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Coronal transients during two solar minima: their source regions and interplanetary counterparts

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Abstract. We have investigated two full solar rotations belonging to two distinct solar minima, in the frame of two coordinated observational and research campaigns. The nearly uninterrupted gathering of solar coronal data since the beginning of the SOHO era offers the exceptional possibility of comparing two solar minima for the first time, with regard to coronal transients. This study characterizes the variety of outward-travelling transients observed in the solar corona during both time intervals, from very narrow jet-like events to coronal mass ejections (CMEs). Their solar source regions and ensuing interplanetary structures were identified and characterized. Multi-wavelength images from the space missions SOHO, Yohkoh and STEREO, and ground-based observatories were studied for coronal ejecta and their solar sources, while in situ data registered by the ACE spacecraft were inspected for interplanetary CMEs and magnetic clouds. Instrumental aspects such as dissimilar resolution, cadence, and fields of view are considered in order to discern instrumentally-driven disparities from inherent differences between solar minima.

Keywords. Sun: corona, Sun: coronal mass ejections (CMEs), Sun: activity, solar wind

1. Introduction

The Whole Sun Month (WSM) and the Whole Heliosphere Interval (WHI) consisted of two series of coordinated efforts carried out almost 12 years apart during two consecutive solar minima, covering the periods August 10 - September 8, 1996 and March 20 - April 16, 2008 respectively. The characterization and modeling of the large-scale solar minimum corona in connection to in-situ observations of the solar wind and interactions with Earth are among their main goals. The campaigns led to a wealth of in-depth studies of the solar corona's configuration during those solar minima (e.g., Gibson *et al.* 1999, Riley *et al.* 1999, Gibson *et al.* 2009, Gopalswamy *et al.* 2009, Landi & Young 2009). Only the two latter papers directly deal with coronal mass ejections (CMEs), key drivers of space weather; while only Gibson *et al.* (2009) have explored differences between two solar minima, i.e. between WSM and WHI, though focusing on solar wind high-speed streams.

This survey attempts to gain insight into intrinsic dissimilarities of the solar ejective aspect, during two solar rotations of two distinct but consecutive solar minima, whilst distinguishing from instrumentally-produced effects (see Cremades *et al.* 2011). It considers all distinguishable types of ejecta, from the most impressive wide and bright CMEs to the narrowest and faintest events, as well as their possible in situ counterparts.

2. Identification of events

The proposed approach to compare the ejective aspects of these two particular solar rotations requires the inspection of the coronagraph data available during those time intervals. These catalogs were consulted and taken as a basis: The SOHO LASCO CME Catalog at the CDAW Data Center, the list by O. C. St. Cyr at the SOHO LASCO NRL website, the COR1 CME Catalog at NASA GSFC, and the COR2-based CACTUS list of detections at the Royal Observatory of Belgium. Moreover, this study tends to complement independent surveys by Sterling (2010), Webb *et al.* (2010), and Webb *et al.* (2011). In particular, we have considered all kinds of “clustered” outward-traveling material in the white-light corona as coronal ejecta. This broad criterion includes not only bright, significant CMEs but also extremely faint ones, as well as thin and narrow jets. Data from the SOHO/LASCO C2 coronagraph were inspected for ejective activity both during WHI and WSM. The images have a pixel size of 11.2 arc sec and a spatial coverage of 2.2-6.0 Rs. During WSM, the practical cadence rarely overcame two images per hour, while the field of view (FOV) was frequently cropped from the full 1024 × 1024 pixels to 1024 × 576 centered on the Sun. During WHI, inspected data also included STEREO SECCHI COR1 and COR2 coronagraphs. The inner COR1 coronagraph covers 1.4-4.0 Rs with a pixel size of 7.5 arc sec, while the outer COR2 extends from 2.0 to 15 Rs with a pixel size of 14.7 arc sec. During WHI, COR1 and COR2 recorded images with a cadence of 20 and 30 minutes, respectively.

A total of 45 (in LASCO C2) and 143 (in LASCO C2, COR1A&B, and COR2A&B) were found respectively in each of these solar rotations. The number of ejective events identified by us in data of each instrument exceeded the numbers reported by the respective catalogs, likely because of the strict selection criteria we systematically followed. Out of the 143 events identified during WHI, 84 were observed by LASCO C2, 131 by COR1A and/or B, and 85 by COR2A and/or B.

3. Coronal events and candidate sources

The identified ejecta for both investigated time periods were classified according to their white-light appearance, into: i) CMEs, bright, significant, “conventional” events as defined by Hundhausen *et al.* (1984); ii) Faint CMEs, similar but weak compared to the background corona, hence frequently not reported by catalogs; iii) Jets, very narrow and fast ejecta (see e.g., St. Cyr *et al.* 1997); and iv) Streamer-swelling events, persistent outward flows of material, commonly at equatorial streamers.

Table 1 contains the number of ejective events identified during WSM and WHI, sorted according to the above categories. The number of all ejecta types during WSM is significantly lower than those during WHI, except for the “Streamer Swelling” kind. The latter seems to have been characteristic of Cycle 22’s solar minimum, which portrayed well-formed polar coronal holes (CHs), an almost lack of low-latitude ones, and a streamer belt confined to equatorial latitudes. The situation during Cycle 23’s solar minimum was radically different, implying a more complex global coronal structure, likely hindering persistent outflows of the streamer-swelling type. Jets are usually very fast events, prone to occur at polar position angles, and best detected at low heights and if travelling in the plane of the sky. LASCO C2’s lower cadence and frequently cropped FOV at the poles thus made their detection difficult during WSM; while COR1’s lowest threshold

Table 1. Types of ejecta identified during both time intervals.

