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Key Points:

- Advance warning that a region on the Sun may produce a coronal mass ejection can increase forecasting lead time
- Observations can aid the assessment of whether a region may be likely to produce a coronal mass ejection in the following hours or days

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Identifying and Predicting Coronal Mass Ejection Occurrence: Observational Checklists for Space Weather Forecasters

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Abstract Ejections of magnetized plasma from the Sun, known as coronal mass ejections, can drive major geomagnetic activity if Earth-directed, and are therefore monitored by space weather forecasters. The current focus being the forecast of the arrival time of a coronal mass ejection at Earth and the level of geomagnetic impact. Available instrumentation, data sets and modeling that support a timely assessment of Earth-directed coronal mass ejections are improving, but there remains a gap in the ability of forecasters to predict the occurrence of a coronal mass ejection ahead of time. We assess over 50 years of observational studies of coronal mass ejection source regions, and their evolution toward eruption, in order to provide guidance for those working in space weather forecasting. The aim being to provide an overview of the indicators that a region may have: (a) already produced a coronal mass ejection, that is, not identified in coronagraph images in a timely way, and (b) that a region may be likely to produce a CME in the near future. Checklists are provided as a practical tool for day-to-day forecasting.

Plain Language Summary Space weather forecasters are tasked with monitoring the Sun on a daily basis and issuing actionable information to various sectors that are impacted by solar activity. For example, the aviation sector, electricity distributors and satellite operators. The aim being to mitigate the risks posed by the Sun's activity. One particular form of solar activity can be particularly impactful at the Earth; coronal mass ejections. Currently, space weather forecasters do not have a method by which coronal mass ejections can be forecast ahead of their occurrence. Instead, coronal mass ejection arrival time at Earth is forecast once an event has been confirmed to occur. In this work, we assess 50 years of solar physics research to create checklists for space weather forecasters to enable an assessment of when a coronal mass ejection has occurred and also the likelihood of a coronal mass ejection occurring in the following hours or days.

1. Introduction

Certain conditions in the solar wind, the constant stream of magnetized plasma emanating from the Sun, such as fast speeds, enhanced plasma density, and/or southward directed magnetic field drive disturbances to the Earth's magnetic field known as geomagnetic storms. However, the most intense geomagnetic storms are caused by the arrival of a coronal mass ejection (CME; for a review see Temmer, 2021). Geomagnetic storms create changes to the Earth's magnetic field and ionosphere that can have a serious impact on modern systems and ultimately cause interruptions to radio communications, electricity distribution, and satellite operations, leading to societal, as well as economic, impacts. Due to this, forecasting the arrival of a CME at the Earth must be in the toolkit of every space weather forecaster.

Current approaches focus on forecasting the arrival time of a CME and estimate properties such as bulk speed and plasma density at Earth. This approach relies heavily on the use of coronagraph data to evidence the eruption of the CME directly, and EUV imaging data to provide context and further support for CME occurrence. Coronagraph images are used in models such as Enlil (Odstrcil, 2003), EUFORIA (Pomoell & Poedts, 2018), HUXt (Barnard & Owens, 2022; Owens et al., 2020) and SUSANOO (Shiota & Kataoka, 2016) that propagate a representative synthetic CME(s) through the solar wind flow to the Earth. The fastest CMEs have a Sun-Earth transit time of less than one day, and availability of the necessary data to run the models (i.e., coronagraph

data) can lead to a delay of several hours from the time at which a CME occurs to its confirmation and the initiation of CME arrival-time models. This potentially leaves little advance warning of an impending CME impact. An additional challenge for forecasters is that Earth-directed CMEs may appear as a halo CME that encircles the Sun. Halo CMEs are faint in coronagraph imagery, making their detection harder than those CMEs that erupt from a region closer to the limb of the Sun. Since both near-side and far-side CMEs can appear as a halo, additional observations are required in order to determine their propagation direction (i.e., Earth-directed or from the far-side of the Sun).

In the following, we aim to provide support for day-to-day forecasting activities related to CME occurrence monitoring. In particular, we aim to fill a gap in the current practice by providing an overview of how remote sensing observations can be used to assess likely future CME occurrence. To achieve this, we synthesize over 50 years of observational research and provide an overview of the signatures that are seen in CME source regions when an eruption has occurred. We include a brief summary of the data needed to assess CME occurrence and likely occurrence, and whether these data sets are available in an operational capacity (summarized in Appendix A). We highlight the specific patterns and trends that regions on the Sun have been observed to exhibit in the time leading up to a CME. From this analysis, we create bespoke checklists that can be used by space weather forecasters to (a) support the confident identification of CME occurrence using data other than coronagraph imagery and (b) allow an assessment of which regions on the Sun may produce a CME in the future. The checklists can be found in Appendix B.

1.1. Where on the Sun Do Coronal Mass Ejections Originate?

The progenitor of a coronal mass ejection is a magnetic structure that becomes unstable or loses equilibrium in the solar atmosphere and erupts outwards, escaping the Sun (for a review see Green et al., 2018). Observations have shown that these eruptive magnetic structures form in active regions at all evolutionary stages; from young active regions that are newly emerging through to active regions that have been present on the Sun for weeks/months, at which point the active region magnetic field has dispersed over a wide area. These dispersed magnetic fields then get carried into the quiet Sun, where CMEs are also seen to originate. For a review on how active regions evolve, from birth to death, and the occurrence of CMEs during these evolutionary stages see van Driel-Gesztelyi and Green (2015).

Zhou et al. (2003) found that 79% of CMEs in their study came from active regions and 21% from outside active regions. A more recent study by Majumdar et al. (2023) of the source regions of 3327 CMEs observed between the years 1998 and 2017, found that 65% of the CMEs originated in active regions (defined as regions of relatively strong magnetic field with relatively hot, dense plasma as compared to the surrounding corona), 23% were associated with filament/prominence eruptions originating outside active regions, and 12% from filament/prominence eruptions that had at least one footpoint in an active region. These findings align with earlier work that showed that young active regions, especially during times of magnetic flux emergence, produce CMEs more frequently than older active regions that have weak and dispersed magnetic field and which may no longer be referred to (or classified) as active regions due to their lack of sunspots (Démoulin et al., 2002; Green et al., 2002).

At the slow end of the CME speed distribution are so-called stealth CMEs, which are clearly identified in coronagraph data but which produce only faint indications of their occurrence in EUV images of the corona (Alzate & Morgan, 2017; Robbrecht et al., 2009). Stealth CMEs can harbor relatively strong magnetic fields though, and therefore produce space weather impacts (Nitta et al., 2021; O'Kane et al., 2021). Studies using image processing techniques and long timelines have revealed that stealth CMEs can originate across a range of altitudes and be associated with dimmings, small flares, jets and filament eruptions (Alzate & Morgan, 2017; O'Kane et al., 2019). Ma et al. (2010) found that 30% of CMEs studied during 8 months around solar minimum were stealth CMEs. It is not yet known what percentage of CMEs are stealthy at other solar cycle phases. Slow CMEs can also be associated with the eruption of a coronal cavity (Gibson et al., 2006). These structures are ubiquitous in the corona and are identified as dark voids, indicating a depleted plasma density, at the solar limb when view using EUV imaging or coronagraphs that can image the lower solar corona. Coronal cavities are the upper portion of a filament channel and can be embedded in a coronal streamer. For cavities that are embedded within a streamer, the eruption leads to the streamer being disrupted or destroyed in events known as streamer blowouts (see Section 3.6).

In summary, CMEs can occur in magnetically simple or complex regions, with strong or weak magnetic field. However, CMEs always originate along the line that demarcates the positive magnetic field from the negative in the photosphere: a so-called polarity inversion line. This diversity of CME source region characteristics has so far hindered the creation of a robust operational CME forecasting approach based on observations of the solar surface and atmosphere.

1.2. Space Weather Forecasting Summary

In the UK, space weather forecasts are published by the Met Office Space Weather Operations Centre. Here we provide an overview of the forecasting process and products relevant for CME monitoring. Although the likelihood of CME occurrence is not forecast, the likelihood of solar flare occurrence is forecast ahead of time, according to flare categories on the NOAA scale (e.g., C, M and X GOES-class). Flares can be CME-associated, with the association rate increasing with flare energy, meaning that flare forecasting has a direct relevance for CME forecasting (see Section 2.1). A 24-hr flare forecast is created every 6 hr and a 4-day forecast is made every 12 hr, generated by forecasters working a 12-hr shift pattern 24 hr a day, every day of the year. When creating a flare forecast, forecasters first determine the Modified Zurich Class (McIntosh, 1990) of each NOAA active region using Solar Dynamics Observatory (SDO) Helioseismic and Magnetic Imager white light and line-of-sight magnetogram images (HMI, Scherrer et al., 2012). Next, additional details about the region, including ongoing growth, development and complexity are noted. Including, for example, whether the orientation of the active region follows Hale's Law (Hale et al., 1919). After each active region has been assigned a Modified Zurich classification, the flare activity of similar active regions in a historical data set is used to determine a flaring probability. This probability is then adjusted by taking into account the Mount Wilson classification of the active region, along with an assessment of the observed evolution and prior activity level of the region. For example, whether sunspots are moving relative to each other, exhibiting rotational motion or whether new flux is emerging. SDO Atmospheric Imaging Assembly (AIA, Lemen et al., 2012) images in the wavebands 94 Å, 171 Å, 211 Å and 304 Å are also used to assess the status and evolution of the active region. Forecasters may also use the Solar Monitor Active Region Tracking tool (SMART, Higgins et al., 2011) to support their assessment with numerical indicators of growth and complexity such as total magnetic flux, area, and the Schrijver R-value (Schrijver, 2007). Numerical indicators are discussed in Section 3.1.

Although forecasters do not make a forecast of future CME occurrence, CMEs that have already occurred are identified and analyzed using a wide range of data. This analysis begins even before the CME reaches the field of view of a coronagraph. Given that filaments can be a CME progenitor, an assessment of filaments that are present on the solar disc is performed as a part of forecasters' drawing of a twice-daily synoptic solar map. Filaments are monitored for motion, increase in altitude or disappearance, using H-alpha GONG images (Hill et al., 1994), which might indicate that a CME has occurred. Upon the occurrence of a flare or filament disappearance, and before any CME confirmation in coronagraph data, a forecaster will use the following information to make an assessment of whether or not a CME has occurred:

1. Strength and duration of the flare soft X-ray flux, along with the region's history of producing CMEs.
2. Presence of a two-ribbon flare configuration appearing in for example, SDO AIA 304 Å images, especially if temporally and spatially associated with a disappearing filament in H-alpha images.
3. Evidence of mass ejection in SDO AIA images and formation of dimmings in AIA 211 and/or 193 Å wavebands. This analysis is supported by using tools such as Solar Demon to identify dimming regions (<https://www.sidc.be/solardemon/dimmings.php>).
4. The occurrence of a type II radio burst, using information provided by the NOAA Space Weather Prediction Center.

Coronagraph images (i.e., from SOHO LASCO and STEREO-A, Brueckner et al., 1995; Howard et al., 2008) are then monitored throughout the 12-hr forecasting shift, and once a CME becomes visible in coronagraph observations, an assessment of its size, apparent source location, and speed is performed. This is achieved by modeling the CME as a cone leaving the Sun and by using difference images to track the leading edge of the CME. A simple distance/time calculation can then be done. If no coronagraph data are available, but a Type II radio burst is observed along with a flare at a location forecasters consider at risk of producing an Earth-directed CME, then a CME is inferred to have occurred and its speed estimated using the Type II radio burst. These analyses are then fed into models such as Enlil in order to assess the likelihood and strength of any Earth-directed impact.

