International Journal of Advance Research in Science and Engineering
Volume No. 14, Issue No. 02, February 2025
www.ijarse.com
IJARSE
ISSN 2319 - 8354

A Comprehensive Review of Coronal Mass Ejections: Observations, Classifications, and Implications Across Solar Cycles 23 and 24

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ABSTRACT

Coronal Mass Ejections (CMEs) are among the most energetic and dynamic phenomena in the solar atmosphere, playing a crucial role in space weather and interplanetary conditions. Since their discovery in 1971, extensive research has sought to define, classify, and understand their physical properties and implications. This study provides a comprehensive review of CME observations spanning 23 years (1996–2018), primarily utilizing white-light data from the Large Angle and Spectrometric Coronagraph (LASCO) onboard the Solar and Heliospheric Observatory (SoHO). It analyzes CME properties across multiple observation catalogs, including CDAW, CACTus, SEEDS, ARTEMIS, and CORIMP, to assess discrepancies in classification methodologies and parameter measurements. The study also explores the mechanisms underlying CME initiation, such as magnetic reconnection, mass-loading, and breakout models, while evaluating their broader impact on heliospheric disturbances, geomagnetic storms, and planetary magnetospheres. Additionally, observational biases, data gaps, and statistical limitations in existing datasets are discussed, with a particular focus on long-term trends and variations across Solar Cycles 23 and 24. This research aims to enhance the understanding of CMEs by integrating multi-catalog analyses, improving forecasting techniques, and refining space weather prediction models.

Keywords: *Coronal Mass Ejections, Space Weather, LASCO, Solar Cycles, Magnetic Reconnection.*

1. INTRODUCTION

Coronal Mass Ejections (CMEs) are still among the most intense and intricate phenomena seen in the solar atmosphere. They were first called "transients" when they were discovered in 1971. A widely recognized definition of CMEs has not yet been developed, despite decades of research. CMEs were first defined in 1984 when Howard et al. (1985) defined them as "an observable change in coronal structure that (1) occurs on a time scale of a few minutes to several hours and (2) involves the appearance of a new, discrete, bright, white-light feature in the coronagraph field of view." Subsequent revisions highlighted their ephemeral nature and link to coronal disruptions by characterizing them as "sudden expulsions of dense clouds of plasma from the outer atmosphere of the Sun" (Hundhausen, 1987).

In order to emphasize the observational character of CMEs, Schwenn (1996) added "appearance and outward motion," underscoring the need for a more precise definition. A different word, "Solar Mass Ejections (SMEs)," was proposed by Gosling et al. (1975), but it was not widely adopted. Another definition of CMEs was thought to be succinct, but it might be restricted since it might leave out very slow CMEs. It defined CMEs as “a new, discrete brightening over a time-scale of tens of minutes which is always observed to move outward” (Sheeley et al., 1980). According to Forbes (2000), some scholars support a definition that is more physically oriented and includes the existence of frozen-in magnetic fields as a defining feature.

CMEs are important space weather drivers that impact interplanetary conditions and geomagnetic storms, regardless of the definition. Their frequency, angular width, and speed fluctuate greatly across solar cycles, necessitating a thorough examination using several observation databases, including CDAW, ARTEMIS, SEEDS, and CACTus. The classification methods of CMEs, the differences between several catalogs, and their wider ramifications for solar physics and space weather forecasting are all examined in this paper

Large-scale eruptions known as coronal mass ejections (CMEs) are generally understood to be caused by a shift in the magnetic structure of the solar corona. Plasma is accelerated and propelled into the heliosphere by this mechanism, which transforms magnetic free energy into radiative and kinetic energy. A key factor in this occurrence is magnetic reconnection, which causes the disturbed magnetic fields to reconfigure. A number of ideas, including as the "mass- loading model" (Low, 1996), the "catastrophe model" (Forbes, 2000), the "breakout model," and the "shearing arcade" model, have been put forth to explain the initiation of CMEs.

