The Coronal Imaging Polarizer (CIP):

Observations of the corona during the 2020 total solar eclipse

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Introduction

The solar corona is around one million times fainter than the photosphere. Consequently, observing the corona in visible light is challenging, and can be achieved only through using a coronagraph, or naturally during a total solar eclipse. Despite their infrequent occurrence, total eclipses allow the best simultaneous observations of the extended corona from very low heliocentric distances out to several solar radii (Rs) without the stray light and diffraction effects of coronagraphs. This is important to understand the connections between the Sun and the solar wind.

The corona in visible light can be separated into two main components: the F-corona originates from photospheric light scattered by interplanetary dust particles at a large range of distance from the sun along the line of sight, and the K-corona is produced by the scattering of photospheric light from free electrons in the corona. One key difference between these two types of the corona is that for heights below 4 Rs, the K-corona is polarized whereas the F-corona can be considered to be unpolarized. As a result, the K-corona can be isolated using polarized brightness (pB) observations.

In 2020, we built a new instrument for measuring the pB of the corona during a total solar eclipse called the Coronal Imaging Polarizer (CIP – from the Welsh word meaning "glance"). The main motivation for CIP is to estimate the electron density of the corona, particularly at heights below that reliably observed by current space-based coronagraphs. The electron density is an important parameter as it can constrain key physical properties of the coronal plasma such as solar wind acceleration. Independent estimates of electron temperature can further place constraints on proton temperature. Van de Hulst (1950)[1] first showed that the electron density (n_e) can be determined by inversion of pB observations of the corona. Our eclipse observations, made between 1 to 4Rs, will be used in conjunction with solar rotational tomography (SRT) techniques[2] applied to coronagraph observations above 4 Rs to help better understand the solar wind acceleration profile.

December 14th 2020 Total Solar Eclipse

The total solar eclipse on December 14th 2020 was successfully observed by a team from Aberystwyth University at a site near Neuquén Province, Argentina. Totality lasted roughly 130 seconds, and conditions were not optimal with high winds and dusty/moist sky. However, the CIP observations were successful, and the Aberystwyth team were lucky to make one of the few successful scientific observations of this eclipse. Figure 1 shows the path of totality across Chile and Argentina. During this eclipse, most of the path of totality was shrouded in heavy clouds with only a few windows of clear skies.

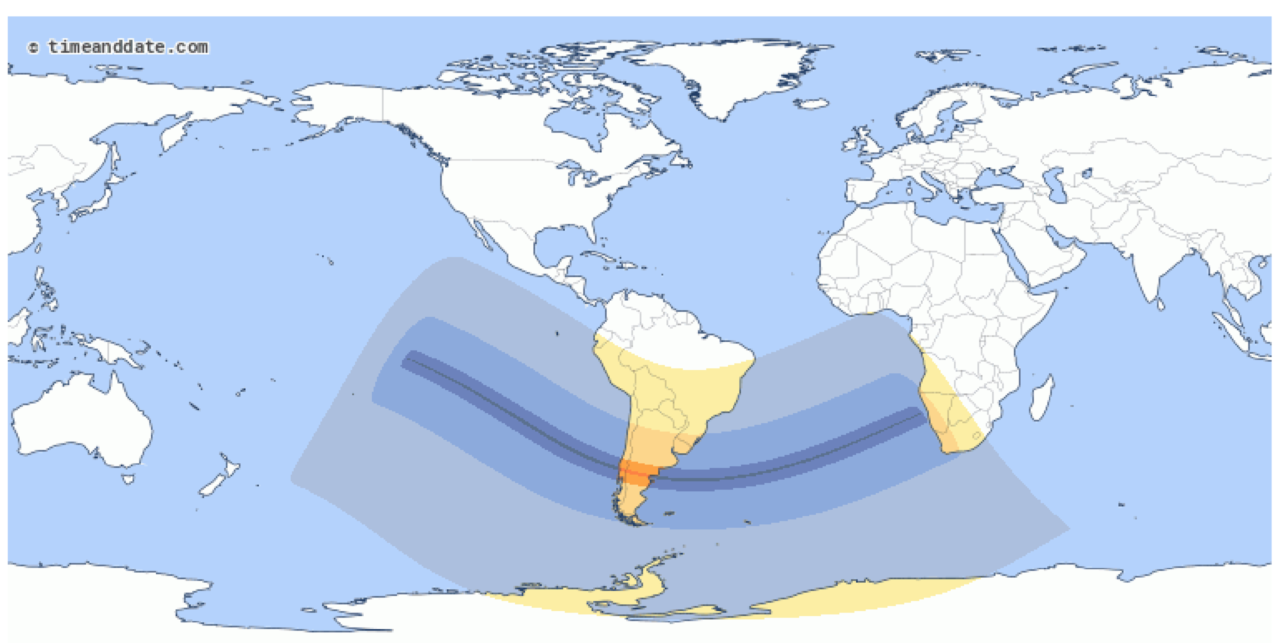
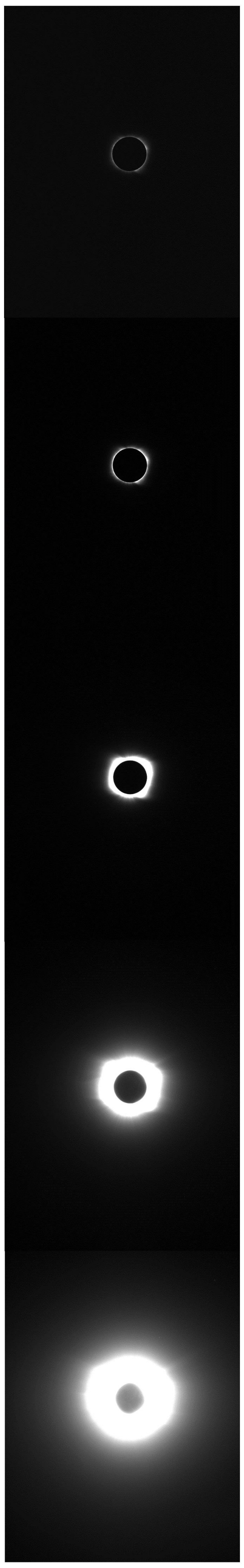


