Coronal Hole-Active Region-Current Sheet (CHARCS) Association with Intense Interplanetary and Geomagnetic Activity

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Abstract

Intense geomagnetic storms ($Dst \leq -100\ nT$) have been associated with *interplanetary* structures involving large-intensity ($B_s \geq 10\ nT$) and long-duration ($T \geq 3$ hours) *values* of the southward component *of the IMF. We show* that near solar maximum, the *solar* origin of such structures *seems to be* associated with active regions (flares and/ or filament eruptions) occurring *close to the streamer belt* and to growing low-latitude *coronal holes. It* is *also shown that such* type *of* coronal holes, had a dual-peak *solar cycle* distribution during *solar* cycle *21, similar* to that *previously* reported *for* the *above* mentioned interplanetary *and* geomagnetic *phenomena*.

1. Introduction. Although there has been considerable amount of work published about the general role of solar Coronal Mass Ejections (CMEs) in the development of interplanetary and geomagnetic activity [e.g. Sheeley et al., 1985; Gosling et al., 1991], very little information exists about the specific nature of the CMEs involved in such a solar- interplanetary-geomagnetic coupling [e.g. Dryer, 1994].

It is the purpose of this letter to examine some new solar aspects of this coupling for the 10 intense geomagnetic storm events that occurred in the interval of August 1978 - December 1979, as studied initially by Gonzalez and Tsurutani [198'7]; Tsurutani et al. [1988]; Tang et al. [1989] and Gonzalez et al. [1989].

2. Solar features of the 1978- 1979 events. During the interval of August 16, 1978, and December 28, 1979, ten intense magnetic storms ($Dst \leq 100$ nT) were associated by Gonzalez and Tsurutani [1 987] with interplanetary structures having southward magnetic fields of large amplitude ($B_s > 10$ nT) and long duration (T $\geq$ 3 hours). For this study, these authors used continuous plasma and magnetic field data collected by the ISEE-3 satellite at its halo orbit around the L_1 Lagrangian point of the sun-earth system. Later, Tsurutani et al, [1988] studied in more detail the types of these interplanetary structures, from which about half were found to be of the *driver gas* type and half of the *sheath field* type.

Subsequently, with the interest of learning where at the sun and to what type of solar phenomena these interplanetary structures could be associated with, Tang et al. [1989] reported a list of possible *solar* sources involving flare or prominence eruption candidates, which could have occurred about 2 to 4 days prior to the geomagnetic storm onset. The flares ranged from MI to X2 in peak soft X-ray emissions. However, the largest of the ten storms ($Dst \approx$ - 200 nT) as well as the strongest shocks (magnetosonic Mach Number > 3.0) were associated with prominence eruptions.

Clearly we realize that the flares and/or prominence eruptions are not causing CMEs, but that some phenomena at the sun are causing both and we can use the solar events as a marker for when and roughly where the CME was released. We also realize that flares generally occur at one footpoint of the CME and that the actual location of the center of the CME is unknown, but we can say we know the general location of the CME. With respect to the controversy on the role of flares/filament eruptions and CMEs [e.g. Miller, 1995] our position assumes that some solar condition leads to both, the flares and the CMEs. One does not "cause?' the other, but both are "caused" by the same phenomenon.

In this paper we try to study solar phenomena, which together with that reported by Tang et al. [1989] may help us to better understand the solar source of the intense interplanetary and geomagnetic activity during the 19'78-19'79 interval. In addition to the *active region* information provided by Tang et al. [1989], and recently complemented by the work by Bravo and Rivera [1994], We have studied the location and dynamics of low-latitude coronal holes and of the heliospheric current sheet at its solar base. The location of coronal holes were studied following the works by Hewish and Bravo [1986] and by Gonzalez and Tsurutani [1994], and updated with revised data published by the NOAA-Boulder Solar Geophysical center, using H_α synoptic charts as well as HeI observations. The location of the current sheet was obtained from H_α synoptic charts [McIntosh et al., 1991] and supplemented by the Stanford maps [Hoeksema and Scherrer, 1986]. It is important to mention that a better quality and more complete information about H_α and HeI observations is available only from Carrington rotation 1678 onwards [McIntosh et al., 1991].