The wide-ranging effects of CMEs on solar, interplanetary, and planetary physics make them extremely interesting. They aid in the study of solar and coronal processes by providing insight into the accumulation, storage, and release of magnetic energy in flux systems. CMEs aid in the renewal of the solar cycle by facilitating the removal of significant magnetic flux and helicity from the Sun (Low, 1996). If they lose magnetic helicity, they can also affect the solar dynamo (Low, 2001). CMEs produce heliospheric disruptions, shocks, and charged particle acceleration, which results in radio bursts and solar energetic particle (SEP) occurrences from an interplanetary standpoint. CMEs are essential to space weather research because of these factors, and their forecasting has become more and more significant. Additionally, especially in the vicinity of solar maximum, CMEs play a major role in the solar wind mass flux. When CMEs interact with planetary magnetospheres, they can amplify ring currents, increase auroral activity, and cause magnetic storms on a planetary scale. Artificial satellites, telecommunications networks, and power grids on Earth may all be seriously disrupted by such impacts.

The field of CME research has grown significantly during the last forty years. According to Aschwanden (2017), this subject has been the subject of at least 80 review articles and more than 2,000 academic papers. White-light observations from the Large-Angle and Spectrometric Coronagraph (LASCO) on the Solar and Heliospheric Observatory (SoHO) have provided the most comprehensive information on CMEs (Brueckner et al., 1995). Five main CME catalogs have been developed as a result of these observations: CDAW, CACTus, SEEDS, ARTEMIS, and CORIMP. It is necessary to analyze statistical distributions, create physical scaling rules, and look at the long-term evolution of CMEs' physical attributes in order to improve our understanding of them. All of these tasks require large datasets. Large-scale statistical analyses are still few and frequently take into account only a few physical characteristics, whereas many CME investigations concentrate on single or small groups of occurrences. Only Solar Cycle 23 (SC 23) is often covered in studies done prior to 2011, and only a small number of recent assessments go into Solar Cycle 24 (SC 24), with data available up to 2013 or 2014. Moreover, the majority of these statistical analyses use only one catalog—usually CDAW—and make scant use of CACTus.

A thorough analysis of CME observations covering SC 23 and SC 24 over a 23-year period (1996–2018) is presented in this article. In comparison to earlier coronagraphic observations from OSO-7, Skylab, Solwind, Solar Maximum Mission, and even STEREO, it provides a statistical analysis of CME features based on the longest continuous dataset available. White- light LASCO/SoHO observations and the information gathered from the five main CME catalogs—CDAW, CACTus, SEEDS, ARTEMIS, and CORIMP—are the main sources of data used in this work. To assess the accuracy of the stated CME parameters, a thorough comparison of these catalogs is carried out. An outline of previous CME observations, an examination of LASCO data and CME catalogs, and a discussion of their drawbacks and difficulties—with special attention to the ARTEMIS catalog, which has not yet been extensively utilized for statistical analyses—make up the article's framework. It also looks at observational biases that affect coronagraphic observations, including projection effects, duty cycle limitations, and visibility function constraints, as well as the appropriate corrective techniques. Lastly, the study looks into the mass distributions, intensity changes, and CME occurrence rates as reported in the accessible catalogs.

2. CMES OBSERVATIONS

The study of coronal mass ejections (CMEs) has benefited greatly from space missions since 1971, and white-light coronagraph observations are essential to comprehending the statistical characteristics of CMEs. On December 14, 1971, the coronagraph aboard the seventh Orbiting Solar Observatory (OSO-7) made the first clear-cut observation of a CME from space (Tousey, 1973). Coronagraphs aboard Skylab-ATM, P78-1 Solwind (Howard et al., 1985), and the Solar Maximum Mission (SMM) (MacQueen et al., 1980) were used for subsequent observations. In addition to measurements from Helios 1 and 2, whose zodiacal light photometers spotted CMEs in the heliosphere despite missing dedicated coronagraphs, these missions' 17 years of continuous observations yielded excellent data on CME occurrence rates.

Ground-based data from the Mauna Loa Solar Observatory (MLSO) Mark III K-coronameter helped fill the gap in space-based CME observations prior to the next major solar mission. Following the start of long-term observations by the Large Angle and Spectrometric Coronagraph (LASCO) aboard the Solar and Heliospheric Observatory (SoHO) in January 1996, five important CME catalogs were created: CDAW (Yashiro et al., 2004), CACTus (Robbrecht & Berghmans, 2004), SEEDS, ARTEMIS, and CORIMP. Using its COR2 A and B coronagraphs, the STEREO (Solar Terrestrial Relations Observatory) mission routinely performed stereoscopic imagery of CMEs from March 2007 to September 2014. The Heliospheric Imagers (HI-1) onboard STEREO and the Solar Mass Ejection Imager (SMEI) onboard the Coriolis spacecraft also tracked CMEs in the heliosphere.