	CME	Faint CME	Jet	Streamer Swelling
WSM	14	7	16	8
WHI	29	30	84	0

altitude and stereoscopic view allowed the detection of a large amount of jets during WHI. LASCO C2 Faint CMEs during WHI were double those during WSM, also likely due to the poorer cadence during WSM. Many of the faint CMEs are evident only when viewed in consecutive images, because the human eye is very sensitive to the motion of an organized structure rather than by the structure itself. Thus, having fewer images of a faint event implies that there is less of a chance of detecting it.

From the above analysis it could be generalized that the "conventional" CME rate during WHI was double that during WSM also because of instrumental differences between both periods. However, WSM cadence was good enough to detect fast CMEs, while the cropped FOV at the poles should not be a limitation since CMEs at WSM times typically travelled close to equatorial latitudes. The comparison between observations registered by the same instrument (LASCO C2) thus reveals an inherent difference in this category of ejecta, independent of instrumental issues.

Candidate source regions could be recognized for 27 out of the 45 ejective events identified during WSM, while candidate sources for the WHI period could be deduced for 89 of the 143 events. Low-coronal data were inspected for eruptive signatures: images from SOHO/EIT and Yohkoh/SXT were used during WSM, and from SOHO/EIT and STEREO SECCHI/EUVI during WHI. The latter extended the Sun's longitudinal coverage to almost 230°. $H\alpha$ data from the Global High-Resolution $H\alpha$ network were inspected for flares, filament disappearances, and erupting prominences.

After careful inspection of eruptive signatures, four types of source regions could be discerned: active regions (ARs), quiescent filaments, bipoles in quiet Sun locations, and bipoles within or at the boundary of coronal holes, both polar and low latitude. Table 2 summarizes the productivity of each of these during both time periods. Active regions appear to have played a major role as sources of white-light ejecta during WSM. Out of the 18 identified transients from ARs, nine seemed to originate from AR 7981, one in AR 7982, and eight in unnumbered ARs. However, during WHI all AR sources were numbered (10987-10990). On the quiet Sun, quiescent filament disappearances represent a small fraction of the identified candidate sources in our survey. The number of bipoles within/next to coronal holes as source candidates drastically increased during WHI with respect to WSM. This can be attributed to the low operational cadence of SOHO/EIT and Yohkoh/SXT, far from enough to detect such a fast episode as the launch of a jet, except for a few fortunate cases. Bipoles not associated with CHs were scarce, accounting for $\sim 18\%$ of jet sources. Jets are mainly produced by bipoles, and associated with ARs only in exceptional cases. Unidentified source regions represent doubtlessly the largest fraction. A smaller amount of unidentified sources during WHI is likely not only related to instrumental differences between both periods, but also to the fact that STEREO could survey a larger portion of the solar sphere, thus being able to observe part of the Sun's far side.

Table 2. Source region types observed during both time intervals.

	Active Region	Quiescent filament	CH-related bipole	Quiet Sun bipole	Unknown
WSM	18	1	5	1	20
WHI	17	12	49	11	54

4. Interplanetary Structures

In situ data from OMNI and from the Advanced Composition Explorer (ACE), respectively, were inspected during WSM and WHI to find solar wind structures potentially associated with the identified transients. The criteria to select interplanetary structures required the existence of magnetic field higher than the surroundings, low proton temperature, low plasma β, and large and coherent rotation of the magnetic field vector. We could ascertain seven candidates to transient interplanetary structures in the OMNI (Wind) data for the WSM period, while only five could be discerned in the ACE data for WHI. The identified structures consist of small flux ropes and even one magnetic cloud (MC) candidate during WHI. Unfortunately, it was not possible to identify their potential source regions at the Sun. The small magnitude of the events and the lack of obvious eruptions in the appropriate time windows, hindered possible associations. It is worth noting that the identified small flux ropes could have been locally generated within the solar wind due to magnetic reconnection across the heliospheric current sheet (Moldwin *et al.* 2000), thus not strictly solar in origin. Still, Feng *et al.* (2007) found continuous size and energy distributions between large and small flux ropes, suggesting a broad range of CMEs, from large and bright to weak ones, hard to detect with coronagraphs.

5. Conclusion

This analysis provides insight into the ejective aspect of two solar rotations during two consecutive solar minima. The high detection rate of ejective events is notably higher for the WHI period, explained by the improved cadence, resolution, and longitudinal coverage achieved by the SOHO and STEREO missions during WHI. However, the elevated number in the case of "conventional" CMEs cannot be accounted for by instrumentally-driven disparities, given the high contrast and extension exhibited by this type of events. Source region identification of the analyzed ejective events was less ambiguous during WHI, while in WSM poor spatial coverage and lower cadence introduced large uncertainties. Large active regions were present in both periods, though with no apparent impact on geomagnetic activity: geoactivity parameters were exceptionally quiet during WSM, while the connection with Earth during WHI was due to recurrent high speed streams (Gibson *et al.* 2009). Investigation of in situ data yielded no significant MC or interplanetary CME at 1 AU, though some candidate flux rope structures could be recognized in both rotations.

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