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Geomagnetic storm sudden commencements and their possible sources at the sun

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RESUMEN

Se analizan seis casos específicos de tormentas geomagnéticas con comienzo repentino (SC) durante 1978 y 1979 con el propósito de determinar los eventos solares (ráfagas, erupciones de filamentos o fenómenos transitorios en hoyos coronales) que las produjeron. Se utilizan las posiciones obtenidas por Hewish y Bravo (1986) mediante las observaciones de centelleo interplanetario (IPS) para las fuentes de los choques cuya llegada a la Tierra provocó los SCs. Tres de estos eventos fueron ya asociados por otros autores a alguna ráfaga o erupción de filamento y los otros tres no han sido discutidos nunca ya que no hubo ráfaga o estallido de filamento alguno en todo el Sol durante los cinco días anteriores al inicio del SC. En todos los casos se encontró un hoyo coronal en o muy cerca del centro de la región fuente estimada por IPS. Se discute la posibilidad de que ciertos cambios bruscos en los hoyos coronales puedan dar origen a la formación de choques en el medio interplanetario con las características de los observados.

PALABRAS CLAVE: comienzos repentinos, perturbaciones geomagnéticas, choques interplanetarios, relaciones solar-terrestres.

ABSTRACT

We analyze six specific cases of geomagnetic storm sudden commencements (SC's) between 1978 and 1979 with the purpose of determining the events at the Sun which produced them. We use the locations of the solar sources of the shock fronts producing these events as obtained by Hewish and Bravo (1986) by means of the IPS technique. Three of the events had been studied by other authors who attributed them to flares or eruptions of filaments based on their times of occurrence. Information on locations of the sources at the Sun enables us to discard some of these associations and to establish the presence of a coronal hole as the only consistent relation with the source. In three other cases of SC's for which no flare or eruptive filament occur at the disk of the Sun up to five days before the beginning of the geomagnetic storm, we show that a coronal hole was located in the source region of the interplanetary shock that produced the SC. Finally, we discuss the capability of some kind of coronal hole transients to produce shock fronts travelling in the solar wind and the actual possibility of occurrence of such transients.

KEY WORDS: sudden commencements, geomagnetic perturbations, interplanetary shocks, solar-terrestrial relationships.

INTRODUCTION

Sudden commencements of geomagnetic storms (SC's) are usually believed to be caused by interplanetary shocks; however, the identification of the solar sources of these shocks remains a major problem. It was first thought that shocks were produced by flares (Sakurai, 1973; Chao and Lepping, 1974; Pudovkin *et al.*, 1979). Joselyn and McIntosh (1981) put forward the proposition that interplanetary shocks might also be produced by the eruption of a prominence which is observed against the solar disk as a disappearing filament. Both types of sources have since then become accepted as explanations for the travelling disturbances in the interplanetary space (Dryer, 1982; Cane and Stone, 1984; Cane, 1985; Cane *et al.*, 1986).

Cane (1988) examined the associations between flares and 116 transient shocks not associated with corotating streams during a period of 18.7 years. She concluded that at most 50% (and probably considerably less) of the interplanetary shocks which produce sudden commencement geomagnetic storms may have their origin in a flare event, and that most are associated with eruptive filaments (see also Poland *et al.*, 1981). As the number of flares and eruptive filaments is always larger than the number of shocks, a selective association must be established. This approach has been tried only with flares but no one-to-one correspondence has been obtained.

Coronal mass ejections (CME) are the closest to the Sun manifestations of what might later become an interplanetary shock. Wagner (1984) shows that, according to Skylab and SMM observations, only 10-17% of observed CMEs can be associated with flares and 30-34% with eruptive prominences. This leaves 30% to 48% of CMEs unrelated to any near-surface explosive event, though many of those are related to interplanetary shocks. Sheeley *et al.* (1985) associated 49 CMEs to interplanetary shocks by combining Solwind coronagraph observations and observations of Helios 1 in the interplanetary medium. Only 24 (49%) of these events could be related to flares or eruptive prominences.