Figure 1 shows, in Carrington rotation plots, the relationship between coronal holes, active regions (flares and/or prominence eruptions) and the current sheet (CHARCS) for the ten events during the 1978-1979 interval of study. Among the low-latitude coronal holes present in each rotation, those nearby the active regions are indicated by hatching, the current sheet section nearby them is indicated by a dashed curve and the active regions are marked by an X if they are flares or by a dotted line if they are prominence eruptions. In each Barrington rotation the small vertical arrow at the top indicates Central Meridian at the time of the active region onset. Note that during this (maximum) phase of the solar cycle the current sheet is highly inclined at low latitudes, as one can see in the sections plotted for these events.

The most important aspect of Figure 1 is the co-existence of three closely spaced phenomena: low latitude coronal holes, active regions and the current sheet, as a combined solar source for the ensuing solar, interplanetary and geomagnetic active events. We have not examined this relationship, for other time intervals yet. However, the fact that this CHARCS association exists for practically each of the ten events of the 1978-1979 interval is, in our opinion, quite interesting and may lead to greater understanding of the release mechanism(s).

In Figure 1, events 1,3 and 8 have, as active regions, prominence eruptions only; events 2, 4, 6, 7 and 10 have flares only; whereas events 5 and 9 have both, *flares* and prominence eruptions. In event 3, besides the CHARCS association indicated at the northern hemisphere, there is another possible CHARCS candidate at the southern hemisphere. Among the CHARCS candidates only the one for event 5 is in question duc to the poor information existent in this case, both for the prominence eruption as well as for the coronal hole.

It is important to note that for some of the events (1, 4, 8, 9 and 10), the coronal hole appears bounded by the current sheet from both sides and that for these events there is a tendency for recurrent CHARCS, for at least two consecutive solar rotations. Other interesting features in Figure 1 are that the solar CHARCS events occurred mostly at low latitudes and near central meridian. We leave for the discussion section the possible geo-effective importance of these characteristics of the CHARCS.

About the temporal evolution of the coronal holes we have noted that this type of coronal holes seem to change their area very fast prior to and in association with the active region event. Within the HeI daily data, scarcely available for the interval of our study, we have noted that the area of the hole tends to grow towards the active region from where the CME probably originated. For instance, Figure 2 shows the evolution of the coronal hole for event 9 of Figure 1, namely prior to the active region manifestation of August 26, 1979. At the top of Figure 2 we show the H_α synoptic chart for the Barrington rotation 1685 where the positive and negative photospheric magnetic field polarities are indicated together with the coronal hole (CH) regions. AR stands for active region, in this case associated with the flare indicated by an X-mark in the event 9 of Figure 1. At the bottom of Figure 2, we show the evolution of the coronal hole for about 3 to 2 days (above) and 1 day (below) before the active region event. The coronal hole is identified as a white area surrounded by a black curve whereas the active region at the left of the coronal hole can be seen as a dark region, becoming more intense and closer to the growing coronal hole about a day before the flare event. In these HeI

pictures one can also notice at the right of the figure a dark and sharp elongated region , which is the filament indicated in event 9 of Figure 1. It is interesting to see the large change (growth) of the coronal hole prior to the date of the active region event. Unfortunately there was no coronal hole data for the same day of the event. This same lack of data, right at the time of the active region event, also occurred with other cases of our interval of study. However for case 4, the largest growth in the coronal hole area occurred on the same day of the active region event (although for this case the coronal hole and magnetic polarity data were not processed as clearly as for case 9, shown in Figure 2).

