good coronal quality. Clear sky conditions for 15 days in a row during daytime were observed. Observation continuity during such a long period is very interesting, for instance for tomography of the coronal magnetic field (Kramar et al. 2006). A Solar Brightness Monitor (SBM) from the Advanced Technology Solar Telescope (ATST) (Lin & Penn 2004) will be installed at Dome C during the austral summer of 2007/2008 (Arnaud et al. 2007). Its measurements will quantitatively assess the coronagraphic properties of Dome C and permit comparizon between this site and the best classical coronal sites.

5 Conclusion

The alternative to the Lyot coronagraph proposed by Aime (2007) is a much simpler technique expected to be more efficient for dimming the diffraction halo around the solar image, this at a price of a slightly reduced spatial resolution and of an important reduction of the transmission. Indeed, in the Lyot coronagraph, spatial resolution and transmission are also reduced by the Lyot stop. The Aime's technique should lead to important advances in our understanding of the physical processes at work in the chromosphere and the corona in permitting coronal lines and chromospheric weak emission spectrum spectro-polarimetry extremely near to the solar limb. Excellent seeing conditions are required for such observations, Dome C is likely to be unique in realizing those conditions a very significant part of the daytime.

We propose to built a 50 cm diameter apodized coronagraph at Dome C. This is the minimum size to really take advantage of seeing conditions at this site. The first steps of this project are to test, first in the lab, then on an existing coronagraph, the apodization method. A quantitative qualification of Dome C for coronal observations is underway.

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