Table 1

Percentage of Flares That Have Associated CMEs, Split According to Flare GOES Classes

	C-class	M-class	X-class
Andrews (2003)	–	55%	100%
Yashiro et al. (2005)	20% (C3–C9)	49%	100% ($\geq$ X3.0)
Toriumi et al. (2017)	–	55% ($\geq$ M5.0)	75%

Note. In the study of Yashiro et al. (2005) the percentage given for C-class flares considers C3–C9 only, and for X-class only magnitude X3 and greater are considered. In the study of Toriumi et al. (2017), only flares of $\geq$ M5.0 are studied.

2. Observational Indicators That a CME Has Occurred

The occurrence of a CME is typically confirmed in near real-time using coronagraph data that directly shows the bulk expulsion of the magnetized plasma and its escape into the heliosphere. However, there are occasions when delays in accessing coronagraph data mean these data sets cannot be used in a timely manner for forecasting purposes. For example, lack of contact with the spacecraft and data download delays. However, this issue is being addressed with the CCOR-1 instruments on the GOES spacecraft (Thernisien et al., 2025). Uncertainty about whether a halo CME is front-sided or far-sided, and CME structures being faint in the coronagraph data, also make Earth-directed CME identification difficult. In these situations, observations of the CME source region can assist. It should be noted, that not all CME

source regions show all of the signatures we discuss below. For example, a study by Hernandez Camero et al. (2025) identified the source region of 1132 CMEs observed by SOHO LASCO between the years 2010 and 2018, inclusive, using an automated method. A CME's source region was allocated if it showed one or both of the signatures of flaring (see Section 2.1) or dimming (see Section 2.3) at the time of the eruption. Active regions at all evolutionary stages, and which are included in the HMI SHARP catalog (Bobra et al., 2014), were used in the study. Hernandez Camero et al. (2025) found that 500 out of their 1132 CME source regions exhibited weak flaring of GOES classification less than C5 at the time of the CME, whilst only 200 CME source regions exhibited flaring of C5 class or greater. Only 415 source regions showed some form of EUV dimming along with a flare.

2.1. Flare Association and Flare Characteristics

Many CMEs occur in concert with a solar flare, although there is not a one-to-one relationship (CMEs can occur without an associated flare and vice versa). Both phenomena are outcomes of the erupting and reconfiguring magnetic field. For a comprehensive review of the formation and evolution of flare-productive ARs, including observational characteristics and their relationship to CME activity, see Toriumi and Wang (2019) who discuss that magnetic complexity and stored free magnetic energy in active regions are central to the occurrence of flares and CMEs. The frequent association between flares and CMEs has led to a multitude of studies seeking to determine whether flares that are CME-associated show any identifying characteristics. The characteristics that are most commonly investigated are derived from full-Sun data, such as soft X-ray emission light curves and EUV imaging, which we discuss in this section. We focus on studies that have been conducted using LASCO data, since this coronagraph package provided the first high-quality continuous observations of the eclipsed corona. Using LASCO data reduces the risk of missed CME detection, although CMEs originating near disk-centre and CMEs with low electron density remain challenging to observe even with modern coronagraphs when using only one viewpoint.

The likelihood that a flare will have an associated CME increases with peak soft X-ray intensity. Table 1 shows the rates at which flares were found to have an associated CME in the studies of Andrews (2003), Yashiro et al. (2005), and Toriumi et al. (2017), of 229, 1301 and 51 flares, respectively. In the study of Toriumi et al. (2017), four of the five non-eruptive X-class flares were from NOAA active region 12192, which is considered an outlier in terms of its activity and not representative of the whole active region population. These five non-eruptive X-class flares had the following GOES classifications in order of size: X1.0, X1.5, X1.6, X2.0, X3.1. However, it should be noted that the rate at which flares of different GOES classes are associated with a CME varies with magnetic flux content of the host active region. In study of 719 flares of GOES class C5.0 and above, Li et al. (2021) found that for X-class flares only, 14/19 (74%) were CME-associated when considering active regions of all sizes. But when considering X-class flares that occur in active regions with $\geq 1 \times 10^{23}$ Mx (i.e., large active regions), only 1/4 flare (25%) was CME-associated (see their Figure 1a). Similarly, in a study of 216 flares of GOES class M1.0 and above, Kazachenko (2023) found that CME-associated flares tended to occur in occur in smaller active regions with weaker magnetic field strengths. This work also studied the thermodynamic flare properties and found that CME-associated flares of GOES M1.0 class and above have longer durations and slightly smaller peak temperatures than do non CME-associated flares.

Durations of flares that are associated with CMEs versus those that are not have been studied since the early days of CME research. Initial indications were that CME-associated flares had relatively long durations in terms of

their soft X-ray emission lifetime. For example, Sheeley et al. (1975) studied 16 so-called long-duration flares, defined as having a lifetime of at least 3 hr. All events were CME-associated. Another study, of 69 CME-associated and non-CME-associated flares, showed that flares associated with CMEs tend to be of longer duration than flares that have no associated CME (Kay et al., 2003). However, definitions of what constitutes a long-duration flare and how flare lifetime is determined from the GOES soft X-ray light curve vary from study to study. Currently, there is no threshold flare duration that can be used to identify a flare that has an associated CME. Although the study by Andrews (2003) finds that 95% of flares are CME-associated when using the criteria of soft X-ray peak intensity reaching $6 \times 10^{-5} \text{ W m}^{-2}$ (in the GOES M-class range), total flux of 0.07 J m^{-2} and flare duration of 4 hours or longer (duration defined as beginning when the soft X-ray emission starts to rise sharply and ending when it has decreased to $\frac{1}{e}$ of the peak value).

In addition to characterizing flares using their GOES soft X-ray light curve, images of the flare loops can be analyzed. Using SOHO/EIT 195 Å images from February 1997 to December 2002, Tripathi et al. (2004) identified occurrences of the formation of extended flare-loop systems that brighten over several hours and which have an average length of 15 heliographic degrees. The study identifies 236 such structures and the authors conclude “a near one to one correspondence between PEAs (post-eruptive arcades) observed by SOHO/EIT at 195 Å and white-light CMEs detected by SOHO/LASCO.” These extended flare loop systems were found to remain bright for a couple of hours to 20 hr, with a mean duration of 7 hr. These flare loop systems are the source location of the long-duration soft X-ray emission discussed earlier in this section.

At the footpoints of flare arcades form flare ribbons, which can be seen in data sets such as H-alpha and SDO AIA wavebands 1700 Å and 1600 Å (see Figure 1). The flare ribbons give clues as to whether or not a flare has an associated CME. In CME-associated events, flare ribbons can take the form of two roughly parallel ribbons that elongate along the polarity inversion line and then separate from each other, leading to the name two-ribbon flares (Vršnak et al., 2005). The two ribbons separate over a time period of minutes to hours. Hinterreiter et al. (2018) studied 50 flares that occurred between June 2000 and June 2015; 62% were CME-less (mostly GOES C-class) and 38% were CME-associated (mostly GOES M-class). They tracked the evolution of the flare ribbons as seen in H-alpha imagery and found that there was a tendency for the ribbons of CME-associated flares to separate over a greater distance than for those flares without a CME association. The ribbons of all the CME-associated flares had separations of more than 10 Mm, whilst 70% of the ribbons of flares with no CME association had separations less than 10 Mm. Toriumi et al. (2017) found that flare ribbon area normalized by sunspot area can be used to discriminate flares that are CME-associated from those that are not. However, it should be noted that flare ribbons can be complex in their configuration and that a two-ribbon appearance will not be present in all CME-associated events.

2.1.1. Flare Association and Flare Characteristics: Factors to Consider

The following should be taken into account when using flare observations to assess whether an associated CME has occurred:

- M-class flares have a ~50% chance of being CME-associated.
- Flares with a GOES classification of $\geq X3.0$ are expected to be CME-associated.
- Flares with a soft X-ray peak intensity reaching $6 \times 10^{-5} \text{ W m}^{-2}$, with a total flux of 0.07 J m^{-2} and duration of 4 hours or longer (duration defined as beginning when the soft X-ray emission starts to rise sharply and ending when it has decreased to $\frac{1}{e}$ of the peak value) can be considered to be CME-associated.
- Flares exhibiting ribbons either side of the polarity inversion line that separate from each other by more than 10 Mm have a 70% chance of being CME associated.

Operational data needed to determine flare occurrence and magnitude exist via the XRS instrument onboard the GOES satellites (Chamberlin et al., 2009). Operational data needed to observe flare occurrence, location, arcade formation, and flare ribbon structure and evolution exist via GOES SUVI instrument (Darnel et al., 2022) and H α via the GONG network that provides H-alpha images. However, it should be noted that GOES SUVI imaging data are provided at a cadence of 4 min, which will mean these data are better suited for analysis of flare ribbons that are visible for tens of minutes. The H-alpha data provided by GONG may be provided at a cadence of 20 s making it more suitable to study flare ribbons of a wider range of durations. See Table A1 for details.

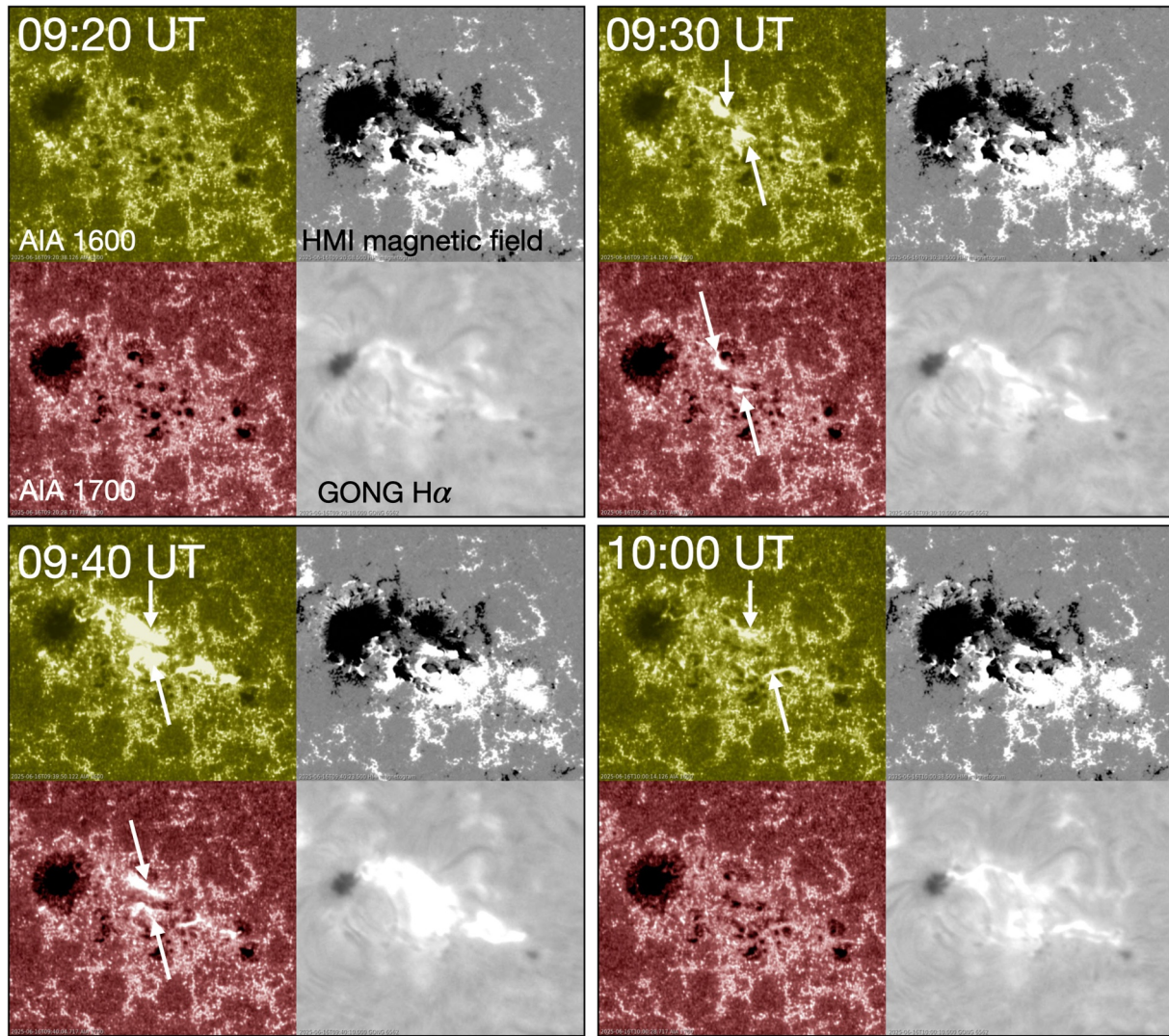


Figure 1. Flare ribbons observed in NOAA active region 14114 on 16 June 2025 during an eruptive M6.3-class flare. As viewed in 1600 Å, 1700 Å, HMI magnetic field data and in H α . Images courtesy of JHelioviewer.