The number of months of active observation was used to modify the incidence rates for incomplete years in order to maintain consistency in statistical analyses. This was especially important for datasets like CORIMP, which didn't capture any CME occurrences during several eras. We now have a far better understanding of CMEs, their evolution, and their effects on the heliosphere and planetary environments because to these missions and improvements in observation.

3. CMES LASCO OBSERVATIONS

Launched on December 2, 1995, the Solar and Heliospheric Observatory (SoHO) took off on a transfer trajectory in the direction of the L1 Lagrangian point. It experienced a modest trajectory modification on March 20, 1996, after undergoing a halo-orbit injection maneuver on February 14, 1996. April 16, 1996, marked the official transfer of the spacecraft to the scientific community.

The LASCO instrument, which consists of three coronagraphs (C1, C2, and C3), carried out its check-out operations and made sporadic observations of the solar corona throughout this phase. In early May 1996, routine synoptic observations were initiated, especially for coronal mass ejections (CMEs). The externally occulted telescopes C2 and C3 have been the main instruments for detecting CMEs among them. Whereas C3's field of view extends from 3.8 to 30 solar radii ($R_\odot$), C2's observes the corona within a range of 2.2 to 6.5 $R_\odot$. These telescopes have supplied vital information for statistical research and CME catalogs. Despite helping to identify CME, C1's operational lifespan was short—it was only in place for 2.5 years.

Routine synoptic observations utilize broadband filters, with C2 using an "orange" filter (540– 640 nm) and C3 employing a "clear" filter (420–860 nm). Images are captured in full CCD format (1024 × 1024 pixels). Prior to September 1997, due to telemetry constraints, the northern and southern polar regions of C2 and C3 images were often truncated into an equatorial band to balance field of view and cadence. This restriction was later lifted, allowing full-frame image transmission. However, between January 10 and 22, 2008, approximately 50% of recorded images were half-frame (512 × 1024 pixels), covering only the eastern hemisphere, which created challenges in generating the synoptic map for Carrington Rotation 2065.

Instrument and spacecraft problems have caused sporadic disruptions to LASCO since launch. Operations only resumed on October 22, 1998, after SoHO was inadvertently lost during a roll maneuver on June 25, 1998, creating a significant data gap. Following the spacecraft's gyroscope breakdown, which stopped observations from December 21, 1998, until February 6, 1999, there was yet another major disruption. Due to the antenna steering motor failure in June 2003, the spacecraft had to rotate 180 degrees every three months in order to maximize telemetry transmission. Up until October 29, 2010, solar north appeared either up or down in LASCO photos because SoHO's reference axis was in line with the sky-projected solar rotational axis. After this date, the reference orientation was fixed perpendicular to the ecliptic plane, which caused the projected solar rotational axis to oscillate around the vertical direction in images. Variations in stray light patterns caused these changes to affect some scientific programs, but they had little effect on CME observations.

In the early years of the mission, C2 and C3's image acquisition rates for CME investigations varied greatly until leveling off at about 67 images per day for C2. LASCO captured 971 full- format (1024 × 1024 pixels) and 4,638 reduced-format (1024 × 576 pixels) pictures between

May 10, 1996, and January 24, 2017. 3,452 full-format photos and 3,959 reduced-format images in 1024 × 768 were taken between January 1 and August 25, 1997. About 30 photos were taken in the reduced format in February 1999. The C2 cadence increased to about 117 photos per day in September 2010 after LASCO got additional telemetry after numerous SoHO devices were decommissioned. This was a significant improvement.

4. LASCO CMES' CATALOGS AND DIFFICULTIES

It is extremely difficult to identify and categorize Coronal Mass Ejections (CMEs) due to their complex and varied structures, especially when creating large event catalogs. Vourlidas et al. (2013) divided LASCO CMEs into six morphological classes in order to handle this complexity; they subsequently improved their categorization with STEREO COR2 observations (Vourlidas et al., 2017). A circular front, a cavity, and a brilliant center make up the three-part structure that distinguishes the "flux rope CME" from the other different morphologies. On the one hand, the "jet CME" is relatively thin and does not show characteristics of the other two types, whereas the "loop CME" does not have a cavity or core. Furthermore, a sizable fraction of CMEs are classified as "Other" or "Unknown," which together make up around 50% of the occurrences that COR2 records. The observed morphology of CMEs is impacted by extrinsic factors including the observer's perspective, which introduces biases into morphology-based classification, as well as by their intrinsic structural features, which are dictated by the ejection process.