Figure 1 : Path of totality for the December 14, 2020 total solar eclipse (timeanddate.com)

Figure 2: The solar corona observed by CIP for a polarization angle of 0° at five different exposure times



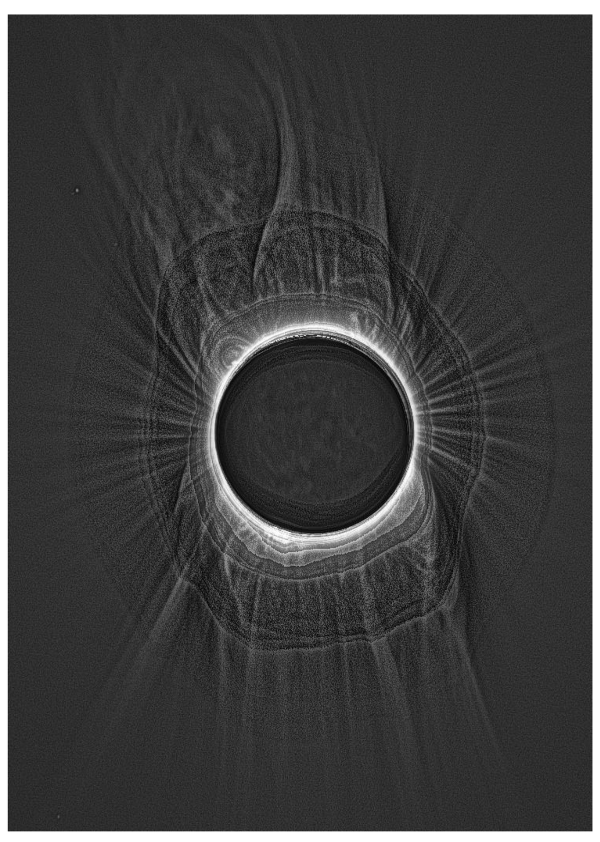


Figure 4: Preliminary combined and processed eclipse image

Coronal Imaging Polarizer (CIP)

CIP, shown in figure 3, consists of a Takumar f-5.6, 200 mm objective lens, white-light broadband bandpass filter, a rotating polarizer stored in a metal housing with a rotating actuator, and a 16 MP Atik Horizon II CMOS camera. The observation sequence was automated using a Python script which rotated the polariser to the desired angle then took the required exposure times for that angle. This was then repeated for a pre-determined set of 6 polarisation angles and 5 exposure times: 0°, 30°, 60°, 90°, 120°, and 150°; and 0.001s, 0.01s, 0.1s, 1s, and 3s, respectively. Several exposure times are necessary to create composite images which are important since the lower exposures contain the detail from the lower corona and the higher exposures contain the detail from the outer corona. As can be seen in figure 2, the inner corona is clearly over-exposed and so in order to clearly image the entire corona, the exposures need to be combined. Current space-based coronagraphs make pB observations using three separate polarisation angles. CIP is designed to make observations at a much higher number of angles, with the choice of 6 set by the limited eclipse totality interval. Observing more polarization angles can help improve the estimate of pB.