2.2. Filament Eruptions

Filaments, also known as prominences when viewed at the solar limb, consist of relatively cool, dense, chromospheric plasma suspended in the solar atmosphere. They form above and along polarity inversion lines inside

Table 2

Radio Bursts Observed at and Near the Sun Are Typically Categorized Into Different Types

Type I	Observed at frequencies $\sim 10^2$ MHz, and exhibiting no significant drift in emission frequency over hours or even days.
Type II	Metric wavelength range ($\sim 10^1$ – 10^2 MHz). Exhibits a relatively slow drift rate in observed frequency with time (for tens of minutes and drifting in frequency by tens of MHz).
Type III	Metric wavelength range, with bursts lasting only a few seconds. The emission drifts 3–4 orders of magnitude (from high to low frequencies) during this time.
Type IV (stationary)	Broadband continuum emissions showing no drift in observed frequency.
Type IV (moving)	Broadband continuum emissions showing a frequency drift.

Note. This table summarizes the burst types relevant for CME occurrence and forecasting.

active regions, at the boundary of active regions (known as intermediate filaments), close to polar coronal holes (known as polar crown filaments) and in the quiet Sun (known as quiescent filaments, Babcock & Babcock, 1955; Mackay et al., 2008). Their formation rate follows the solar cycle. Filaments (prominences) are seen as dark (bright) elongated structures in spectral lines such as $H\alpha$ (6562.8 Å) and He II (304 Å) (Parenti, 2014). Although best observed in $H\alpha$ and He II, these structures can also be seen in absorption in EUV wavebands (e.g., 171, 193, 211 Å of SDO/AIA). In the pre-SOHO era, Munro et al. (1979) found that at least 70% of 777 coronal mass ejections were associated with the eruption of a filament/prominence.

Filaments and prominences can be stable on the Sun for some time. They may activate (during which time there is plasma motion but no escape of plasma from the Sun) and they may erupt (when some or all of the filament plasma escapes the Sun). The study of Gilbert et al. (2000) found 17 out of 18 (94%) eruptive prominences were associated with a CME, whereas only 12 out of 26 (46%) active prominences were CME-associated. The study of Hori and Culhane (2002) found that 92% of erupting prominences had an associated CME (46 out of 50 events studied). The study of 33 eruptive filaments by Sinha et al. (2019) found that 73% were CME-associated. The disappearance of a filament/prominence can therefore provide evidence of the occurrence of a CME before the CME is detected in coronagraph data/before coronagraph data is available.

The height attained by a prominence also appears to be related to its progression to become a CME. Munro et al. (1979) found that prominences reaching a height of at least $1.2 R_{\odot}$ (measured from Sun-center) will successfully erupt, and Gilbert et al. (2000) similarly found that all of the CME-associated erupting prominences reached this height, while only two-thirds of the CME-associated active prominences did.

It should be noted that if filament plasma is heated it may become invisible in $H\alpha$ images in an event referred to as a disappearance brusques. However, whilst the filament disappears in $H\alpha$ images, the plasma will appear bright at EUV wavelengths allowing heating versus eruption to be distinguished from each other (for a review of filaments see Parenti, 2014).

2.2.1. Filament Eruptions: Factors to Consider

The following should be taken into account when using filament and prominence observations to assess whether a CME has occurred:

- The disappearance of a filament or prominence that has reached an altitude of $1.2 R_{\odot}$, especially when observed in both H-alpha and EUV data and leaving flare loops in its wake, is a strong indication that a CME has occurred.

Operational $H\alpha$ data that can be used to monitor filament eruptions can be gained via the GONG network, and in EUV data via GOES SUVI.

2.3. Coronal Dimmings

Coronal dimmings are localized regions of reduced emission in the solar corona observed at soft X-ray and EUV wavelengths. Coronal dimmings resemble small coronal holes, but dimmings have a transient nature and shorter lifespan of typically less than 24 hr (Krista & Reinard, 2017; Reinard & Biesecker, 2008). It has become widely accepted that coronal dimmings are low coronal signatures of CMEs, formed when the rapidly expanding magnetic volume of a CME produces a reduction in plasma density and a corresponding reduction in soft X-ray/EUV emission (Hudson et al., 1996; Sterling & Hudson, 1997). Several statistical studies show a clear association between the appearance of coronal dimmings and the onset of CMEs. For example, a study of 168 coronal dimmings observed at the solar limb (using two coronal emission lines, representing temperatures of 1 MK and 2 MK plasma) between 1998 and 2005 by Bewsher et al. (2008) found that 55% of the observed dimmings were associated with a CME, which is significantly higher than random occurrence. A study of 154 dimmings identified with SDO AIA 193 Å images, located close to the disk centre, found that 42% of the coronal dimmings were CME-associated (Krista & Reinard, 2017). Krista et al. (2022) used observations during SOHO-STEREO quadrature to identify corresponding on-disc coronal dimmings and off-limb CMEs using the two viewpoints, and found that 79% of coronal dimmings detected by STEREO-A and -B EUVI 195 Å were associated with CMEs seen in SOHO LASCO coronagraph. Most CME-associated dimmings form within ± 10 min of the first appearance of CME in white-light images (Dissauer et al., 2019).

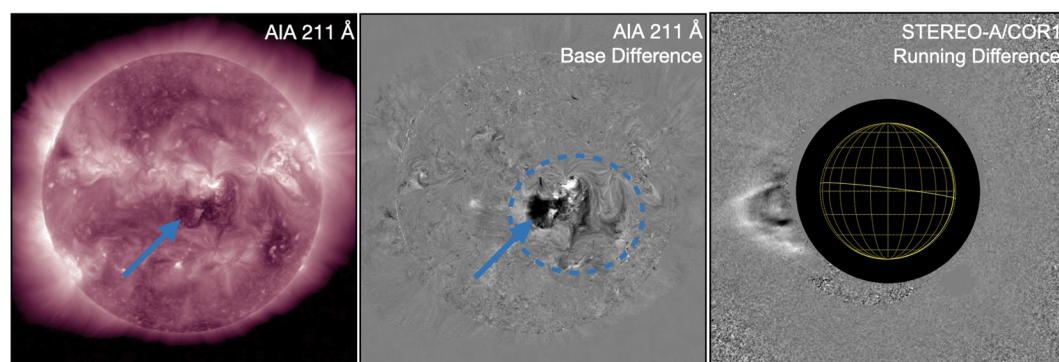


Figure 2. Coronal dimming and its associated CME as seen on 2011 October 2, 01:15 UT by SDO and STEREO-A. Left and middle panels show the appearance and extent of the dimming in AIA 211 Å normal and base-difference EUV images, respectively. The blue arrow shows the location of the strongest dimming and the blue dashed oval the wider extent of the dimming. The associated CME is shown in a visible-light running difference image (right panel) from STEREO-A COR1. Note that STEREO-A was at $\approx 90^\circ$ from the Sun–Earth line. Images courtesy of JHelioviewer.

Normally, EUV observations in 193 Å, 195 Å and 211 Å wavebands (corresponding to plasma temperature of 1–2 MK) are used to detect coronal dimmings, as these wavebands provide the best contrast between the dimming and surrounding corona. Coronal dimmings can be identified directly in EUV images (Krista & Reinard, 2013). However, the detection of dimmings becomes easier when a comparison is made between pre- and post-CME coronal brightness. For example, using such a base-difference image technique (G. D. R. Attrill & Wills-Davey, 2010; Reinard & Biesecker, 2008) or a logarithmic base-ratio image (Dissauer et al., 2018). The Solar-Demon catalog (Kraaikamp & Verbeeck, 2015), which is a popular coronal dimming catalog for space weather forecasting, lists dimmings observed in real-time SDO data using a running difference image technique. The dimmings are then characterized using base-difference images. Figure 2 shows an example of a coronal dimming observed in normal and base-difference EUV images in the AIA 211 Å waveband.

It has been suggested that the properties of coronal dimmings have a direct correlation with the properties of CMEs. The loss of coronal plasma that produces the dark appearance of the dimmings may make a significant contribution to the total mass of the CME, with an estimated contribution ranging from 30% to 70% (Aschwanden et al., 2009; Harrison & Lyons, 2000; Tian et al., 2012). A statistical study of 62 CME-associated coronal dimmings by Dissauer et al. (2019) reported a significant correlation between coronal dimming parameters measured at their maximum extent (e.g., dimming area, brightness, and total unsigned magnetic flux) with CME mass. The maximum rate of change of these parameters is also correlated with the CME peak speed. A similar positive correlation between dimming parameters and CME mass/brightness is reported in Krista et al. (2022). Hence, it can be inferred from these results that larger and/or darker coronal dimmings may correspond to more massive CMEs.

Studies of coronal dimmings with their associated interplanetary CMEs (ICMEs) show that the total magnetic flux derived from the area of the dimmings (at their maximum extent) is of the same order of magnitude as the total magnetic flux in the ICME (G. Attrill et al., 2006; Mandrini et al., 2005; Temmer et al., 2017; Webb et al., 2000). These results confirm the popular interpretation that (at least parts of) the coronal dimmings correspond to the footpoints of the interplanetary CME. Moreover, the expansion of the dimming regions is related to the early evolution and propagation of the associated CME. Thompson et al. (2000) noticed that the dimming regions observed in EUV wavebands map out the footpoints of CMEs observed in white-light coronagraph images. Assuming that a CME expands isothermally, J. X. Cheng and Qiu (2016) suggested that the brightness curves of the dimming regions are approximately scaled with the height-time profile of the propagating CME. By combining observations of coronal dimming expansion with established CME models, Chikunova et al. (2023) found that the dimming regions reflect the inner 3D structure of the reconstructed CMEs, and the dominant direction of the dimming expansion is closely related to any filament eruption direction. This idea was further developed by Jain et al. (2024), who created methods to estimate the early propagation of a CME before it enters the coronagraph field of view based on dimming expansion.