3. **Solar cycle variability of low-latitude coronal holes.** Gonzalez et al. [1990] have studied the solar-cycle variability of intense geomagnetic storms ($Dst \leq -100$ nT) as well as of interplanetary B_s events of large intensity (≥ 10 nT) and long duration (≥ 3 hours), both for solar cycle 21. They showed that both distributions have a dual-peak, the less intense one occurring about a year before solar maximum (sunspot number), and the more pronounced one occurring 2 to 3 years after maximum.

Figure 3 shows the solar cycle distribution, for the same cycle 21, of the number of low latitude coronal holes (within $\pm 30°$ of the equator) according to HeI observations. It is interesting to note that this distribution is also of a dual peak type, with the peaks corresponding to those reported by Gonzalez et al. [1990].

4. **Discussion.** As presented in Section 2, a clear CHARCS association exists for 9 of the 10 intense storms of the 1978-1979 interval. If we assume that this association is not coincidental, we need to look into its possible physical meaning and implications.

The association of active regions (AR.) with the current sheet (CS) is perhaps the most straightforward to explain at the moment, since they form the basic ingredients of the widely discussed coronal mass ejection (CME) phenomena [e.g. Hildner, 1977; Kalher, 1987; Webb, 1991; Hundhaussen, 1993]. The current sheet is the main site of the helmet streamers, which can lead to CMEs with related flaring and/or prominence eruptions [e.g. Low, 1993]. Thus it is natural to expect, as seen in Figure 2, that the observed active regions are practically lying on the current sheet demarcation (dashed line).

Since it is known that CMEs are associated with enhanced intervals of interplanetary and geomagnetic activity [e.g. Gosling, 1991], what the information presented in Figure 1 could be showing us is that CMEs need to occur close to low-latitude coronal holes in order to lead, as a combined solar source (CHARCS), to more intense interplanetary and geomagnetic activity. In other words, CHARCS could be regarded as a highly gee-effective class of CMEs.

If this hypothesis becomes substantiated by a larger data base study similar to the presented one, the CHARCS association can become an important observational tool to help us predict the occurrence Of intense geomagnetic activity. At the moment there are some preliminary ideas about the possible role of coronal holes in the gee-effective character of the CHARCS association:

1. Since the coronal holes involved in the ten storm events of the 1978- 1979 interval occurred mostly near central meridian and at fairly low-latitudes, the interplanetary open magnetic field lines rooted in such coronal holes could serve as effective *transmission* lines between the sun and the earth for the propagation of the ejected material and of its effective arrival to earth.

2. The different open magnetic topology of coronal holes nearby that of a closed helmet streamer base could help to destabilize the current sheet and the nearby potential active regions [Low, private communication, 1993; and Low, 1993]. Further this combined open-closed topology may be considered as an ideal one from an energetic point of view as far as the overall energy release is concerned [Priest, private communication 1992].

3. Tsurutani and Gonzalez [1987] and Gonzalez and Tsurutani [1995] have discussed the gee-effective importance of large amplitude, interplanetary Alfvén waves in leading to enhanced geomagnetic activity and in some cases to intense geomagnetic storms, as the ones involved in the 1978-1979 interval of our present discussion. Since these Alfvenic fluctuations are known to be originated mainly at the coronal holes [e.g. Hollweg, 1978; Tsurutani et al., 1994], the Alfvenic solar wind rooted at the CHARCS coronal holes can in several instances serve as a seed for the formation of intense southward fields [Gonzalez et al., 1995].

However from the overall behavior of the CHARCS, as learned from Figures 1 and 2, one could also suggest the following points:

(a) The coronal hole tends to grow in area with the release of a CME at the helmet streamer, namely more closed field lines become open,

(b) The coronal hole can persist for more than a solar rotation (as in events 1 and 2, 4 and 6, and 9 and 10) and re-activate the CHARCS behavior.

(c) 'This type of low-latitude holes could have initially originated from a CME release (opening of closed field lines at a helmet streamer) and evolved through further CME releases, not necessarily being all gee-effective due to several possible limitations, such as low speeds and large distances from central meridian. In fact the other (not hatched) coronal holes shown in Figure 1 may have not been geo-effective due to those (or other as yet unknown) limitations. However the CHAR. CS-holes could have also originated from detachments or extensions of larger high-latitude holes [McIntosh, 1993]. Some evidence of this latter possibility can be observed in events 3, 4, 6, 8 and 9, the latter evolving to an attachment again with a high-latitude hole, as observed in event 10.