A third candidate for a possible source of large-scale interplanetary disturbances are low-latitude unstable coronal holes (Hewish *et al.*, 1985). Of about 100 major interplanetary disturbances detected and tracked by the interplanetary scintillation (IPS) technique during the rising phase of solar cycle 20 (1978-1979), Hewish and Bravo (1986) report a very good coincidence between the estimated sources of the disturbances tracked back to the Sun and low-latitude coronal holes, or low-latitude extensions of polar holes. Further studies suggest a connection between polar coronal hole areas and cosmic ray intensities observed at Earth (Hundhausen *et al.*, 1980; Bravo *et al.*, 1987, 1988), and between the occurrence of aurorae and the evolution of polar and low-latitude coronal holes (Bravo and Otaola, 1990). It is widely accepted that corotating high-speed streams produced by large stable low-latitude coronal holes are responsible for recurrent geomagnetic perturbations. However, the effects of the unstable, short-lived, and fast-changing coronal holes have not been as thoroughly discussed.

In this paper, we present six specific cases of sudden commencements of geomagnetic storms associated not with corotating streams but with radially moving interplanetary shocks. Alternative solar sources, such as flares, disappearing filaments and coronal hole transients are discussed and the capability of coronal hole transients to produce travelling shock fronts in the solar wind is analyzed.

SOME CASES OF SUDDEN COMMENCEMENT GEOMAGNETIC STORMS

Some SC's studied by other authors are assumed to be related to flares or disappearing filaments. The association is established in terms of the times of occurrence; that is, an eruptive event happening at the Sun between one and five days prior to the occurrence of the SC is considered as a possible source for the disturbance.

The IPS technique used by Hewish and Bravo (1986) allowed the detection of the perturbations in the interplanetary space and made possible the location of their solar sources by daily mapping of the scintillation index of about one thousand stellar radio sources of small diameter. This scintillation index is related to the electron density of the solar wind along the line of sight and so enables us to map and track the compression and rarefaction regions of the interplanetary plasma. It is possible to determine whether a perturbation observed in the maps is of the type produced by a corotating high-speed stream or by an eruptive stream, and to decide whether the centre of the perturbation is located in the northern or the southern hemisphere, or near the solar equator. High-latitude events can also be distinguished from medium-latitude ones. In the case of eruptive streams, it is possible to tell whether the event was originated at the east, the west or near the central meridian of the Sun. The travel time of the perturbation from the Sun to the Earth can also be estimated. With all this information, the solar region where the perturbation originated can be identified.

We analyze here some of the eruptive streams studied by Hewish and Bravo (1986) that were also studied by other authors by means of a temporal association with flares or disappearing filaments. These selected events all gave rise to a sudden commencement of a geomagnetic storm. As we shall show, however, they may be more naturally related to a coronal hole transient.

a) *Sudden commencements related to flares or eruptive prominences*

1. The SC of 9 September 1978 was attributed by Joselyn and McIntosh (1981) to an erupting filament on the 3rd of September. Figure 1 shows the Carrington map corresponding to those days (CR 1672) on which the