2.3.1. Coronal Dimmings: Factors to Consider

The following should be taken into account when using coronal dimmings to assess whether an associated CME has occurred:

- Coronal dimmings are a useful tool for assessing CME occurrence, especially Earth-directed CMEs, which appear as faint halos in coronagraphs situated along the Sun-Earth line.
- Base-difference and base-ratio images are preferred for coronal dimming identification and tracking.
- The strong association between coronal dimmings and CMEs apparent from multi-viewpoint observations suggests that nearly 80% of dimmings may be interpreted as having an associated CME.
- The area covered by coronal dimmings may correlate with CME mass, and the evolution of coronal dimmings may reflect the propagation of their CME counterparts.
- EUV dimmings map out the footpoints of the CME that will then be observed in white-light coronagraph images.

Operational GOES SUVI data can be used to monitor the Sun for coronal dimmings. However, SDO AIA data are routinely used to provide near real-time identifications of dimmings that are made available via the SolarDemon catalog.

2.4. EUV Waves

EUV (also known as coronal) waves are events that are seen in full-Sun EUV images as a rapidly propagating bright front moving outwards from a CME source region and crossing large portions of the corona. Although an observation of an EUV wave indicates the occurrence of an associated CME not all CMEs have an associated coronal wave (Biesecker et al., 2002). The leading theory for EUV waves is that they are a large amplitude wave and shock generated by the rapid lateral expansion of the magnetic structure of the CME (Long et al., 2017). When observed in EUV imagers that have a wide field of view, such as GOES SUVI, the wave may be seen to reach to a relatively high altitude in the corona (e.g., around $1.9R_{\odot}$, Seaton & Darnel, 2018). Some EUV waves propagate outward from the CME source site as a front only covering a narrow arc, whereas others subtend a full 360° . EUV waves can show asymmetries in their propagation direction that result from the non-uniform corona into which they travel, but the asymmetries may also reflect a true non-radial trajectory of the CME (Möstl et al., 2015). In addition, rotation of the EUV wave front has also been detected, which may reflect a true rotation of the CME ejecta (G. D. R. Attrill et al., 2014). These EUV wave properties may provide useful actionable information for forecasting, but statistical studies are needed to build a clear understanding that is broadly applicable to all EUV wave observations.

EUV waves are normally too faint to be detected in the original EUV images and instead need to be identified using a difference image technique in which a former image is subtracted from the latter. EUV waves then appear as propagating bright fronts. Typically, an image cadence of 1 min is needed so that the fastest waves can be captured and they are best identified using the 193 Å, 195 Å and 211 Å wavebands of EUV imagers.

2.4.1. EUV Waves: Factors to Consider

The following should be taken into account when using EUV waves to assess whether an associated CME has occurred:

- EUV waves propagate outwards from CME source regions and are an extremely strong indicator of CME occurrence.
- The properties of the EUV wave (e.g., direction and/or rotation of the wavefront) may have relevance for space weather forecasting following further study.

Operational SUVI data can be used to monitor the Sun for EUV waves, although SDO AIA data are routinely used due to the higher cadence of AIA data. Automated EUV wave detection methods have been developed by the science community for research purposes (Kraaikamp & Verbeeck, 2015; Long et al., 2014; Podladchikova & Berghmans, 2005). The AWARE method developed by Ireland et al. (2019) is open access and available in Python.

2.5. Radio Emission

Radio emission is often observed during activity events in the solar corona. Specifically, during the eruption of a CME, the reconfiguring magnetic field leads to the acceleration of electrons, which in turn can lead to the generation of radio emission. The literature commonly refers to radio emission being of different types (Wild et al., 1963). The main types of relevance to CMEs are types II, III and IV.

Type II radio bursts refer to those in the metric wavelength range ($\sim 10^1$ – 10^2 MHz), which exhibits a relatively slow drift of frequency with time (for tens of minutes and drifting in frequency by tens of MHz). Sometimes, type II emission can be seen at two emission frequencies simultaneously. This is due to emission at the fundamental plasma frequency and the second harmonic of the plasma frequency. Kumari et al. (2023) conduct a statistical study of 435 type II radio bursts and found a median duration and drift rate of 9 min and 0.06 MHz s^{-1} , respectively, during solar cycles 23 and 24. Type II radio emission is interpreted as being produced when a relatively fast CME drives a shock that propagates away from the Sun, since the frequency of the radio emission is proportional to the plasma density. Kumari et al. (2023) also find that the rate at which the CME expands laterally plays a role in the formation of the type II radio emission, and that the rate of frequency drift may be used to estimate the speed of the CME, using an accompanying plasma density-distance model.

Type III radio emission is caused by beams of accelerated electrons traveling through coronal plasma. These electrons travel at typical speeds $\sim 30\%$ the speed of light, meaning they rapidly move from regions of higher plasma density in the low corona toward lower densities in the outer corona, and therefore the observed radio frequencies produced by plasma emission drift rapidly by orders of magnitude in only a few seconds. Type III radio bursts can drift by 3–4 orders of magnitude in frequency in only a few seconds (from high to low frequencies) and are created when beams of electrons are accelerated in the solar corona and interplanetary space along magnetic field lines that are very extended and considered “open” (Lin, 1974). Type III bursts occur at metric wavelengths and are interpreted as being related to flare reconnection processes (Reid, 2020). However, there are case studies that indicate the production of type III emission may be linked to the passage of a CME through the corona (Morosan et al., 2014).

Type IV radio bursts are broadband continuum emissions; their frequency bandwidth is much broader, and their intensity much less patchy than other kinds of radio bursts. Type IV bursts are sub-categorized in two ways. First, stationary type IV bursts do not exhibit a drift in observed frequency with time, meaning that they originate from a plasma structure that is not moving or changing its density (e.g., associated with the leg of the magnetic flux rope that later erupts and comprises the core of a CME; Salas-Matamoros & Klein, 2020), or the flare loops left in the wake of a CME (Wild, 1970). Second, moving type IV radio bursts drift in frequency over time as the emitting plasma reduces in density as the CME expands and escapes the Sun. Therefore, moving type IV emission can be a signature of CME occurrence. In addition to observing the drift in frequency over time, radio imaging spectroscopy can be used to infer the movement of type IV radio sources and help identify and track CMEs.

A survey of 446 type IV radio bursts in solar cycle 24 by Kumari et al. (2021) identified 366 stationary type IV events, 78% of which were accompanied by a CME seen in LASCO C2 within two hours of the burst. Of the 80 moving type IV events, 91% were accompanied by a CME.

For both stationary and moving events, type IV bursts are caused by electrons trapped in closed magnetic field structures. Two emission mechanisms can contribute to the production with varying proportions: plasma emission, which contributes to type IV bursts in the same way as type II bursts, and gyrosynchrotron emission, which occurs as energetic electrons gyrate around a magnetic field and is generally smoother in intensity. Gyrosynchrotron emission is also less circularly polarized than plasma emission, so detectors that observe the polarisation state of radio waves can be used to identify the primary emission mechanism (e.g., Nançay Radiograph). In cases where gyrosynchrotron emission dominates, estimations of the magnetic field strength in the erupting CME structure have been made (Bain et al., 2014; Carley et al., 2017; Chen et al., 2025). Table 2 and Figure 3 summarizes these radio emission burst types. For a review of CMEs and associated radio emissions, see Vourlidas et al. (2020).

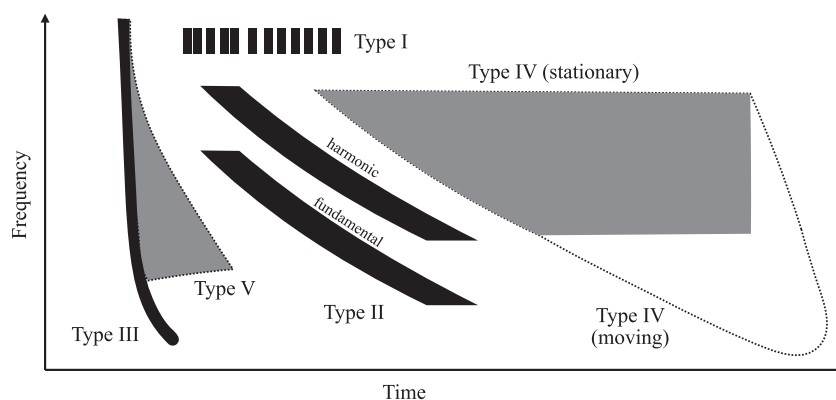


Figure 3. Schematic examples of the five main types of radio burst. Each has a different characteristic combination of frequency drift rate, bandwidth, duration, and intensity profile (gray-black from weaker to stronger intensity). Based on a similar diagram from Wild et al. (1963).

2.5.1. Radio Emissions: Factors to Consider

The following should be taken into account when using radio emission to assess whether an associated CME has occurred:

- An observation of a type II radio burst can be used to confirm that a CME has erupted.
- Moving type IV emission has a ~91% chance of being a signature of CME occurrence.
- Imaging data provides important spatial information in addition to spectral information but it not yet available on an operational basis.
- Radio emissions can provide information related to both the onset and propagation of a CME (e.g., CME speed).

Currently, radio observations of the Sun for space weather forecasting purposes are provided by the US Air Force's Radio Solar Telescope Network, which gives 24/7 coverage via the use of 4 ground stations. This network provides radio flux and spectral time series data so that radio burst types can be identified. In addition, the YAMAGAWA solar radio spectrograph in Japan (<https://solarobs.nict.go.jp>) is operated as part of the National Institute of Information and Communications Technology's (NICT) operational space weather forecasting activities. Dynamic spectra produced by radio observatories that are dedicated to scientific studies of the Sun are available from the Nançay Radio Heliograph (NRH), the Expanded Owens Valley Solar Array (EOVSA), the Nançay Decameter Array (10–80 MHz and the space-based Wind/WAVES (20 kHz–14 MHz), covering the outer corona. However, imaging radio data are required in order to determine the spatial location of the radio emissions and from this determine spatial information about the CME. No imaging radio data are provided on an operational basis but publicly accessible data are provided by NRH and EOVSA, which cover approx. 150–450 MHz and 1–18 GHz, respectively. For a review of currently available, and future radio observatories, see Gary (2023).

3. Observational Indicators of Likely Future CME Occurrence

Although the transit time of CMEs between the Sun and the Earth allows for several hours or days for preparation and risk mitigation activities, there remains enormous value in forecasting CME occurrence ahead of time. There has been a stated desire in the electricity distribution sector for a 5-day warning of CME arrival at Earth, for example, Krausmann et al. (2016). So, what can currently be achieved in terms of advance warning? Here we utilise our scientific understanding that CMEs are the end product of an evolutionary process in which sufficient free energy is injected into the pre-eruptive structure, and that the pre-eruptive structure itself has to form. We don't discuss here the specific physics of CME onset (for a review see Green et al., 2018), but rather the observational indicators that have so far been identified across the wide variety of CME source regions, highlighting general features that have been determined.

3.1. Polarity Inversion Line Characteristics

The observation that CMEs involve the eruption of magnetic fields situated along photospheric polarity inversion lines, has led to the search for whether polarity inversion lines that are the site of an eruption show any unique characteristics when approaching an eruptive state. It has already been shown that major flares, such as M- and X-class flares, originate in active regions that have a high degree of magnetic shear and a strong magnetic field gradient. For a review of the drivers behind M and X-class flares see Schrijver (2009). In this section we review what has been found in relation to CME activity.