(d) Finally, as observed in events 1, 4, 8, 9 and 10, part of the geo-effective character of the CHARCS could be due to the behavior of the hole when it appears bounded by helmet streamers at both sides (enhancing perhaps in this situation a pressure influence by the hole-open fields on the helmet-streamer closed fields towards a destabilization at the latter and a consequent CME release). It is interesting to note that these events seem to also show a recurrent behavior, namely the CHARCS recurring at least during two consecutive solar rotations.

It is also important to point out that the opening of helmet-streamer closed field lines by a CME, enlarging the area of the nearby hole in a CHARCS configuration, could involve a large velocity jump from typical low helmet streamer speeds (around 350 Km/s or so) to much higher coronal hole speeds (around or larger than 700 Km/s), which could lead to a formation of a fast forward shock leading the ejected plasma. This appears to be in accord, at least partially, with the claiming by Hewish and Bravo [1 986] and Bravo [1995] that coronal holes are the sources of interplanetary shocks during transient solar phenomena, such as those studied in this article.

Since the CHARCS relationship study of Section 2 involves only the interval of 1978--1979, the information given in Figure 3 can be regarded as a possible confirmaion during a longer time interval about the importance of the role of low latitude coronal holes in the solar origin of transient interplanetary and geomagnetic enhanced activity. It is interesting to point out that the coronal hole distribution of this figure shows a similar dual-peak as those shown by the intense interplanetary and geomagnetic disturbances reported by Gonzalez et al. [1990] for solar cycle 21. Since the solar cycle distribution of CMEs is known to follow that of the sunspot number [e.g. Hildner, 1997; Webb, 1991], we do not know at the moment if the presence of coronal holes in the CHARCS make the CMEs geo-effective for the development of intense storms, or if some, as yet, unknown class of geo-effective CMEs, not necessarily involving coronal holes, could also lead to the development of intense interplanetary and geomagnetic events, showing a dual-peak solar cycle distribution as well.

Acknowledgments. The authors would like to thank the supp given by *Fundo Nacional de Desenvolvimento Científico e Tecnológico de Brasi* and by the *Space Environmental Laboratory of NOAA*. Portions of this work were done at the *Jet Propulsion Laboratory, California Institute of Technology*, Pasadena, under contract with NASA, one of the authors (W.D.G.) would also like to thank the National Research Council of the Academy of Sciences for support during his research associateship residence at the Space Environmental Laboratory of NOAA in 1993. The authors have benefited from discussions with A. Hewish, E. Hildner, J. A, Joselyn, M. Dryer, S, Bravo and N. Srivastava.

Figure Captions

Figure 1. Barrington rotation maps of CHARCS for the ten events of the 1978-1979 interval. Solar active regions are indicated with X marks for flares and dotted lines for prominence eruption. The nearby current sheet section(s) are indicated with a dashed curve and the syarb coronal hole is indicated with hatching. The small arrow at the top of each map indicates Central Meridian at the onset time of the observed active region event.

Figure 2a. H_α synoptic chart for Barrington rotation 1685, involving event number 9. The white (gray) areas have positive (negative) magnetic polarities and the darker regions show coronal holes. The active region of this event is also indicated as AR nearby the coronal hole (CH) at about 10° N latitude.

Figure 2b. *HeI* pictures of the evolving coronal hole for event number 9, shown as white areas (surrounded by a black curve) for about 3 to 2 days (top) and 1 day (bottom) prior to the active region onset on day August 26,1979. The large dark area nearby the coronal hole is the active region whereas the dark elongated feature at the other side of the corona] hole is the filament (indicated also in Figure 1 for this event).