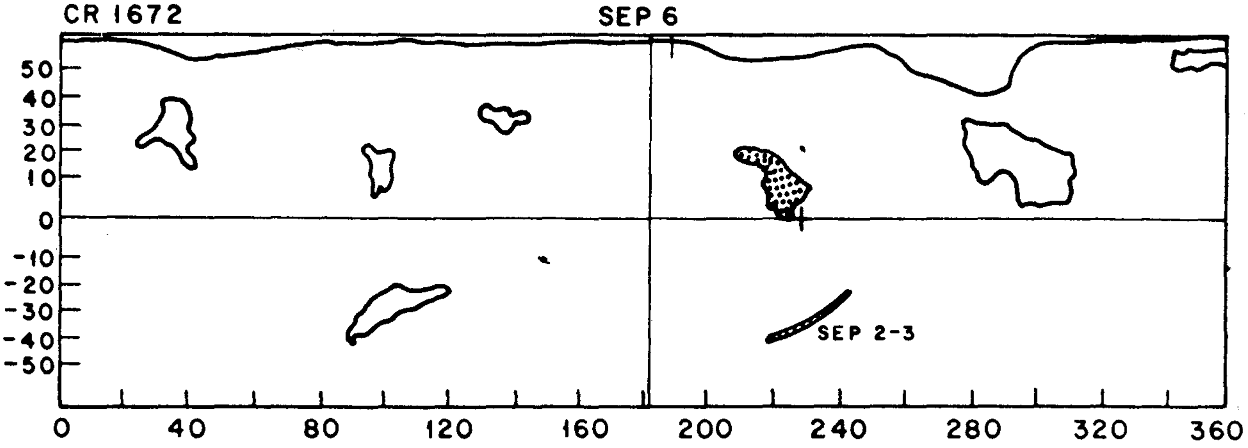

Fig. 1. Carrington rotation map 1672 showing the filament which erupted on the Sun between the 2nd and the 3rd of September, the IPS source centre (cross), and the coronal holes as observed in HeI 10830 Å. The vertical line at $\phi = 182^{o}$ indicates the position of central meridian at the estimated date (Sep. 6) of the eruption at the Sun which produced the SC. The closest hole to the IPS centre is stippled.

filament proposed by Joselyn and McIntosh is drawn. The coronal hole borders obtained from observations in the HeI 10830 Å line for the same rotation, taken from the Solar Geophysical Data, are shown as well. The filament was located in the southern hemisphere; at the time of the eruption it was passing close to the central meridian. However, the disturbance registered by IPS was observed to come from the west side of the Sun near the equator (Hewish and Bravo, 1986).

Associating this SC with the erupting filament implies a mean velocity of propagation of the shock of about 280 km/s. Yet the background velocity during the days prior to the shock arrival was about 370 km/s and the velocity of the wind observed after the shock was about 490 km/s. Considering that the shock velocity must be higher than that of the background solar wind, the eruptive event at the Sun was more likely to occur around the 5th or the 6th of September, when the Carrington longitude of 190° (indicated in Figure 1 as a vertical line) was about central meridian. The IPS centre (that is, the centre of the solar source obtained by IPS tracking) was located by Hewish and Bravo about longitude 230° and near the equator, as indicated by a cross on the map. Notice that a coronal hole (stippled on the map) is more suitably positioned as the source of the interplanetary shock and of the SC on the 9th of September, than the filament considered by Joselyn and McIntosh (1981).

2. Cane (1985) attributes the SC of 4 October 1978 to a flare on 1 October (0718 UT) localized at λ = 13°S and ϕ = 155°. The corresponding Carrington rotation (CR 1673) is shown in Figure 2. The flare site is marked with a star