D. A. Falconer et al. (2002), in a small study of 12 bipolar active regions found that CME productivity is significantly correlated with certain polarity inversion line characteristics: (a) the length of the strong field and high shear region, (b) the net electric current arching from one polarity to the other polarity, and (c) a flux-normalized measure of the twist in the magnetic field, as determined from vector magnetic field data. The strong field, high shear region is defined as: the portion of the main polarity inversion line where the observed transverse field is strong (>150 G) and strongly sheared (shear angle $>45^\circ$). D. A. Falconer et al. (2003) used the same 12 active regions but only the line-of-sight magnetic field component to search for polarity inversion line characteristics in a way that might be more practical for forecasting purposes. This method involves computing the transverse component of the potential field, and using this in addition to the line-of-sight magnetic field component, to quantify the length of the strong-shear region L_{SS} and the length of the strong magnetic field gradient L_{SG} region along the inversion line. In D. A. Falconer et al. (2008), the method was developed to be usable for multipolar active regions (rather than bipolar) with the quantity WL_{SG} , which is the line integral of the vertical field horizontal gradient over all strong-field portions of the neutral lines in the active region. The methods developed by Falconer and collaborators find that, for CME forecasting windows of 0–1, 0–2, or 0–4 days, the success rate is about 75% (D. A. Falconer et al., 2006). These studies acted as the foundation of the Mag4 and MagPy methods to forecast CMEs (and also flares and SEP events; D. Falconer et al., 2011; D. A. Falconer et al., 2014).

A complementary approach uses the so-called R-value that is calculated as being the total unsigned flux within ~ 15 Mm of strong-field, high-gradient polarity inversion lines (Schrijver, 2007). The probability of a major solar flare in the 24 hr after a measurement of R is made approaches unity for polarity inversion lines with an R-value of around 2×10^{21} Mx. Given the strong association of CMEs with M and X class flares, this approach has relevance for CME forecasting (see Section 2.1).

3.1.1. Polarity Inversion Line Characteristics: Factors to Consider

The following should be taken into account when using polarity inversion line observations to assess whether a CME may occur:

- The quantity WL_{SG} can be used to indicate the probability of a CME occurrence in the next 0–4 days, via the Mag4 and MagPy tools for active regions within 30° from central meridian.
- Polarity inversion lines exhibiting an R-value of around 2×10^{21} Mx have a high likelihood of producing a major solar flare in the following 24 hr, and should be considered likely to produce a CME.

Polarity inversion line properties such as WL_{SG} and the R-value can be derived from either line of sight or vector magnetic field observations (line of sight magnetic field data to assess CME likelihood may be most appropriate for those active regions within 30° of central meridian, Barnes et al., 2016). Operational data needed to derive these quantities exist via the GONG network (which provides full-Sun images of the line-of-sight magnetic field in the photosphere), with additional vector magnetic field data provided by SDO HMI. The quantity WL_{SG} is computed in near real-time and used to provide near real-time CME forecasts (based on magnetic field data provide by SDO HMI and including probability estimates and confidence intervals). These forecasts are created by the MagPy model, which is completely automated and provides a probabilistic forecast for CME occurrence, that is, available via the Community Coordinated Modeling Center (<https://ccmc.gsfc.nasa.gov/models/MagPy/v3/>). However, it should be noted that both WL_{SG} and the R-value are quantities derived from polarity inversion lines that exhibit strong magnetic fields and/or a strong magnetic field gradient, which may only be relevant for relatively young active regions. That is, these quantities may not be universally applicable to all active regions and throughout their lifetime (including decayed active regions with weak and dispersed fields).

Table 3
Flux Emergence Rates, Collisional Shearing and CME Activity for Four Active Regions With High Flux Emergence Rates

NOAA no.	Mean flux emergence rate [10^{20} Mx h $^{-1}$]	Collisional shearing	CME no.	Hale	Joy's
11024	1.30	N	0	Y	Y
12192	8.04	N	0	Y	Y
12673	4.93	Y	11	N	N
13664/8	6.90	Y	14	Y	N

Note. Columns five and six list whether or not the active region follows Hale's Law and Joy's Law.

3.2. Rapid Flux Emergence

As discussed in Section 1.1, the rate at which CMEs occur in an active region can be higher during times of flux emergence and active region formation/growth than during times of flux decay and dispersal (Démoulin et al., 2002; Green et al., 2002). However, the number depends on the specifics of the active region. For example, in a study by Yardley et al. (2018) of 20 isolated, short-lived (<2 weeks) small bipolar active regions, 13 out of the 20 regions produced CMEs (24 CMEs in total). 13 of the 24 CMEs occurred during active region emergence while 11 of the 24 CMEs occurred during active region decay. In this study it was found that there was a tendency for CMEs occurring along polarity inversion lines internal (external) to the active region to occur during the decay (emergence) phase of the region.

So far, there has been no comprehensive study into the relationship between flux emergence rates and CME activity, but a few case studies of active regions that exhibited a high flux emergence rate provide interesting insight. For example, NOAA active region 12673 was present on the Sun during September 2017 and exhibited one of the fastest flux emergence rates observed by that time (into a pre-existing active region) with a mean flux emergence rate of 4.93×10^{20} Mx h $^{-1}$ (Sun & Norton, 2017). The rapid emergence of flux into the corona of 12673 was accompanied by 11 CMEs between 4th and 10th September (Yardley et al., 2022). Similarly, NOAA active region 13664/8 had an even higher flux emergence rate (average rate was 6.90×10^{20} Mx h $^{-1}$) and produced 14 CMEs over a 7 day period (<http://hmi.stanford.edu/hminuggets/?p=4216>). NOAA active region 12192 is a counterexample in which a rapid flux emergence rate was observed, but with no accompanying CME activity (Sun et al., 2015).

Rapid flux emergence does not always lead to CME occurrence, but when it does, major emergence episodes can lead to several CMEs in quick succession. What may set apart regions of rapid flux emergence with CME occurrence is when the rapid flux emergence involves more than one bipole simultaneously, with non-conjugate opposite polarity bipoles colliding and shearing past each other. This scenario has been termed collisional shearing by Chintzoglou et al. (2019) in their studies of NOAA active regions 11158 and 12017, and was the focus of Wang et al. (2024) in their study of NOAA active regions 13664/8. Table 3 and Figure 4 show the flux emergence rates for active regions with some of the highest values observed so far, the presence or absence of collisional shearing and number of CMEs produced during the time of rapid flux emergence. Collisional shearing has been proposed to be causally related to CME activity because the colliding polarities can lead to a flux rope being built within the sheared arcade along the polarity inversion line via the mechanism proposed by van Ballegoijen and Martens (1989). However, there have not yet been statistical studies carried out that enable an assessment of which particular conditions are needed for collisional shearing to lead to CME activity and the conditions under which collisional shearing does not lead to CME activity. This open question should be addressed in future research and should be considered along side the characteristics of the polarity inversion line and the resulting configuration of the coronal magnetic field.

Therefore, from a forecasting perspective, both the flux emergence rate and the presence or absence of collisional shearing should be monitored when assessing CME likelihood. Whether emerging bipoles follow Hale's law and Joy's law should also be considered, as deviations from these laws increase the likelihood of the formation of collisional shearing occurring during flux emergence.

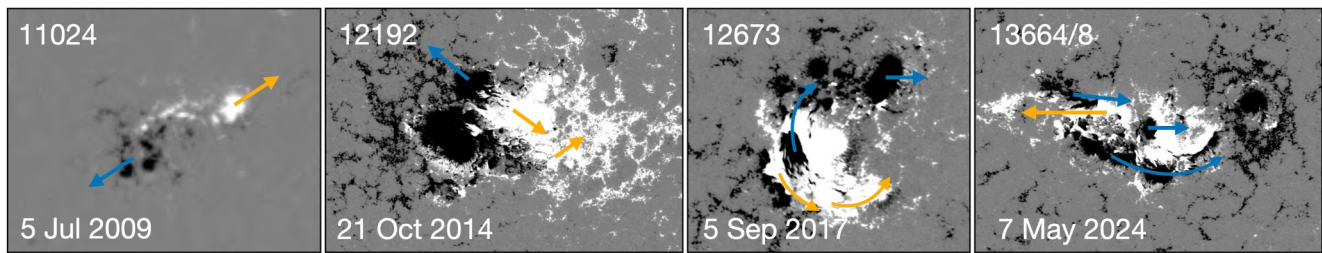


Figure 4. Line of sight magnetic field snapshots for NOAA active regions 11024, 12192, 12673 and 13664/8, which all show high flux emergence rates. Orange (blue) arrows show indicative overall motion of the emerging positive (negative) flux. All images are from SDO HMI, except for NOAA 11024 which is imaged using SOHO MDI. Images are available via JHelioviewer.

3.2.1. Rapid Flux Emergence: Factors to Consider

The following should be taken into account when observing rapid flux emergence through the photosphere:

- Flux emergence rate does not necessarily indicate likelihood of future CME occurrence but, if conditions are sufficient for CMEs to occur there may be several in quick succession.
- The emerging flux should be monitored for likely collision and shearing of non-conjugate opposite polarity magnetic fields.

Operational data needed to determine flux emergence characteristics exist via the GONG network that provides full-Sun line-of-sight magnetic field information in the photosphere. However, SDO HMI data provide more detailed imagery. All currently available data sets suffer from projection effects when considering active regions within approx. 30° from the solar limb, which limits the ability to confidently determine flux emergence characteristics until the active region is closer to the central meridian.

3.3. Filament Evolution

Section 2.2 describes how the eruption of a filament can manifest as a CME, successfully escaping the Sun. But determining whether and when a filament will erupt in the future is challenging. Filaments residing in active regions are short in length ($\sim$ tens of Mm) and lifetime (hours to days), whereas quiet Sun filaments often extend across large portions of the Sun (hundreds of Mm) and remain stable for longer time periods (several days to a few months). However, an “activation” phase may precede the eruption of a filament and therefore act as an eruption precursor. Case studies have shown that during an activation phase, various features or dynamics may be observed. For example, an increased darkening of the filament as seen in $H\alpha$ images or turbulent motion in the filament plasma (Martin, 1980; Ramsey & Smith, 1966; Smith & Ramsey, 1964), enhanced counter-streaming flows (in a quiet sun filament, 24 hr before eruption, Schmieder et al., 2008), plasma heating episodes that are observed as discrete, localized X-ray brightenings from 2 to 50 min before filament eruption (Chifor et al., 2007), brightenings in $H\alpha$ (Ramsey & Smith, 1966) and oscillations in the filament plasma. Some of these studies pre-date the discovery of CMEs but relate to filament and prominence eruptions. Therefore, modern studies are needed to confirm these results.

Filaments can exhibit a slow rise prior to the main eruption, which must be differentiated from solar rotation effects in the plane of sky images that may give the impression of a gradual ascent. The case study of Sterling et al. (2001) found that, for a quiet Sun filament, the filament rose slowly at a speed of around 1 km s^{-1} for roughly 6 hr, before finally erupting. In the case of an active region filament, Sterling and Moore (2005) found that it underwent a slow rise phase with a velocity of $\sim 15 \text{ km s}^{-1}$ that lasted about 10 min before its eruption. In a study of 106 filament eruptions seen at the limb (including both quiet Sun and active region filaments), McCauley et al. (2015) found that the filaments had on average a slow-rise phase that lasted about 4.4 hr and velocity of approx. 2 km s^{-1} . The shortest slow-rise phases were found for active region filament eruptions, and the longest slow-rise phases are found for polar crown filament eruptions.