A number of LASCO CME catalogs, each using different detection and characterization techniques, have been created in light of the intricacy of CME appearances. St. Cyr et al. (2000) carried out one of the first systematic investigations, examining 841 CMEs that were seen between January 1996 and June 1998 and offering statistical information on their size, speed, latitudinal distribution, and occurrence rates. Four significant LASCO CME catalogs are currently in use, and numerous attempts have been undertaken since then to construct CME catalogs. Furthermore, a separate discussion is given to the ARTEMIS catalog, which employs a distinct technique. These catalogs' disparate detection methods lead to variances in the CME attributes that are provided. Hess & Colaninno (2017) and Byrne (2015) have conducted thorough comparisons of these catalogs.

5. THE CMES ARTEMIS CATALOGS

The ARTEMIS catalogs use an automated detection and characterisation method based on synoptic Carrington maps of K-corona radiance, in contrast to other CME catalogs that depend directly on LASCO photos. The time-series LASCO-C2 "orange" pictures used to create these maps are corrected instrumentally, calibrated in mean solar disk radiance units, and resized to a standard 512 × 512 pixel format. A specialized pipeline was created by the LASCO team at the Laboratoire d'Astrophysique de Marseille for this processing, which includes creating synoptic maps and separating the K-corona component. Lamy et al. (2002) initially presented the methodology, which was subsequently improved in research by Lamy et al. (2014) and Barlyaeva et al. (2015). These unconventional synoptic maps are very useful for detecting CMEs because they simultaneously show the east and west solar limbs.

The maps are created by extracting circular profiles at various radial distances from the Sun's center, stacking them, and then evenly resampling them over time using linear interpolation to account for erratic picture capture. These maps' horizontal (x) axis shows time, moving from left to right (according to the Sun's central meridian's longitude), and their vertical (y) axis shows the solar polar angle, which increases counterclockwise from the north pole from 0° to 360°. Instead of using latitude (-90° to +90°) as in traditional synoptic charts, this format improves CME analysis. With intervals of 0.5 R⊙, the maps are produced at radial distances between 3 and 5.5 solar radii (R⊙) inside the LASCO-C2 field of view.

The ARTEMIS-I catalog was created using first-generation synoptic maps that used a consistent temporal resampling step of 27.3 days/1000 = 39.3 minutes and an angle step of 1° (Boursier et al., 2009). Later, the ARTEMIS-II catalog (Floyd et al., 2013) has temporal and spatial resolution that was optimized. Two angular increments were used: 0.25° beyond and 0.4° for radial distances of 3 and 3.5 R⊙. The time resampling step was also adjusted to 27.3 days/1440 = 27.3 minutes, which is equal to about 67 photos per day and closely matches the average temporal cadence (~21 minutes) of LASCO-C2 images over a 12-year period (1999–2010). To prevent bias in the dataset, the synoptic maps' temporal resolution was kept at 27.3 minutes even though the cadence rose to about 118 photos each day starting in September 2010.

6. KINEMATICS

6.1 CMES'S APPEARANT SPEED

A number of reasons make determining the apparent speed of coronal mass ejections (CMEs) via coronagraphic imaging a challenging task. First, the initial acceleration patterns of CMEs vary, even though most of them retain relatively constant speeds beyond about 2R⊙. As they move through the LASCO-C2 and C3 fields of view, slow CMEs frequently accelerate while fast CMEs typically decelerate (Webb & Howard, 2012). Thus, CME catalogs that use both LASCO-C2 and C3 photos (e.g., CDAW and CACTus) and those that only use C2 images (e.g., ARTEMIS and SEEDS) differ from one another. Secondly, it is oversimplified to attribute a single speed figure to a CME since the many components of the ejection move at different speeds. To account for these variations, a velocity field would need to be constructed (Boulade et al., 1997; Robbrecht & Berghmans, 2004; Colaninno & Vourlidas, 2006; Byrne, 2015) in order to depict the situation more accurately.