Figure 3. Yearly number of low latitude (within ±30°) coronal holes for solar cycle 21 together with the smoothed sunspot number curve.

References

Bravo, '(A solar scenario for the associated occurrence of flares eruptive prominences, coronal mass ejections, coronal holes, and interplanetary shocks". Solar Phys., in press, 1995.

Bravo, S.; Rivera, A.I.., "The solar causes of major geomagnetic storms". Ann. Geophysicae, in press, 1995.

Dryer, M., "InterPlanetary studies: Propagation of disturbances between the sun and the magnetosphere". Space Sci. Rev., 67, 363, 1994.

Gonzalez, W.D.; Tsurutani, B.T. "Criteria of interplanetary parameters causing intense magnetic storms ($Dst < -100nT$)". Planet. Space Sci., 35: 1101, 1987.

Gonzalez, W. D.; Tsurutani, B.T.; Gonzalez, A. L.C.; Tang, F.; Smith, E. J.; Akasofu, S.1. "Solar wind-magnetosphere coupling during intense geomagnetic storms (1978-1979)". Journal of Geophysical Research, 94(A7): 8835, 1989.

Gonzalez, W. D.; Tsurutani, B.T., "Interplanetary-magnetosphere coupling from ISEE-3". Proceedings of the 1992 STEP Symposium/5th COSPAR Colloquium . In *Solar Terrestrial Energy Program*, ed. D.N. Baker, V.O. Papitashvili and M.J. Teague, Pergamon Press, pp 97-204, 1994.

Gonzalez, W. D.; Gonzalez, A. L.C.; Tsurutani, B.T. "Dual-peak solar cycle distribution of intense geomagnetic storms". Planet. Space Sci., 38(2): 181, 1990.

Gonzalez, W.D.; Gonzalez, A. L.C.; Tsurutani, B.T., "Geomagnetic response to large-amplitude interplanetary Alfvén wave trains". Physical Scripts, in press, 1995.

Gosling, J.T.; McComas, D. J.; Phillips, J,I,.; Same, S, J., "Geomagnetic activity associated with earth pasage of interplanetary shock disturbances and coronal mass ejection". J. Geophys. Res., 96,7831,1991.

Hewish, A.; Bravo, S., '(The sources of large-scale heliospheric disturbances", Solar Phys., 106, 185, 1986.

Hildner, E., "Mass ejections from the corona into interplanetary space". In *Study of traveling Interplanetary Phenomena*, *ed.* M.A. Shea, D. F. Smart and S.T. Wu, p.3, D. Reidel, Hingham, Mass, 1977.

Hoeksema, J.T.; Scherrer, P.H., "The solar magnetic field -1976 through 1985". World Data Center, Report UAG-94, 1986.

Hollweg, J. V. "Some physical processes in the solar wind", Rev. Geophys. Space Phys. 16, 689, 1978.

Hundhaussen, A. J., "Sizes and location of coronal mass ejection: SMM observations from 1980 and 1984-1989". J. Geophys. Res., 98, 13177, 1993.

Low, B. C., "Magnetohydrodynamic processes in the solar corona: flares, coronal mass ejections, and magnetic helicity" Bull. Am. Phys. Sot., 38, 2042, 1993.

McIntosh, P. S., "Coronal holes and solar predictions", in *Solar-Terrestrial Predictions IV*, Ed. J. Hruska, M.A. Shea, D.F. Smart and G. Heckman, NOAA/Environmental Research laboratories, Boulder, Colorado, pp 20-47, vol 2, 1993.

McIntosh, P. S.; Willock, E. C.; Thompson, R. J., "Atlas of stackplots derived from Solar Synoptic charts", National Geografical Data Center, Report UAG-101 , October 1991.

Miller, J. A., "Controversy over 'solar flare myth' explored: much about nothing", EOS, Trans. AGU, 76(41), 401, 1995.