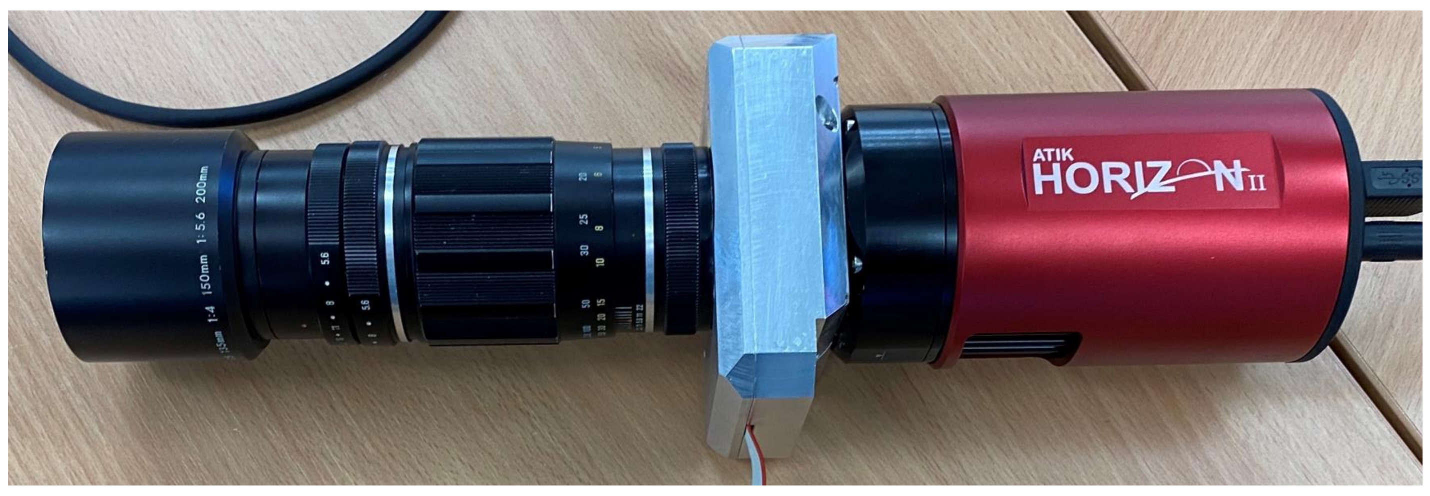


Figure 3: Coronal Imaging Polarizer (CIP) – the white-light filter and the rotating polarizer are stored in the metal housing between the objective lens and the camera.

Image Calibration and Processing

The raw data from the eclipse (as shown in figure 2) are currently being calibrated and processed. The calibration process involves subtracting dark and flat frames from the raw data using equation (1).

$$C_{p,e} = \frac{(R_{p,e} - \overline{D_e}) * m}{(F_p - D_e)} \qquad (1)$$

where $C_{p,e}$ is the calibrated image, $R_{p,e}$ is the raw image taken at a specific polarisation angle (**p**) and exposure time (**e**), D_e is the dark frame for that particular exposure, F_p is the flat-field for that particular polarisation angle, and m is the image-averaged value of (F_p - D_e). Further steps involve deconvolution and creating a single image combining the various exposure times. A critical part of this effort is to align the images with sub-pixel resolution. A Python program is currently in development which will utilise a phase correlation method, developed by M. Druckmüller (2009)[3], in order to co-align the different exposures. A preliminary combined and processed image is shown in figure 4.

Following calibration and processing, the images will be inverted to estimate the electron density of the lowest corona. Rather than a standard inversion (e.g. based on local spherical symmetry), we plan to use constraints on the distribution of density along the line of sight using tomography density maps at 4Rs, information from potential field source surface magnetic models, and information based on synoptic maps of extreme ultraviolet (EUV) intensity observed by AIA/SDO.

References

1. H. van de Hulst, *The Electron Density of the Solar Corona, (Bulletin of the Astronomical Institutes of the Netherlands: 1950)*
2. H. Morgan, *The Width, Density, and Outflow of Solar Coronal Streamers, (The Astrophysical Journal: 2020)*
3. M. Druckmüller, *Phase Correlation Method for the Alignment of Total Solar Eclipse Images,* (The Astrophysical Journal: 2009)

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