CMEchaser, Detecting Line-of-Sight Occultations Due to Coronal Mass Ejections

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Abstract We present a python-based tool to detect the occultation of background sources by foreground solar coronal mass ejections. The tool takes as input standard celestial coordinates of the source and translates those to the helioprojective plane, and is thus well suited for use with a wide variety of background astronomical sources. This tool provides an easy means to search through a large archival dataset for such crossings and relies on the well-tested AstroPy and SunPy modules.

Keywords Coronal mass ejections, initiation and propagation · Coronal mass ejections, interplanetary

1. Introduction

Magnetic activity of the Sun is responsible for the generation of solar eruptions such as coronal mass ejections (CMEs) and solar flares (see, e.g., Vršnak, 2016). Solar flares result in broadband electromagnetic emission, while CMEs are a significant release of plasma with an embedded magnetic field (Kahler, 1992). CMEs directed towards the Earth may interact with the Earth’s magnetosphere, leading to a number of well identified phenomena such as aurorae, magnetic reconnections on both the day and the night sides of the Earth’s magnetosphere and potentially adverse space weather conditions. Key parameters to forecast the impact of CMEs on the Earth’s magnetosphere are their magnetic field direction and strength (see, e.g., Vourlidas et al., 2000).

Estimating the magnetic fields of CMEs is a challenging task as coronal densities are not suitable for direct estimation of the magnetic field by Zeeman effect, as is commonly done for the solar photosphere (Howard, 1962). The only means to probe a CME magnetic field is by studying the Faraday rotation that it induces on the linearly-polarized radio emission of background sources, such as pulsars or quasars, during an occultation or via satellite borne
probes, if those are fortunately located. In order to properly select the relative background sources, the location of the erupting CME needs to be well known in advance and this to date remains challenging. For this reason, it is important to identify any astronomical background source with a significant linear polarisation along the trajectory of the erupting CME.

In this article we present CMECHASER, a software package able to calculate whether, during an observation, a certain astronomical object has been occulted by a CME. In Section 2 we thoroughly describe the software and its outputs. In Section 3 we demonstrate the effectiveness of the algorithm, while in Section 4 we show its possible applications. The conclusions are presented in Section 5.

2. A Python-Based Searching Algorithm for CME Occultations

CMECHASER searches for the occultation of a background source by a CME given the observing epoch, the galactic coordinates of the source itself, and the CME characteristics. While the original background sources utilised were radio pulsars, the software itself is agnostic of the details and can detect line-of-sight crossings for any given coordinate pair on the sky.¹

2.1. Code Description

The software requests as inputs the galactic coordinates of the background source along with the reference epoch at which they were determined and, if measured, the proper motion of the background source. The coordinates are then propagated to the epoch of observation $T_0$ (note that this affects significantly only nearby sources with very high proper motions). This is implemented via the SkyCoord class of the AstroPy library, which we use to store and subsequently update the coordinates and proper velocity. The updated coordinates are then transformed to the helioprojective plane, using the Stonyhurst Stereographic projection (see, e.g., Thompson, 2006), since that is the coordinate system used by the Large Angle and Spectrometric Coronagraph (LASCO) on board the Solar and Heliospheric Observatory (SOHO) white-light observations which we use to confirm our detections. This transformation follows conventions that can be found in Meeus (1998). Briefly, this is the same problem as measuring distances on a geodesic and hence the techniques used are derived from pre-existing methods in cartography. Specifically, we implemented the estimation of the helioprojective coordinates using Vincenty’s (1975) method. Vincenty’s method can fail for nearly antipodal points, and hence a fallback method using the Haversine expansion is also provided. An excellent description of the two translations can be found in Skokić (2019).

A correction to account for the misalignment between the ecliptic north and the solar north is also implemented at this stage, utilising methods from the SunPy library. The angle theta between the Earth, the background source, and the Sun (see Figure 1) is converted into the minimum (i.e. perpendicular) distance to the line-of-sight (MDLOS) from the Sun. The software then selects all the CME events which, given a linear speed and associated acceleration, will arrive at the line of sight at $T_0$.