Sheeley Jr., N. R.; Howard, R. A.; Koomen, M. J.; Michels, D. J.; Schwenn, R.; Mühlhäuser, K.H.; Rosembauer, H., "Coronal mass ejections and interplanetary shocks", J. Geophys. Res., *90*, 163, *1985*.

Tang, F.; Tsurutani, B.T.; Gonzalez, W.D.; Smith, E. J.; Akasofu, S.1. "Solar sources of interplanetary southward *Bz* events responsible for major magnetic storms (1978-*1979)*". J. Geophys. Res., 94(.44): 3535, 1989.

Tsurutani, B. T.; Gonzalez, W.D. "The cause of high-intensity long- duration continuous AE activity (HILDCAAS): interplanetary Alfvén wave trains". Planet. Space Sci., 35:405, 1987.

Tsurutani, B.'T.; Gonzalez, W. D.; 'Tang, F.; Akasofu, S.1.; Smith, E. J., "origin of interplanetary southward magnetic field responsible for major magnetic storms near solar maximum (1978- 1979)". J. Geophys. Rex., 93, 8519, 1988.

Tsurutani, B. T.; Ho, C. M.; Smith, E. J.; Neugebauer, M.; Goldstein, B.E.; Balogh, A.; Southward, D.J.; Feldman, W.C., "The relationship between interplanetary discontinuity and Alfvén waves: Ulysses observations". Geophys. Res. Lett., 21, 2267, 1994.

Webb, D.F., "The solar cycle variation of the rates of CMEs and related activity". Adv. Space Res., 11, (1)37, 1991.