Vršnak et al. (1991) reported that the eruptive potential of a prominence may be assessed from the height of the prominence material and the pitch angle that helical threads seen in the fine structure of the prominence make with its axis. In their study of 15 non-eruptive and 13 eruptive filaments, it was found that eruptive events were at a

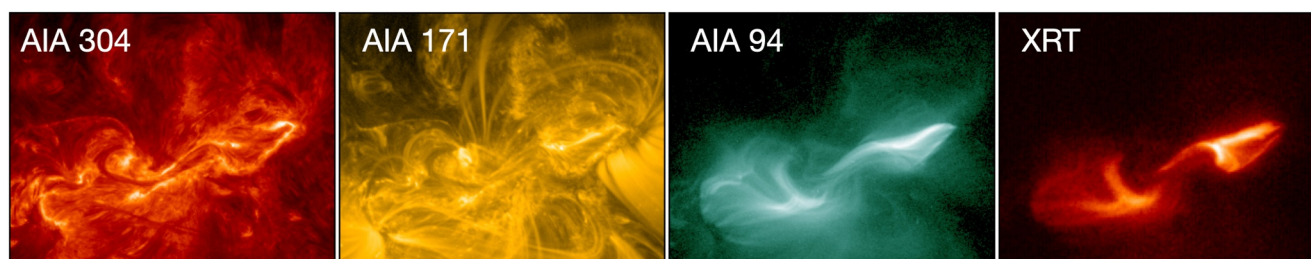


Figure 5. Sigmoid in NOAA active region 11158 as viewed in SDO AIA 304 Å, 171 Å, 94 Å wavebands, and in Hinode XRT soft X-rays. All images are at 00:00 UT on 11 February 2011, which is approximately 1 hr and 40 min before the time of the CME onset.

height of 0.8 d, where d is the footpoint separation distance. Prominences showing pitch angles below 35° and heights below 60% of the footpoint separation were stable and did not erupt.

3.3.1. Filament Evolution: Factors to Consider

The following should be taken into account when using filament observation time series to assess whether a CME is likely to occur:

- The occurrence of a slow rise phase of a filament that can be confidently identified. Slow rise plane of sky speed may be as low as a few km s⁻¹ for quiet Sun filaments, or a >10 km s⁻¹ for active region filaments.
- Prominence/filament material that reaches a height 0.8d, where d is the footpoint separation distance may be likely to erupt.

Operational H α data that can be used to monitor filament slow-rise and altitude can be gained via the GONG network, and in EUV data via GOES SUVI.

3.4. Sigmoids

The name sigmoid is given to a plasma emission structure observed in the solar corona that has a distinctive forwards or backwards S-shape (Rust & Kumar, 1996). Sigmoids are fairly common, being observed in around 6%–50% of active regions (Canfield et al., 2007; Sterling, 2000) but these shapes can also be found between active regions and in the quiet sun (where they appear much fainter). Typically, sigmoids are best identified via their soft X-ray emission, but following the launch of SDO with its multiple EUV wavebands, this type of structure has also been observed at EUV wavelengths. Figure 5 shows a sigmoid that formed in NOAA active region 11158 in February 2014. The figure shows the structure as seen in the AIA wavebands 304 Å, 171 Å, 94 Å and in soft X-rays using Hinode XRT.

Interest in sigmoids in relation to CME onset developed in the 1990s as a result of studies that showed sigmoidal shaped regions have a high likelihood of producing an eruption (Canfield et al., 1999; Pevtsov et al., 1996; Rust & Kumar, 1996). In the study of Canfield et al. (1999), sigmoidal active regions were shown to be 68% more likely to be eruptive than non-sigmoidal regions. So, their presence can potentially be used to raise an alert that an eruption might occur from that region. Sigmoids can form in active regions when they are in their emergence phase or their decay phase. For example, NOAA active region 11158 in which a sigmoid formed along the polarity inversion line created from the collision of two bipoles (Zharkov et al., 2011), versus regions NOAA 10977 that was in its decay phase (Green et al., 2011).

However, it should be noted that there is no precise and consistent definition of a sigmoid used in the research community. For example, some authors define a sigmoid to be a diffuse collection of loops that has an overall S-shape, whereas other authors require the structure to appear to be a coherent, continuous and fully formed S-shape. The subjective nature of sigmoid classification makes a comparative review of previous studies challenging as one sigmoid paper cannot necessarily be directly compared to the next.

In this section, we take a sigmoid to mean that a continuous and well defined S-shaped plasma emission structure (that does not appear to be composed of multiple loops) has formed in the solar atmosphere. At least to the resolution of the telescope used. Figure 6 shows an example of the shape of the plasma structure that we define to

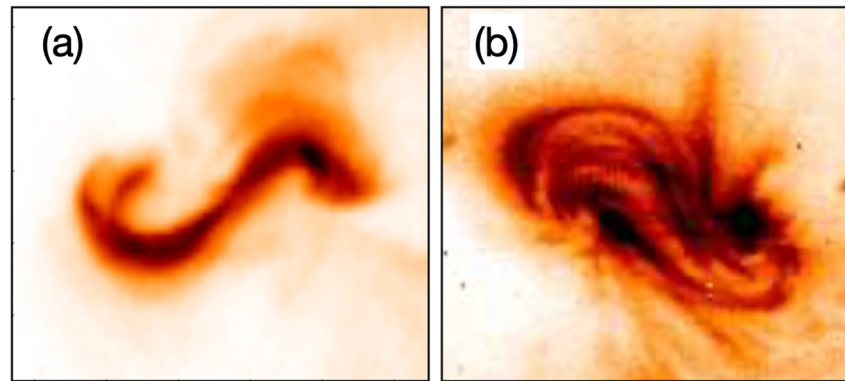


Figure 6. Panel (a) shows a continuous S-shaped structure that we use as our definition of a sigmoid, panel (b) shows a collection of loops that overall have a S-shape and which we do not class as a sigmoid. Both images are taken by the Soft X-ray Telescope on Yohkoh. Panel (a) image is from 19 December 1996 and panel (b) is from 11 December 1994.

be a sigmoid and an example of a structure that we do not count as being sigmoidal due to its apparent composition as being a series of loops. Sigmoids may have a darker section in their very centre, which interrupts the continuous S shape, that is likely due to the presence of filament material in that location absorbing EUV/soft X-ray radiation.

The formation sequence of a sigmoid is normally one that starts as an arcade, evolves into double J and then into single S shape. See Figure 1 in Green and Kliem (2014) and the case studies of Green and Kliem (2009), Savcheva and van Ballegooijen (2009), Green et al. (2011). The formation of a sigmoid appears to be driven by flows in the photosphere that bring together footpoints in a sheared arcade, either due to flux emergence or due to the dispersal of active region flux during its decay phase, following the filament/flux rope formation model of van Ballegooijen and Martens (1989). Indeed, filaments form along the same polarity inversion line as the sigmoid in many cases (Pevtsov, 2002). However, these filaments do not appear to be fully ejected during the CME process. Once a sigmoid has formed, it may erupt within 1 hr to 2 days (see Table 4).

Sigmoids may only be discernible if their structure and plasma emission dominate that of the host region so that the continuous S-shape can be seen against the overall collection of loops. Additionally, sigmoids are more readily detectable when formed in a region, that is, not too far from the centre of the solar disk, so that the viewing angle doesn't hamper the determination of the presence of an S-shape. It must be stressed that sigmoids are most readily observed in soft X-ray imaging data and these data sets are not accessible to operational space weather forecasters. Although there were operational soft X-ray data imaging provided by the Solar X-Ray Imager onboard the GOES 12 to 15 satellites (operational between August 2001 and March 2020), these telescopes are no longer included in the GOES payload. Currently available data is supplied by the X-ray Telescope onboard the Japanese Hinode mission, which does not capture full Sun images at a high temporal cadence, meaning that regions cannot be routinely monitored for sigmoid formation.

3.4.1. Sigmoids: Factors to Consider

The following should be taken into account when using sigmoids to assess whether a CME is likely to occur:

- Sigmoids that appear in soft X-ray images as well-defined continuous S-shapes indicate a high likelihood of an eruption.
- Once a sigmoid is observed, an eruption may occur in a time period of a couple of hours to one day.

Table 4

Example Sigmoidal Active Regions, Showing the Time of the Appearance of a Continuous Sigmoid in Soft X-Ray Imaging Data Versus the Time of the Eruption From the Region

NOAA no.	Time (sigmoid [UT])	Time (CME [UT])	ΔT (hours)
7790 ^a	18 October. 1994 00:45	19 October 1994 20:45	44
8005 ^b	19 December 1996 14:00	19 December 1996 15:30	1.5
8872	17 February 2000 19:15	17 February 2000 20:15	1
10977 ^c	6 December 2007 15:50	7 December 2007 04:20	12.5
— ^d	11 February 2007 21:00	12 February 2007 07:00	10
11012	18 February 2009 11:30	18 February 2009 22:00	10.5
11158	14 February 2011 23:45	15 February 2011 01:50	2
12441	1 November 2015 05:50	1 November 2015 21:30	15.5

Note. All times are estimates, given the image cadence of the telescope/observing sequence. ^aMoore et al. (2001). ^bGreen and Kliem (2009). ^cGreen et al. (2011). ^dDecayed active region with no NOAA number allocation (Green & Kliem, 2014).

Table 5

Summary of Hot Channel Appearance as Considered From Three Viewing Angles Defined by Nindos et al. (2015)

Edge-on	Face-on	Intermediate
Blob or ring-like structures, appearing to lie above structures such as flare arcades exhibiting a variety of shapes for example, Λ -shaped loop-like structures, cusp-like structures or thin stretched lines that are possibly current sheets.	Appearing to show threads of EUV emission that are twisted and writhing. Can also be seen as twisted shapes that have fuzzy and ill defined edges.	Hot channels that share features from both edge-on and face-on morphologies, without fitting into a single category, then they are defined as viewed from intermediate angles.

Soft X-ray imaging data are not available in an operational capacity. However, SDO AIA and GOES SUVI 94 Å wavebands may provide usable alternative images.

3.5. Hot Channels

A hot channel is observed as an active region-sized diffuse channel of EUV emission in wavebands such as 131 Å and 94 Å (X. Cheng et al., 2011; Nindos et al., 2015; Reeves & Golub, 2011). They have also been observed with the *Hinode* X-Ray Telescope (Reeves & Golub, 2011) and IRIS (X. Cheng & Ding, 2016). Nindos et al. (2015) studied all M-class and X-class flares that occurred between November 2010 and the end of March 2014, at longitudes equal to or larger than 50° from central meridian. 70 of these flares had an associated CME with 34/70 (49%) showing a hot channel either at the time of CME onset or before. Hot channels can be seen to form and simultaneously erupt as a CME or they can form minutes to hours prior to eruption (Nindos et al., 2015). The hot channels that form prior to their eruption have potential utility for space weather forecasting, and therefore, we focus on them in this section. The physical interpretation of a hot channel is that it represents heated plasma located in a flux rope magnetic field configuration (e.g., James et al., 2018; Patsourakos et al., 2013). The published literature uses both hot channel and hot flux rope to refer to these structures.