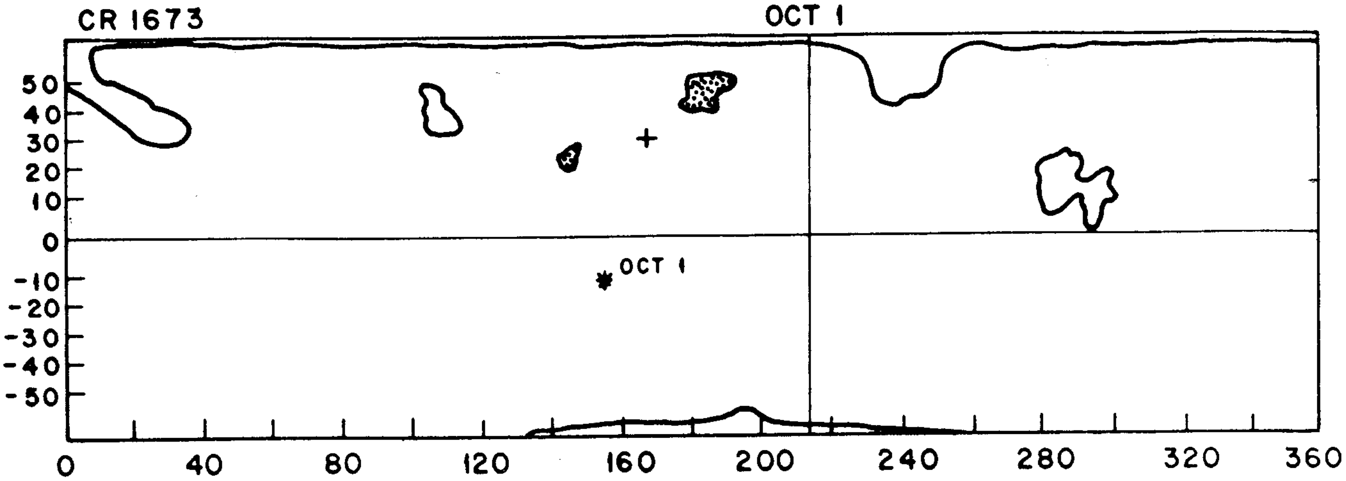

Fig. 2. Carrington rotation map 1673 showing the IPS source centre (cross), the coronal hole boundaries, and the flare (*) which flashed at the Sun on 1 October 1978. The vertical line at ϕ = 215° indicates the position of central meridian at the Sun when the eruptive event responsible for the SC is estimated to happen (Oct. 1). The closest hole to the IPS source is stippled.

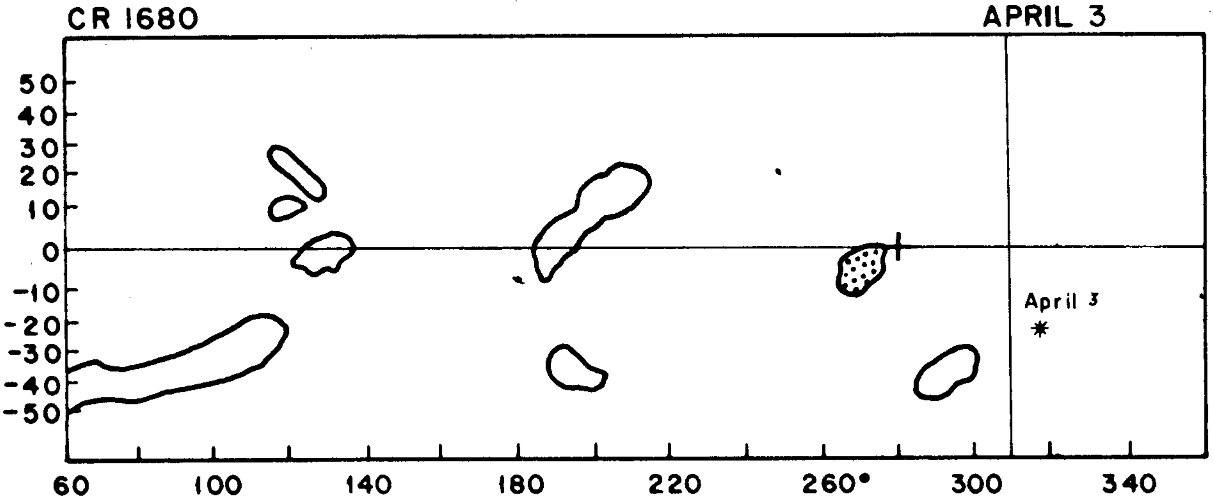

Fig. 3. Carrington rotation map 1680 showing the IPS source centre (cross), the coronal hole boundaries, and the flare (*) which flashed on the Sun on 3 April, 1979. The vertical line at ϕ = 310° shows the location of the central meridian at the estimated date (April 3) for the eruptive event responsible for the SC. The closest hole to the IPS centre is stippled.

and the central meridian on 1 October is shown as a vertical line. This association implies a mean velocity of about 650 km s^{-1} for the shock in the interplanetary medium while the observed velocity of the wind at 1AU was around 450 km s^{-1}. The IPS observations report, in this case, an erupting stream coming definitely from north-east leading to the location of a source at about λ = 30°N, ϕ = 166°. The accuracy of locations of solar sources by means of IPS is not very high; yet disturbances generated in the north hemisphere, about the equator, or in the south hemisphere can be actually distinguished (cf. Tappin, 1987). In this case the disturbance was clearly coming from the north. Again the IPS source is closer to two coronal holes (stippled in the figure) than to the flare proposed by Cane (1985).