CORONAL HOLE-ACTIVE REGION -CURRENT SHEET (CHARCS) ASSOCIATION AT SOLAR MAXIMUM

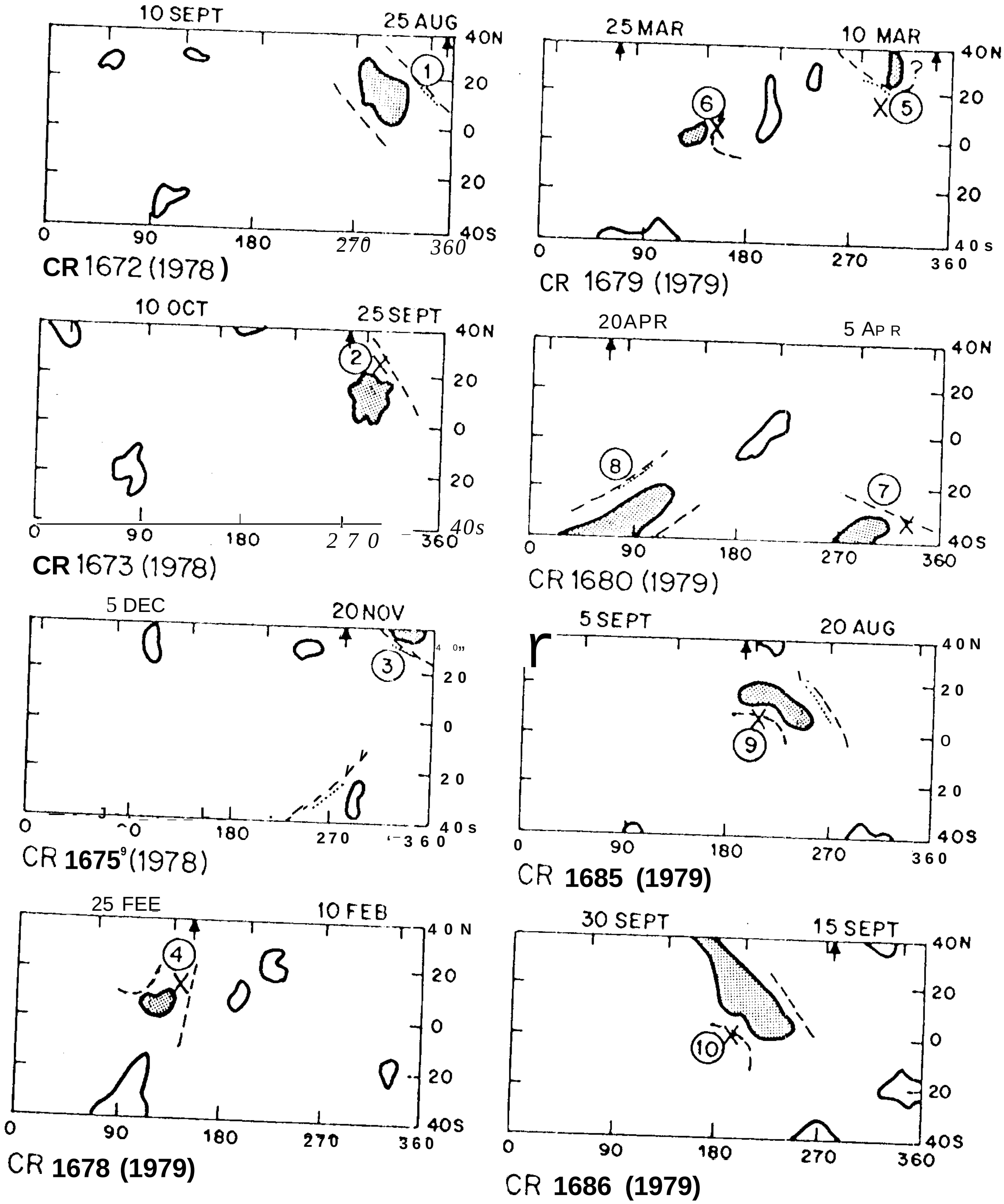
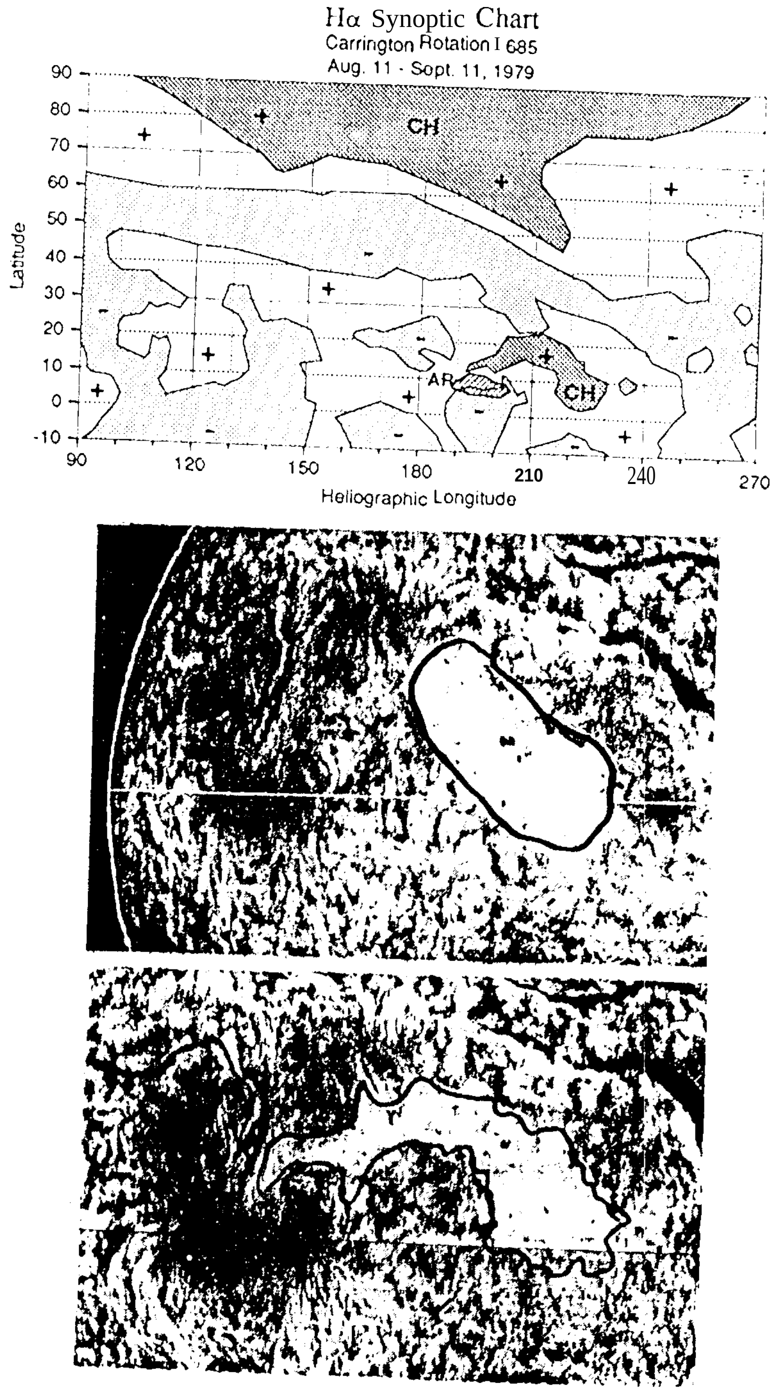