Hot channels that form near Sun-centre, that is, viewed from above, are seen as channels of diffuse emission, which sometimes appear S-shaped. When hot channels form away from Sun-centre, that is, they are not observed from above, three viewing angles are possible that affect their appearance: (a) edge-on, (b) face-on, and (c) intermediate angles. Table 5 and Figure 7 summarize the morphologies of hot channels viewed from these three perspectives. In addition, flare loops may form underneath, and simultaneously with, a hot channel. Events in which a flare and a hot channel form in concert, but when there is no ensuing CME, are referred to as confined events. Hot channels that form before their eruption illuminate in EUV and then fade in intensity. A series of papers discuss observational aspects of hot channels for example, (X. Cheng & Ding, 2016; X. Cheng et al., 2011, 2013; James et al., 2017, 2020; Kliem et al., 2021; Nindos et al., 2015, 2020; Patsourakos et al., 2013; Reeves & Golub, 2011; Zhang et al., 2012).

The plasma temperature in a hot channel is of the order of 10 MK and it should be noted that the temperature response functions of the AIA 131 Å and 94 Å wavebands are double-peaked, capturing emission from cooler plasma around $10^{5.5}$ – 10^6 K (Lemen et al., 2012). Therefore, hot channels that are visible in AIA 131 Å and 94 Å,

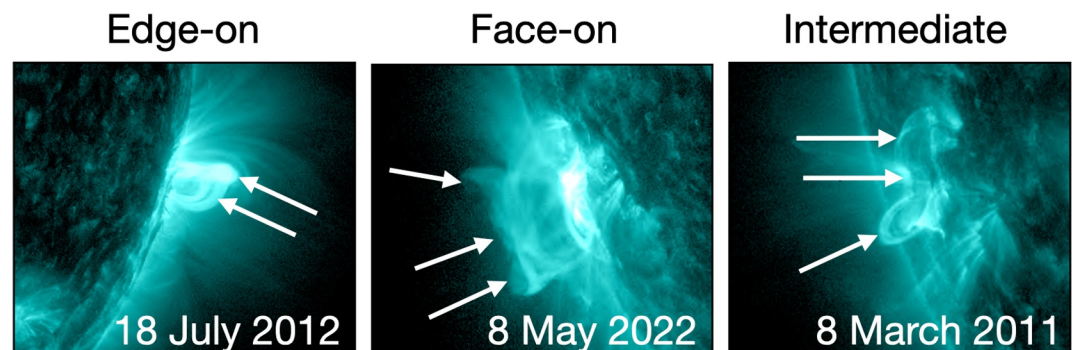


Figure 7. Hot channels seen as seen in the AIA 131 Å waveband showing three different viewing perspectives. White arrows indicate the location of the hot channel. The hot channels formed in the edge-on, face-on and intermediate cases erupted as CMEs 6 hr, 2 hr and ~1.5 hr later, respectively. Images made with JHelioviewer.

Table 6

Examples of Hot Channel Formation Time Versus the Time of the Ensuing CME, Detailing the NOAA Region in Which the Hot Channel Formed and Erupted, the Date of the CME and the Time Between Its Formation and Eruption

Study	NOAA no.	CME date	ΔT (hours)
James et al. (2020)	11429	13 March 2012	19
	11504	13 June 2012	42
	11504	13 June 2012	18
	11585	8 October 2012	63
	12665	14 July 2017	115
Nindos et al. (2020)	11171	8 March 2011	1.6
	11165	8 March 2011	9
	11302	22 September 2011	1.6
	11402	27 January 2012	1
	11429	4 March 2012	7

Note. All events are taken from James et al. (2020) and Nindos et al. (2020). These studies use slightly different methodologies and therefore have systematic differences in formation timescales.

but not in the 171 Å channel (which is peaked around $10^{5.8}$ K), can be confirmed by their absence in the cooler wavebands. Furthermore, cooler plasma emission features tend to appear sharper in 131 Å and 94 Å images, whereas hotter plasma emissions tend to be more diffuse.

A subset of hot channels, as mentioned above, form during confined flares and then remain stable for tens of minutes or even several days before erupting as a CME (James et al., 2017, 2020; Kliem et al., 2021; Patsourakos et al., 2013). This corresponds to hot channels forming via magnetic reconnection during one or more distinct reconnection episodes over several hours or days, each of which may be associated with a confined flare. The energy released by magnetic reconnection heats the plasma in the forming flux rope, resulting in the observed hot channel signatures. This can include the observation of a hot sigmoidal channel at the lower edge of the flux rope, as confirmed via magnetic modeling (James et al., 2018). The plasma structure is interpreted as being that of a twisted magnetic field containing hot (approx. 10 MK) plasma. Studies addressing the time between the formation of the eruptive structure and its eventual eruption are limited and vary in their methodology. For example, James et al. (2020) use both hot channel observations and/or confined flares to probe the timescale over which the eruptive structure forms, whereas Nindos et al. (2020) focus on direct observations of confined flares coincident with hot channel formation during an eight-hour window before the CME. Table 6 gives a summary of the results of these two studies.

3.5.1. Hot Channels: Factors to Consider

The following should be taken into account when using hot channels to assess whether a CME is likely to occur:

- The appearance of a hot channel, as seen in EUV wavebands 131 Å and/or 94 Å, is an indicator that a potentially eruptive flux rope is forming in the corona.
- The hot channel may or may not appear in association with a flare (the flare forms underneath the hot channel).
- Time between the appearance of a hot channel and its eruption as a CME may be as short as 1 hr or as long as several hours.
- It should be noted that hot channels can also appear and immediately erupt.

X-ray imagers and/or EUV channels with hot temperature responses ~ 10 MK with good spatial and temporal resolution (cadence of at least tens of seconds) are needed to observe the highly transient signatures of hot channel/flux rope formation before they erupts as a CME. Operational EUV images in the 131 Å and 94 Å wavebands are available via GOES SUVI.

3.6. Coronal Cavities and Streamer Swelling

In this section we group together two coronal structures that are observed at the limb and which may indicate the future occurrence of a CME. Given their location at the limb, these indicators will primarily be of interest when the ESA Vigil mission is launched, since Vigil's location at the Sun-Earth L5 point will mean Earth-directed CME source regions are visible at the west limb as seen from the Vigil perspective. These two structures are coronal cavities and streamers, and in fact they can be related in that a coronal cavity is often observed embedded in the base of a streamer (Fuller & Gibson, 2009).

Coronal cavities can form at high latitudes, near active regions or within active regions. A cavity is essentially the top part of a filament channel that extends high enough in the solar atmosphere and has a sufficiently depleted density compared with the sounding coronal plasma to appear dark in EUV and/or white light coronagraph data. Coronal cavities typically exist below $1.6 R_{\odot}$ (Gibson et al., 2006). Forland et al. (2013) study 19 months of AIA 193 Å observations, determining the overall shape, size and aspect ratio of the detected cavities and fitting each cavity with an ellipse to determine the cavity aspect ratio. In total, 129 cavities were identified of which 39 had an upside-down tear-drop shape (i.e., characterized by a narrower base and broader upper section), 66 were elliptical

and 24 had a semi-circular shape. Of the 129 cavities, 28% were observed to erupt. It should be noted though, that cavities are long-lived structures (days, weeks, months) and it is highly likely that there will have been eruptions involving the cavities when they were away from the solar limb, and therefore not observable. Considering cavity morphology 13% of the semi-circular cavities were observed to erupt, 17% of the elliptical cavities were observed to erupt and 56% of the teardrop cavities were observed to erupt. Cavities overall exhibited on average a width to height aspect ratio of 0.8. That is they are taller than they are wide. The study finds that 40% of cavities with aspect ratios less than this erupt, as compared to 16% for cavities with aspect ratios greater than the average. Since coronal cavities require observations of the low corona, coronagraphs with occulting disks that enable such observations, such as the K-coronagraph (K-Cor) located at the Mauna Loa Solar Observatory (Tomczyk et al., 2016), are used in addition to EUV imagery.

Early CME studies, before the availability of high-cadence EUV imaging data, often focused on streamers seen at the solar limb in coronagraph imagery. Streamers can brighten and swell over a time period of a few hours to a few days and then erupt as a CME (Illing & Hundhausen, 1986). The streamer is disrupted or destroyed as a result of the eruption leading to these events being named streamer blowouts by Sheeley et al. (1982). The swelling of a streamer that indicates an eruption is imminent can be hard to determine due to their slow nature and the need to distinguish a true rise of the streamer from the effect of solar rotation in plane-of-sky imagery. Vourlidas and Webb (2018) discuss that using base-difference images can help identify when a streamer starts to swell. Streamer swelling often includes the eruption of a prominence under the streamer, and the swelling occurs on similar timescales to the slow rise of the prominence before eruption. Vourlidas and Webb (2018) in their study of 909 streamer blowouts observed in SOHO LASCO found that the average speed of the ensuing CME was 390 km s^{-1} and that the average streamer blowout-CME duration was 40.5 hr.

3.6.1. Coronal Cavities and Streamer Swelling: Factors to Consider

The following should be taken into account when using coronal cavities and/or streamer swelling to assess likely CME occurrence:

- Critically assess the shape of the coronal cavity to identify whether a tear drop shape is present, and determine the aspect ratio of the cavity using EUV imagery.
- Ensure that true streamer swelling is distinguished from solar rotation.

Operational EUV imaging data is available via GOES SUVI at $195 \text{ \AA}$ and with the cadence required to monitor cavities as they rotate over the solar limb are available for the purposes of identifying and characterizing coronal cavities. A radial filter may need to be applied to the images to enhance the visibility of a cavity. Operational coronagraph white light imagery is only available via CCOR-1 that has an inner field of view at $3.7 R_{\odot}$. This is too high for the study of coronal cavities. CCOR-1 data are suitable for the study of streamers and streamer swelling. However, more research is needed to develop a method to confidently identify streamer swelling using these data sets. A reliable method could then be deployed using Vigil coronagraph data when they become available.

3.7. Radio Emission

In Section 2.5, we described radio emission across the different categories used in the community, including those emissions that are relevant for determining whether a CME has already occurred. Table 2 summarizes radio emission according to these categories. Here, we describe how radio emission may be useful for assessing the likelihood of future CME occurrence.

Type I radio emission in the corona is typically observed at frequencies $\sim 100 \text{ MHz}$, and exhibits no significant drift in emission frequency over several hours or even days. The frequency of emission is proportional to the local plasma density, and the emission itself is a consequence of energetic, nonthermal electrons, for example, those accelerated during a burst of magnetic reconnection. The long duration and lack of frequency drift suggest a prolonged episode of particle acceleration in a region of constant plasma density. For example, this could occur as a result of persistently driven magnetic reconnection at a single location/altitude in the corona. In this scenario, type I radio emission has been linked to the formation of a pre-eruptive flux rope that was observed in EUV images as a hot channel (James et al., 2017). When flux ropes form via a series of bursts of reconnection (each evidenced by a confined flare and hot channel signatures) in the same

part of an active region (where the plasma density is constant), the reconnection-accelerated particles interact with the local coronal plasma and can produce type I radio emission. Therefore, radio observations could help identify the formation of flux ropes, which may go on to erupt as a CME. However, more research is required to determine whether observations of type I radio emission could be used to routinely identify future CME occurrence (Vourlidas et al., 2020).

In contrast to the moving type IV radio bursts discussed in Section 2.5, which relate to a CME that is already in progress, stationary type IVs are a signature of non-thermal particles being injected into stationary structures. Similarly to type I emission, stationary type IV bursts show little to no drift in frequency over time. However, type IV bursts tend to appear broader in frequency, smoother in intensity, and longer in duration than patchy, short-lived type I bursts. The lack of frequency drift suggests that the stationary type IV emission is produced in a region of constant plasma density, and therefore the emitting structure does not change significantly in volume or altitude over time. For example, the plasma and gyrosynchrotron emissions responsible for a type IV burst may originate from low-density plasma inside a stable magnetic flux rope. Such a flux rope could later erupt as a CME, and therefore stationary type IV radio emission may indicate the presence of a potential CME precursor.