3. Tang *et al.* (1989) attribute the SC of 5 April 1979 to a flare flashing in the southern hemisphere on 3 April. Its location is shown on the corresponding Carrington rotation (CR 1680) in Figure 3, along with the coronal hole boundaries for that rotation. The Carrington longitude passing through central meridian on this date is shown as a vertical line in the map (Figure 3). The IPS observations suggest an eruptive stream coming from the east about the equator; the estimated centre for its source is shown on the map with a cross at ϕ = 280°. Again, the stippled coronal hole is more conveniently located to explain the event.

b) *Sudden commencements not associated with flares or disappearing filaments.*

Three events studied with the IPS technique deserve to be specially considered: these are the sudden commencements of 29 October 1978, 25 December 1978, and 29 May 1979. In association with these events, three eruptive streams were observed on IPS, one from the north, close to central meridian, and two from the north-east. The estimated centres of the sources are shown on Carrington rotation maps (Figure 4 a, b, and c). No flare or disappearing filament was observed anywhere on the solar disk from 1 to 5 days before each of the SC's. Yet a coronal hole appears in each case near the centre of the solar region which had generated the disturbance according to IPS observations.

Interestingly a coronal mass ejection (CME) was observed on 27 May 1979 above the west limb of the Sun. Its central latitude and longitudinal span were given as N15±25 (Schwenn, 1983; Sheeley *et al.*, 1985). Another shock, not observed by IPS and related with this CME, was detected in the interplanetary medium by Helios 1 spacecraft when it was at 0.43 AU and about 90° west of the Sun-Earth line. The west limb location on May 27 is also indicated in Figure 4c with a vertical bar which also shows the latitudinal span of the observed CME. A horizontal bar to each side of the limb delimits the region of the CME source's location. It is possible that the shock detected by Helios may also have reached the Earth; but it seems rather unlikely that it caused the SC of 29 May due to its extreme position. The main point is that in this case a coronal hole is again found in the source region of the CME related to this shock. Indeed, a very good spatial correlation between CMEs related to interplanetary shocks and coronal holes has been found by Bravo and Pérez-Enríquez (1991). This would be expected if coronal holes can be sources of interplanetary shocks as we suggest.

CORONAL HOLE TRANSIENTS AS SOURCES OF INTERPLANETARY SHOCKS

From the events analyzed here, one can see that, once the solar source region of an interplanetary perturbation is determined, a coronal hole may seem a more likely source of the disturbance than an explosive event (flare or disappearing filament). Moreover, even when no flare or disappearing filament can be observed at the Sun, the IPS estimated centre is also located near or inside a coronal hole region. This appears to support the suggestion (Hewish and Bravo, 1986) that some kind of coronal hole activation can lead to the formation of shock perturbations in the solar wind. Unfortunately, coronal holes are drawn on Carrington maps as static features. Only their shape and size during their central meridian passage is recorded. Such maps cannot provide information about changes in the holes during their transit across the solar disk. In the case of low-latitude holes or low-latitude extensions of polar holes such changes can be very large indeed.

Since Skylab observations, we know that coronal holes are usually "born" on time scales of the order of several hours (Solodyna *et al.*, 1977) and exhibit rapid temporal changes, especially in their initial phases (Krieger, 1977). Nolte *et al.* (1978) studied the temporal evolution of low latitude coronal holes ($\lambda \leq 40°$) and found that large-scale shifts in their boundary locations can account for most, if not all, of their evolution. As observed on a time scale of one day, these shifts occur as discrete events, not continuous slow motions. These events involve spatial changes much larger than supergranulation cells, but occur in times shorter than or comparable to one supergranule lifetime. Webb *et al.* (1978) have found that most X-ray coronal transients outside active regions are related to large-scale changes in coronal hole area and tend to occur on the borders of evolving equatorial holes. Since not all the large-scale changes in coronal holes are accompanied by X-ray transients, Webb *et al.* suggest the occurrence of more rapid changes in these cases. More recently, Sheeley *et al.* (1989), studying the effect of newly erupting flux on the polar coronal holes observed early in sunspot cycle 22, found that the hole boundary immediately contracts after the eruption of new bipolar magnetic regions.