6.2 CME SPEEDS' VARIABILITY ACROSS DIFFERENT CATALOGS

The structural elements of coronal mass ejections (CMEs) and the methods employed to calculate velocity in various catalogs affect the apparent speed of these objects. In general, a CME's front part moves at the fastest speed, with the side and back parts moving more slowly.

Different methods are used by different CME catalogs to estimate speed. Following an initial approximation using propagation velocity, the "global" velocity in the ARTEMIS catalog gives greater weight to the fastest and brightest regions, mainly the front and central portions. On the other hand, all angular parts of the CME are given equal weight by the "median" velocity. The peak identified by leading-edge segmentation is used by the SEEDS catalog to calculate speed. The median value of a linear speed profile across the angular width of the CME is reported by CACTus. In order to determine speed, CDAW fits a straight line to height-time measurements at the quickest segment. This is known as the measurement position angle (MPA), and it may not always coincide with the central position angle (CPA), especially for CMEs that do not propagate radially.

Analyzing CME speeds across 23 years of LASCO data reveals some interesting patterns. Lower velocities are found in speed distributions during solar cycle minima, especially during the unusual minimum that occurs between Solar Cycles 23 and 24. Furthermore, there is a little propensity for CMEs to move more slowly in Solar Cycle 24 than in Solar Cycle 23.

When speed distributions from several catalogs are compared, two clear categories show up. While the ARTEMIS "global," CACTus, and CDAW speeds peak at 250–300 km/s, the ARTEMIS "median" and SEEDS speeds peak at 150 km/s. This is consistent with the corresponding ARTEMIS weighting schemes, but a surprising result is found: SEEDS, which was predicted to correspond to the "global" and CDAW speeds, instead corresponds to the ARTEMIS "median" distribution. Similarly, the CACTus distribution more closely resembles the "global" and CDAW distributions, even though it was predicted to fit the ARTEMIS "median" profile. Additionally, cumulative speed distributions show a smaller spread in Solar Cycle 24 than in Solar Cycle 23, which is a pattern that has been repeatedly observed in previous studies.

7. CYCLE-BASED VARIATIONS AND HIGH-SPEED CME ANOMALIES

Concerns regarding possible overestimation are raised by the CACTus catalog's anomalous excess of high-speed CMEs that exceed 1000 km/s and reach up to 2000 km/s. This pattern is not seen in other datasets.

Significant variations between Solar Cycles 23 and 24 are revealed by analyzing the annual evolution of the mean and standard deviation of CME speed distributions from several catalogs. With maxima of about 250 km/s for SEEDS, 400 km/s for ARTEMIS, 550 km/s for CDAW, and 600 km/s for CACTus, the mean speed figures for Solar Cycle 23 varied greatly. The results from all libraries, however, converged in Solar Cycle 24 within a more constrained range of roughly 300–400 km/s. The mean speeds during solar cycle minima are consistently lower in ARTEMIS and CDAW data, while SEEDS only faintly exhibits this trend and CACTus does not exhibit it at all. It is interesting to note that CACTus data experienced a sharp decline in reported speeds after 2009, which is more consistent with other catalogs—perhaps because extremely high-speed events were excluded.

8. VARIABILITY AND TRENDS IN THE ANGULAR WIDTH OF CMES

A CME's angular width (WWW), which is affected by geometric effects and projection, shows how wide it is in the sky plane. Furthermore, it usually rises as the coronal CME expands. Although different catalogs use different measurement techniques, the general patterns are generally the same. Two significant trends emerge from a comparison of the angular width distributions across 23 years of LASCO data. First, whereas wider CMEs show clear changes between Solar Cycles 23 and 24, CMEs narrower than 180° show similar distributions across both cycles. Second, various datasets produce different results when only CMEs with widths less than 180° are taken into account. With ranges ranging from 30° to 60°, the CDAW catalog lists the widest

CMEs. ARTEMIS, CACTUS, and SEEDS are next in line with values between 22° and 42°, 24° and 34°, and 18° and 28°, respectively.

While SEEDS and CACTus show a more constant range of about 10°, CDAW and ARTEMIS show the most noticeable variances between the solar minimum and maxima (30° and 20°, respectively). The temporal variations in CME angular width typically follow the solar cycle. Although these variations are a result of different measuring methods, the general trends are consistent with patterns of solar activity.

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