Radio imaging spectroscopy provides key spatial information, showing where radio emissions are coming from in the solar corona and therefore where potentially eruptive structures may be forming. For example, the Nançay Radioheliograph produces images of the full Sun at 10 frequencies from 150–450 MHz, corresponding to plasma densities found in the low-mid corona. NRH observes during local daylight hours in France at an image cadence of 0.225s. This provides a powerful data set for identifying not only the presence but also and location of all types of radio burst, and therefore potentially eruptive regions of interest. The NRH also measures the degree of circular polarisation of solar radio emissions, and is therefore useful for distinguishing whether the dominant mechanism that produced the radio waves was plasma emission (highly circularly polarized) or gyrosynchrotron emission (lower degree of circular polarisation). In cases in which the dominant emission mechanism is found to be gyrosynchrotron radiation, the observed radio signal may be used to infer the magnetic field strength within the emitting structure (e.g., in the magnetic structure of the CME, Chen et al., 2025).

3.7.1. Radio Emission: Factors to Consider

The following should be taken into account when using radio emissions to assess whether a CME is likely to occur:

- High cadence, multi-frequency radio observations paint a valuable picture of magnetic reconnection, particle acceleration, and the formation of potentially pre-eruptive structures in the solar corona.
- However, it is difficult to draw concrete conclusions based solely on radio observations due to a lack of real-time understanding of the coronal magnetic field structure. Radio observations should be considered alongside other data sets and tools.

Using radio emissions to support CME forecasting requires both spectral and imaging data, the latter not being available in either an operational or research capacity in near real-time. See Table A1 for details.

4. Outlook and Future Opportunities

This review highlights that there exist a wide range of data sets that together provide near real-time operational data covering the following wavebands (and cadence): H-alpha full-Sun images (min. 20 s), photospheric magnetic field (10 min), EUV (4 min), white light coronagraph (15 min), radio spectra (1s). These data sets enable the detection of CME occurrence and the opportunity to monitor regions on the Sun and assess the likelihood of future CME occurrence. See Table A1 for further details on these data sets.

The current complement of instrumentation will be further enhanced in the 2030s once the Vigil space weather mission becomes operational. Vigil will provide a perspective on the Sun 60° off the Earth-Sun line (trailing the Earth in its orbit). Meaning that solar features can be tracked by Vigil instrumentation for approx. 4.5 days before they rotate into view from the Earth. Data from the Photospheric Magnetic Field Imager (PMI) will provide vector maps of the photospheric magnetic field, enabling longer-term monitoring that will be key for those regions that evolve on timescales of days to weeks (e.g., aging active regions and quiet Sun filament channels). Rapid

emergence of complex magnetic field configurations, which can be highly CME productive, occurs over only a few days. The Vigil perspective will be especially valuable for accurate assessment of complex regions that emerge in the eastern hemisphere as seen from the Earth perspective, and which may evolve to become very active in the following days, producing Earth-directed CMEs within a short timescale. Observations of such flux emergence episodes, as viewed from the Earth perspective, will suffer from projection effects. But Vigil will observe the same region near Sun centre from its perspective. Giving more accurate magnetic field information. PMI will have a proposed cadence of 30 min. The Joint EUV Coronal Diagnostic Investigation (JEDI) onboard Vigil, will image coronal plasma in three wavebands (304/335 Å, 193/195 Å and 133 Å) using its Space Weather Operational Coronal imager (SWOC), corresponding to plasma temperatures $8 \times 10^4/6 \times 10^6$, $1.5 \times 10^6/2 \times 10^7$ and $1 \times 10^6/1 \times 10^7$ K and a field of view out to $3R_{\odot}$. Enabling the monitoring and detection of active regions, filament/prominences, coronal cavities and hot channels. JEDI's Enhanced Wide-angle Observations of the Corona imager (EWOC) will observe the corona out to $6R_{\odot}$ in the two wavebands 304 Å and 171 Å, covering 8×10^4 and 1.5×10^6 K. Enabling prominences and streamers to be monitored for a slow-rise phase. SWOC will have an image cadence of 4 min and EWOC an image cadence of 9 min, which is sufficient for identifying the observational indicators of CME occurrence discussed in this review. The Compact Coronagraph (CCOR) will enable the monitoring of coronal streamers and be able to identify their expansion before eruption. Image cadence of CCOR will be 15 min. However, there still exist operational data gaps and missed opportunities for better exploitation of existing science data for example, soft X-ray imaging and radio imaging.

5. Conclusions

Coronal mass ejections (CMEs) have been a major focus of research in heliophysics since their discovery in the early 1970s (Tousey, 1973). Given their potential geoeffectiveness, space weather forecasters are tasked with identifying CME occurrence in a timely way and using inner heliospheric models and observations to forecast arrival times at Earth. However, forecasters aspire to provide an assessment of likely CME occurrence ahead of onset time. To support the work of space weather forecasters, we provide two practical checklists to: (a) create confident assessments of CME occurrence using data sets other than those provide by coronagraphs, (b) assess which regions on the Sun are likely to produce a CME in the coming hours or days (See Appendix B). So far, no unique and identifiable observational pathway has been found toward an eruption, but indicators of a future eruption can be found if utilizing a broad range of multi-wavelength observations.

Data sets that have been specifically made for operational space weather forecasting are increasing in scope and availability. For example, compact coronagraphs (CCOR) on the GOES spacecraft and the recently launched SOLAR-I (formerly known as Space Weather Follow On Lagrange 1, SWFO-L1) mission will enable more timely identification of CME occurrence. The Vigil mission of the European Space Agency will provide a comprehensive view of the Sun, from photosphere to the corona and into the heliosphere, from the Lagrange 5 point when launched in the early 2030s. The additional viewpoint provided by Vigil will act as a catalyst for new approaches to CME forecasting, such as utilizing streamer swelling that may result in Earth-directed CMEs and benefitting from the ability to track potential CME source regions for longer durations than is possible using only an Earth-perspective. However, despite these plans there will remain gaps in key observations such as soft X-ray imaging of the corona. Although SDO AIA and GOES SUVI hot plasma emission wavebands may provide roughly equivalent images.

Given the emergence in recent years of catalogues that link CMEs observed in coronagraph data to their source region at the Sun, there now exists an opportunity to carry out statistical surveys of the evolutionary pathways towards and eruption, as well as seeking specific characteristics that regions exhibit at the time of an eruption. In particular, it is not yet known whether certain flux emergence patterns such as collisional shearing always result in an eruption, and how more information can be extracted from EUV observations of the coronal plasma structure that might indicate an eruptive structure is building. There also exists a significant opportunity for space weather forecasters to feedback their experience of using observations to assess CME likelihood to the research community.

Appendix A: Data Availability

Table A1

Table Summarizing Data Relevant for Assessing CME Source Occurrence and Future Likelihood

Data	Source	Cadence	Latency	Ground-based considerations	Operational
H-alpha imagery	GONG network	60s at a specific site, 20s across multiple sites	1 min after acquisition	Weather may limit data quality or availability	Yes
Photospheric magnetic field	GONG	10-min averages	NRT	Weather may limit data quality or availability	Yes
Photospheric magnetic field	SDO HMI	12 min	20 min for quicklook data, 3 hr for SHARP data		No
EUV imagery	GOES SUVI	4 min	NRT		Yes
EUV/UV imagery	SDO AIA	3 min (for NRT data)	NRT		No
X-ray flux	GOES XRS	1-min average data	NRT		Yes
Soft X-ray imagery	Hinode XRT	Variable	Days		No
White light corona	GOES CCOR-1	15 min	30 min		Yes
Radio spectra	US Air Force RSTN	1s	Real-time	Not affected by cloud cover	Yes
Radio spectra	YAMAGAWA	1s	Real-time	Not affected by cloud cover	Yes
Radio imaging and spectra	NRH	0.2s			No
Radio imaging and spectra	EOVSA	0.5s			No

Note. Please note: this is not an exhaustive summary but one that reflects the discussions in this review and which are of relevant to space weather forecasters. Listing operational data sets is prioritized over non-operational data sets. Operational: designed and operated to provide continuous, reliable, and real-time data for immediate forecasting and warnings. NRT: near real-time, timescale on the order of minutes. The GONG network has telescopes placed at 6 sites of differing longitude enabling 24/7 coverage of the Sun. The US Air Force RSTN has radio telescopes located at four sites. HMI SHARP data are products produced for space weather purposes.

Appendix B: Space Weather Checklists

In the absence of visual (coronagraph) confirmation of a CME, or to assist with the identification of the likely source of any CME that is observed, the following checklist can be used, with multiple occurrences adding further support.

A CME is **EXPECTED** to have occurred if any of the following are observed:

(Forecaster notes)

- GOES X-ray flare exceeding X3.0
- GOES X-ray flare of any level, persisting for a duration of ≥ 4 hr (defined from the start of the flare rise, then decreased to 0.37 the value of the peak)
- EUV Wave (crossing large portions of the corona) observed in 193 Å, 195 Å and/or 211 Å wavebands of EUV imagers.
- Observation of a Type II Radio Burst
- Observation of *moving* type IV Radio burst

Appendix B

Continued

A CME is **LIKELY** to have occurred if any of the following are observed:

- GOES flare of any level exhibiting ribbons either side of the polarity inversion line that separate from each other
- GOES flare of any level of “long duration” (although this has no strict definition)
- Coronal dimming is visible, best viewed through difference imagery and supported via multi-viewpoint observations.
- Disappearance of a filament or prominence, especially when observed in both H-alpha and EUV (e.g. 304, 193 Å wavebands).

CME is **POSSIBLE** if any of:

- GOES X-ray flare exceeding M-class
- Coronal dimming is visible from single view-point data, best viewed through difference imagery.

In order to assess the likelihood of future CME occurrence, the following checklist can be used:

CME is **LIKELY** to occur if the following are observed:

(Forecaster notes)

- Appearance of a sigmoid within an active region. High likelihood of an eruption within 1–2 hr to one day.
- Appearance of a hot channel within an active region, in 131 Å and/or 94 Å, but not in cooler wavelengths for example, 171 Å. Eruption can occur immediately or up to several hours after formation.
- Filament showing a visible slow rise. Or any filament or prominence that reaches a height of 0.8 the distance between its footpoints.
- Swelling of a streamer that is distinguishable from the effect of solar rotation. Especially if accompanied with a prominence under the streamer. Streamer swelling can last from a few hours to a few days before its eruption as a CME.

CME **MAY** occur, but further assessment needed.

- Rapid flux emergence of, or within, an active region, particularly if resulting in collisional shearing and showing departures from either or both of Hale's Law (expected polarity of the leader/trailer spots) or Joy's Law (expected tilt angle of the line connecting the leader and trailer, and the solar equator).
- Presence of a coronal cavity that exhibits a tear drop shape.
- Stationary type IV radio burst, which could suggest the presence of low-density plasma structure, such as a flux rope, potentially later erupting as a CME.

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Conflict of Interest

The authors declare no conflicts of interest relevant to this study.

Availability Statement

Data used are freely available, including in a quicklook format, via the JHelioviewer tool. JHelioviewer can be accessed via: <https://www.jhelioviewer.org>.

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