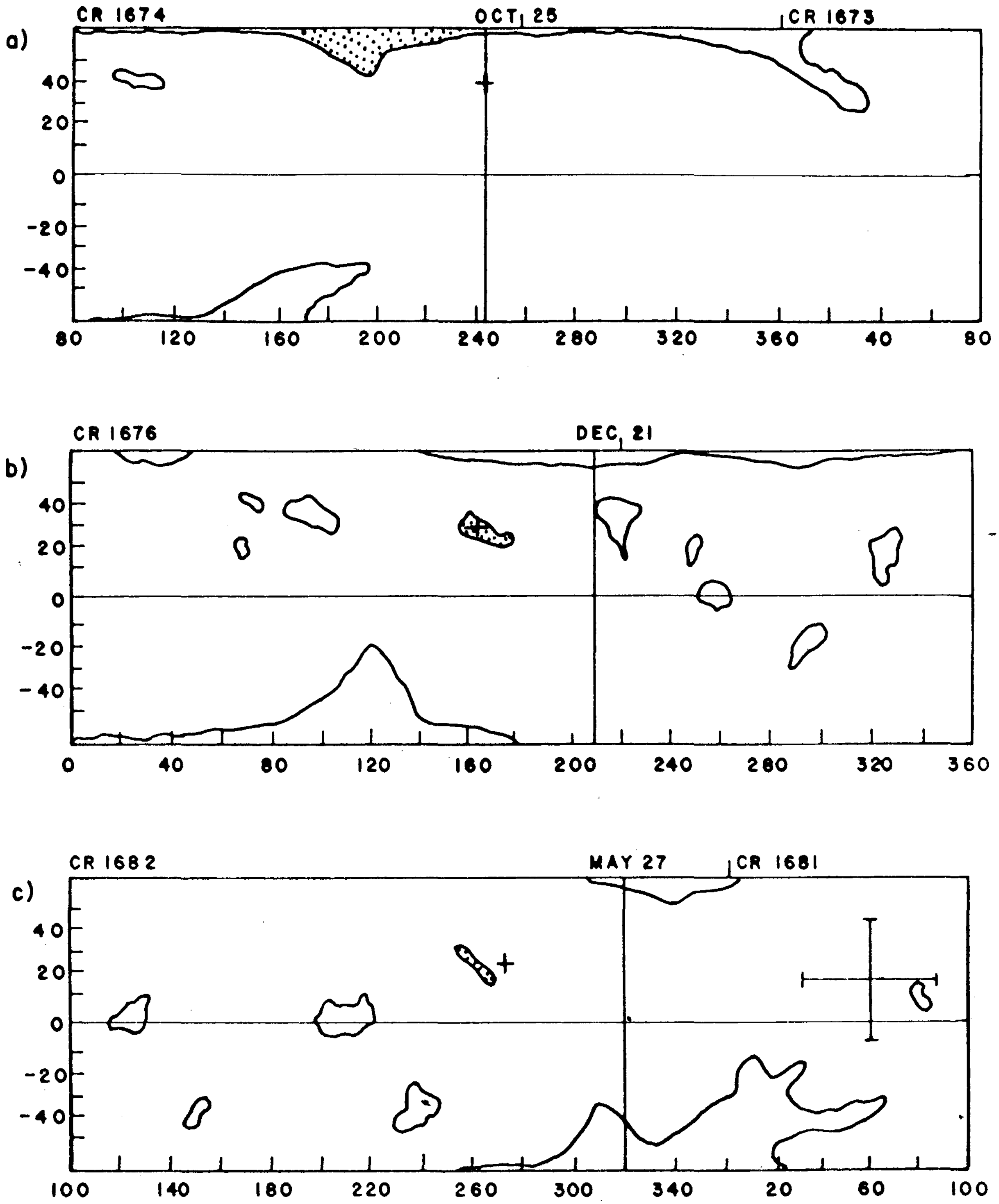

Fig. 4. The three Carrington rotations corresponding to the SC's of: (a) 29 October 1978; (b) 25 December 1978; and (c) 29 May 1979. The crosses show the location of the IPS source centre in each case. The vertical lines indicate the positions of central meridian at the estimated days (25 October, 21 December. and 27 May) of the eruption at the Sun of the events which presumably produced the SC's. The stippled coronal holes are the closest holes to the IPS centre in each case. In figure (c) a vertical bar at a longitude of about 60° indicates the west limb position on the 27th of May and the latitudinal span of the CME observed on that day; the horizontal bar delimits the most likely region for the location of the CME source.