For this purpose, the software uses the SOHO/LASCO coordinated data analysis workshop (CDAW) CME catalogue.² Note that this catalogue is manually maintained and cannot

¹See the appendix for practical notes on the software requirements and usage.
²https://cdaw.gsfc.nasa.gov/CME_list/.
Figure 1  Sketch showing the geometric layout of the problem. The solar (elongation) angle $\theta$ is the angle shaded in grey. MDLOS is the perpendicular distance from the Sun to the LOS to the pulsar from Earth, shown by the solid grey arrow. The pink shaded sector marks the cone of propagation of a CME, lifting off from a position angle of $\approx345^\circ$, relative to the solar north. Images of the Sun and the Earth were taken from publicly available ESA archives.

be used for near real-time detections. A more optimal catalogue for that use would be an automated one, such as the Computer Aided CME Tracking (CACTus) catalogue. However, the CACTus catalogue is known to contain a number of false positive detections of CMEs, and hence we prefer to implement the usage of the CDAW CME catalogue as the default option.

For CMEs occurring in the mentioned time range, the code checks if the background source, at the MDLOS position, falls into the sector into which the CME is predicted to propagate given its position angle (relative to solar north) and opening angle as reported by the CDAW CME catalogue. While the modelling of CME propagation is an involved exercise requiring very careful treatment, we assume that:

i) the CMEs from the CDAW CME catalogue have an average speed which is equivalent to the linear speed of the CME front, as measured from the LASCO white-light difference images;
ii) the CME acceleration is constant;
iii) the angular width of the CME is constant.

Further, the software does not distinguish CMEs on the basis of their launch velocities relative to that of the solar wind, which is another complex problem that must often be modelled on a case by case basis to account for the dynamical properties of the solar wind, as well as the CME itself.

However, we point out that the objective of this code is to provide a means for identifying possible crossings of CMEs in background source observations, and the actual detection

3http://sidc.oma.be/cactus/.
and analysis will be carried out in a forthcoming work on large collections of radio pulsar observations.

Among the outputs that will be described in Section 2.3, CMECHASER produces a Quad plot of the helioprojective plane, showing all of the CMEs that would have crossed the LOS at \( T_0 \). Then, for each of the CMEs identified above, the software downloads the nearest SOHO/LASCO and Solar Dynamics Observatory white-light images using the SunPy interface to the Helioviewer webpage\(^4\) on which it overplots the position of the background source.

2.2. Inputs

The code expects two kinds of inputs. The first kind is the position of the background source in galactic coordinates along with, where available and required, the proper motion terms. The second is a text-based archive of known CMEs, containing columns with headers identifying the launch angle (or position angle, PA) in the helioprojective plane, the linear speed and acceleration of the CME and the date and time of the CME launch. Currently the code is able to check for the presence of the CDAW CME catalogue and download it if necessary. However, this can easily be substituted by a file containing columnar data in the same format as the CDAW CME catalogue, which can be supplied by a command-line handle.

2.3. Outputs

2.3.1. Plot Outputs

CMECHASER produces two kinds of plots: the ‘detection’ plot showing all of the CMEs that might have crossed the LOS of the background source, and the ‘verification’ plot, where for each CME in the detection plot, we produce an overlay of the nearest SOHO/LASCO and SDO images with the background source.

The plots are named using the following convention:

\( \langle \text{SourceName} \rangle \_ \langle \text{Type} \rangle \_ \langle \text{Date} \rangle \_ \langle \text{SrcHelioPA} \rangle \_ \langle \text{mdlos} \rangle \) where:

i) SourceName: Name of the background source supplied to the software with \(-P\).

ii) Type: The kind of plot as described below:

i) Quad: Polar plot of all CMEs that will catch up with the LOS at \( T_0 \) (see text below).

ii) C3: An overlay with the LASCO C3 image for each CME that is on the Quad plot (see text below).

iii) Date: For the Quad plot, this is the date of observation of the source while it is the date on which the CME was launched for the C3 plots.

iv) SrcHelioPA: The angle the LOS makes with the solar north.

v) mdlos: The minimum distance to the line of sight in kpc.

The Quad plot (Figure 2a) is a polar plot of the source in the helioprojective plane, with coloured circles showing, in gold the solar disc and in blue the size of the LASCO C3 field of view. A quadrant in red shows a 90\(^\circ\) region around the heliographic position angle of the LOS.