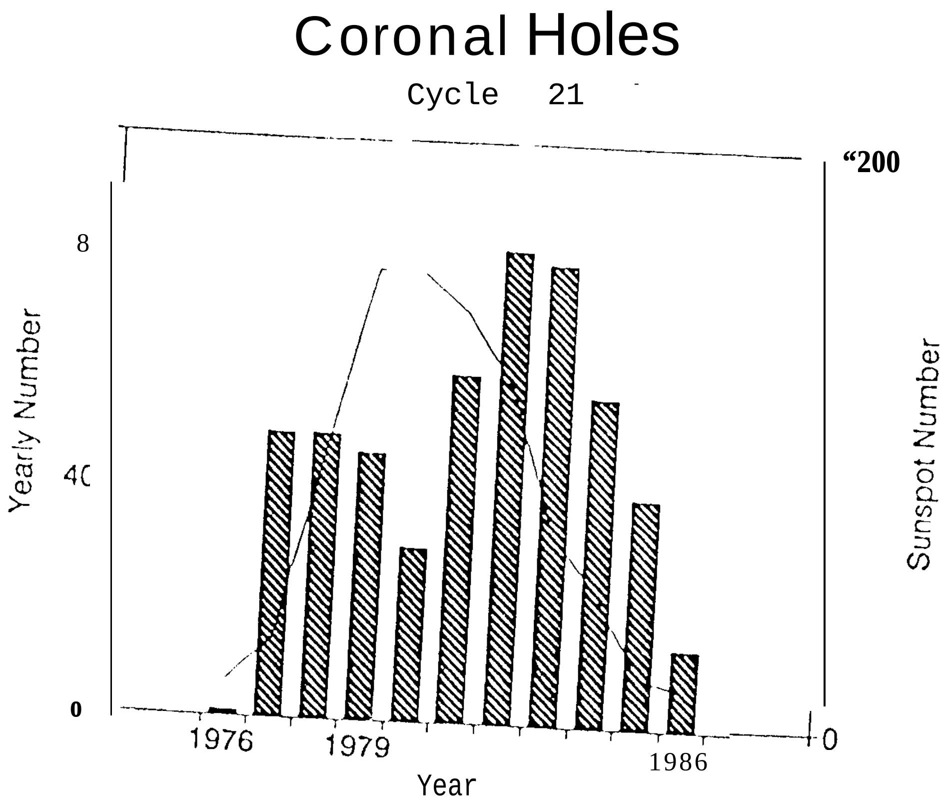
FIGURE I


Hα Synoptic Chart
Carrington Rotation 1685
Aug. 11 - Sept. 11, 1979
Latitude
Heliographic Longitude
CH
AR
CH

(a)

(b)

FIGURE 2



Coronal Holes
Cycle 21
"200
8
40
0
Yearly Number
Sunspot Number
1976
1979
1986
0
Year

FIGURE 3