Little work has been done in the modeling of time-dependent fluxes from coronal holes. The steady-state equations are difficult enough to solve, especially when the plasma-magnetic field coupling is taken into account. But a very detailed (hydrodynamic) parameter study was made by Hasan and Venkatakrishnan (1982) who examined the transient response of the solar wind to changes in geometry, in particular the effect on the flow from a coronal hole tube whose area A(r, t) diverges faster than r^2, the degree of divergence increasing with time. When the geometry changed very rapidly, a shock-like discontinuity developed. Shocks that propagate into interplanetary space can also be generated by another mechanism as demonstrated by Dryer *et al.* (1980) in a numerical two-dimensional MHD study. In this work, a transient increase of thermal energy at the base of a coronal hole is sufficient to produce a propagation shock. The tube area increased faster than r^2 with time as a direct consequence of the transient energy increase and need not to be specified *a priori* as in the one-dimensional study of Hasan and Venkatakrishnan (1982).

The geometry of coronal holes near the Sun is determined by the magnetic field structure. If rapid changes in the local magnetic field may trigger flares or cause the eruption of a filament, they will also affect the structure of a coronal hole, altering the characteristics of its plasma flux. Thus, when some of the lines at the border of a coronal hole suddenly close and its area shrinks, this should increase the divergence of the hole flux. The reason is that the lines wich remain open ought to fill the void left by the plasma "attached" to the now-closed field lines which constrain that plasma from flowing out. In this way, according to simulations by Hasan and Venkatakrishnan (1982) and Dryer *et al.* (1980), a shock can be created in the hole flux and then transmitted into the interplanetary medium.

Shocks expected from this mechanism should be rather wide since they affect the entire flux tube from the coronal hole which has a very large extension in the interplanetary medium precisely because of its more than radial divergence near the Sun (cf. Bravo and Mendoza, 1989). In principle, wide interplanetary shocks moving radially away from the Sun may be generated in rapidly-changing coronal holes. This conclusion agrees with the observations of shocks in the interplanetary medium of 80-100° width (cf. Hewish and Bravo, 1986; Cane, 1988).

The long duration of the high-speed stream behind interplanetary shocks (Borrini *et al.*, 1982) cannot be understood in terms of flares or eruptive prominences as their expected velocity profile at 1AU should present a narrow period of high-speed wind after the shock (Wu *et al.*, 1983; Akasofu and Lee, 1989). The narrowness of the high-speed stream depends on the duration of the explosive event, which on rare occasions exceeds ten hours. In terms of coronal hole transients, such structures are easier to understand.

In the IPS study, all shocks having a wide associated high-speed stream were originated from a source at the east of central meridian (see also Bravo *et al.*, 1991). When a sudden establishment of a high-speed stream from a coronal hole at the east of central meridian produces a shock, most, if not all, of the stream will be east of the Sun-Earth line. It will pass by the Earth for whatever time it takes for the coronal hole's flux tube to pass in front of it following the rotation of the Sun. A more complete discussion may be found in Bravo *et al.* (1991).

CONCLUSIONS

The analysis made in this paper reinforces the conclusions from IPS tracking which had led to the suggestion that coronal holes may be sources of interplanetary shocks. The spatial coincidence of the source with a coronal hole region does not guarantee, however, that anything happened to the hole at the proper time to produce the perturbation observed in the interplanetary medium. Nevertheless, the spatial coincidence between holes and interplanetary shock solar sources is strong enough to encourage the continuous observation of coronal holes in EUV and X-ray. Their rapid temporal changes should be recorded in a systematic manner in order to establish the association of the perturbations with coronal hole transients. Such observations, together with interplanetary tracking of the shocks and continued modeling efforts, should help clarify the role played by coronal holes in the creation of shocks in the interplanetary medium.

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