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\(^4\)https://helioviewer.org/.
Figure 2  Examples of the Quad and C3 plots. (a) Quad plot, showing the detection of an occultation of the line of sight to the pulsar J0034-0534, shown by the small purple marker at 255.3°. The pulsar was observed on April 20, 2014 at 12:18 UTC and was occulted by three CMEs launched on April 18. In this plot the CMEs are shown by light purple sectors spanning their angular widths (360° in the case of the two halo CMEs, and the darker, overlaid sector inside the red quadrant, for the non-halo CME launched at 264°); the propagation is only drawn up to the solar elongation of the background source. The LASCO C3 field of view is shown by the dark purple shaded circle and the gold circle in the centre of the plot denotes the Sun. The radial axis shows the solar elongation converted to a projected separation in fractional au. (b) An example of the C3 plot using the pulsar J0034-0534 as a background source, showing white-light images from the SOHO and SDO timestamp closest to the CME launch time. In this plot, a CME which launched on the April 18, 2014 at 13:45 UTC is shown along with the position of the pulsar, which was observed on April 20. The LASCO C3 field of view is shown by the blue tinted region. The red square section of the image shows the LASCO C2 field of view while the centre of the image shows the SDO/Atmospheric Imaging Assembly (AIA) view of the Sun. The position of the pulsar is marked by the filled crosshair symbol at 255°.

Finally, we mark the individual CMEs that would have crossed the LOS. These are represented as sectors of widths equal to the CME width at launch and the propagation vector passing through the heliographic position angle of the CME;

The C3 plot in Figure 2b is an overlay of the SDO image of the Sun at the centre and the LASCO C3 image of each CME. The image used is the one at or closest to the launch time. Along with these images, we plot the calculated position of the source in the helioprojective plane with the filled crosshair symbol.

2.3.2. Text Outputs

Apart from the plots described above, we produce two sets of text outputs, one useful for any background source, and one specific for pulsars, where we predict the change in dispersion measures due to these CMEs. These are:

i) \texttt{<SourceName>_FinalCMElist.txt} contains the list of CMEs which have reached the LOS for the given pulsar observation date, extracted from the CDAW CME catalogue catalogue along with some extra columns:

   i) \texttt{mdlos}: the minimum distance from the line of sight (mdlos) for the given source which the CME crossed;

   ii) \texttt{Propagation_time_in_s}: propagation time to mdlos, estimated using the linear speed and acceleration of the CME as provided by the CDAW CME catalogue;
iii) ArrivalTime: Arrival time in modified Julian Day (MJD) of the CME at the LOS.

ii) ⟨SourceName⟩_dmcme_per_obs.txt: a list of the excess dispersion measure (DM)\(^5\) due to the individual CMEs, sorted by observing date in MJD;

iii) ⟨SourceName⟩_summed_dmcme_per_obs.txt: total DM excess for each observing date in MJD.

For the final two outputs, we currently utilise a simple spherical expansion model for the CME. Although this model is a relatively poor one for the propagation of CMEs in the solar wind, it allows us to quickly filter CMEs where we might be able to measure DM variations.

3. Code Demonstration

We now demonstrate the effectiveness of the software in correctly identifying astronomical objects in the field-of-view (FoV) of SOHO/LASCO (and SDO). For this test, we refer to the

\(^5\)Here DM is the line integral of the electron density along the LOS. In this case we are concerned only with the value for part of the LOS affected by the CME.
Figure 4  Quad plot showing the position of PSR B0950+08 tracked over August 13 to 28, 2015, as viewed from Earth. Also shown are the tracks of two CMEs marked by light blue shaded sectors which would have occulted the pulsar on August 21. The filled green star symbol immediately to the right of the 180° line shows the position of the pulsar on that date. The positions of the pulsar on other dates were overplotted manually to produce this composite image. The plot was only compared visually to the Howard et al. (2016) result, although orientations and positions were checked against both Helioviewer and common sky chart tools such as stellarium.

graphical information available from the Sungrazer project,\(^6\) where the position of several known astronomical sources is identified during the solar transit within the SOHO/LASCO C3 FoV. In particular, we focus on the position of the B-class star Regulus on August 15, 2012 at 12:00 UTC. In Figure 3, we show the observed position of Regulus, marked by the filled crosshair symbols overlaid on the LASCO C3 composite. The optical position of the star is marginally offset due to the time difference between the C3 image and the observation epoch.

Similarly, in Figure 4, we show the detected position of the pulsar B0950+08 tracked from August 13 to 28, 2015. The track follows that observed by Howard et al. (2016), where the authors observe a CME crossing the pulsar on August 21. In the example plot shown here, two CMEs which were launched from heliospheric position angles of 255° and 148° on August 20 are detected to have crossed the LOS to the pulsar. The pulsar was assumed here to have been observed at 12:00 UTC and the CMEs are marked as light blue shaded sectors, whose widths are equal to the 160° and 93°, respectively.

\(^6\)https://sungrazer.nrl.navy.mil/.
4. Applications

The most immediate application of CMECHASER is for mining archival datasets of any kind of polarised astronomical sources (e.g. long-term pulsar monitoring such as the ones described in Tiburzi et al. 2019). This would allow to select the observations allegedly affected by the passage of a CME and study their properties with respect to the baseline offered by the rest of the dataset.

Besides this, though, CMECHASER can be easily adapted to identify linearly polarised background sources when a CME is launched, and at least its PA and velocity are known. In fact, as mentioned earlier, the presented software can accept customised CME catalogues as input – thus, if a CME occurs it will be possible to create a catalogue with the same format as of the CDAW CME catalogue and parse it with CMECHASER to detect linearly polarised sources whose LOS will be occulted. This application is useful in the case of target-of-opportunity (ToO) observing proposals dedicated to the scientific study of CMEs, but also to trigger warnings in the context of space weather monitoring. As mentioned in Section 1, the recombination of a CME and Earth’s magnetic fields allows charged particles carried by the CME itself to stream down the field lines of the geomagnetic field, compromising the activity of satellites, power grids, geolocalisation systems, etc. The presented software can be used in forecasting methods to understand the orientation of the magnetic field of an incoming CME and the risk level associated with it. As a matter of fact, it has to be noticed that while it is known that the launch of a CME is likely during periods of high solar activity, a timely prediction of a CME occurrence is currently impossible. Further, the dynamics of CME evolution is a region of active research and experimental verification of the expected behaviour of CMEs far away from the Sun are valuable inputs not only to simulation tools but also for forecasting efforts.

5. Conclusions

We have presented CMECHASER, a software able to show if an astronomical object has been occulted by a CME which was launched from the Sun, up to two days before the observation of such object (some practical notes on CMECHASER are included in the Appendix). For this, CMECHASER takes as input the object position and the observation date and searches for suitable CME events in the CDAW CME catalogue, outputting text files containing information about the CME that has possibly occulted the astronomical source and plots of the field-of-view of the LASCO cameras overlaid with the position of the object at the time in which the observation was performed.

CMECHASER has applications in space weather studies, as it will increase the regularity with which it is possible to detect a CME occultation, provided some basic information about the CME (at least its position angle and emission epoch) is available. For this exercise to be successful, it is necessary to continue ToO programs combined with trigger observations of, e.g., solar activity in K-band, or solar bursts.

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See, e.g., the SUNDISH project (https://sites.google.com/inaf.it/sundish/).
This research utilises SunPy (version greater or equal to 1.0.0)\textsuperscript{8} and AstroPy (version greater or equal to 3.0.5)\textsuperscript{9} community-developed core Python packages for solar (The SunPy Community et al., 2020) and general astronomy (Astropy Collaboration et al., 2013, 2018), respectively.

Disclosure of Potential Conflicts of Interest  The authors declare that they have no conflicts of interest.

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Appendix: Practical Notes

Instructions for downloading and using CMECHASER can be found at https://bitbucket.org/golamshaifullah/cme_chaser/wiki/Home. The software is a fully python-based code and, to be run, it needs the most common python packages (numpy, scipy, etc.), along with the SunPy and AstroPy modules. We advise running it after having created and activated the CONDA environment as shown on the CMECHASER wiki to avoid issues with missing packages and libraries.

The software can be run in two ways, depending on the background source that the user wants to search the occultation for. If the background object is a pulsar present in the PSRCAT software,\textsuperscript{10} the user can simply pass the name of the source as referred to the J2000 epoch (e.g. J1022+1001). Alternatively, if the background object is a pulsar missing in the catalogue, or any other source, the user can run the software by supplying the source name, its Galactic latitude and longitude, proper motion in Galactic coordinates and the reference epoch for the astrometric parameters.

To test whether the setting up of CMECHASER was successful, we recommend trying one of the example commands in https://bitbucket.org/golamshaifullah/cme_chaser/wiki/commands_for_star_check.md. These will lead to the identification of position of a known star (i.e. visible in the optical) against the Helioviewer database through the use of a custom CME catalogue MYUNIV.TXT, supplied with the package. Note that, in a real run, the user can supply her or his own customised CME catalogue as a simple text or a file with comma-separated-values with the column header for the CME launch date set to dme, or not parse any catalogue. In this last case, CMECHASER will automatically download and use the CDAW CME catalogue.

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\textsuperscript{9}http://www.astropy.org, DOI: 10.5281/zenodo.2556700.
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