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Increases in the area of coronal holes related to interplanetary shocks

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RESUMEN

El rastreo de perturbaciones del viento solar por medio del centelleo interplanetario (IPS) de fuentes estelares de radio mostró que las perturbaciones interplanetarias más importantes se originan en regiones solares que contienen hoyos coronales. A raíz de esto se sugirió que los choques se originan en hoyos coronales cambiantes que repentinamente emiten viento solar más rápido. En este trabajo presentamos dos casos particulares de observaciones solares e interplanetarias relacionadas con comienzos repentinos de tormentas geomagnéticas (SC) en los cuales se muestra que el choque interplanetario está relacionado con un aumento en el área de un hoyo coronal. Los eventos considerados corresponden al 6 de junio de 1979 y al 1º de octubre de 1991. Se describe un escenario solar para la ocurrencia de estos eventos y se presenta un mecanismo para la formación del choque.

PALABRAS CLAVE: Choques interplanetarios, hoyos coronales, eyecciones de masa coronal.

ABSTRACT

The tracking of interplanetary disturbances by means of the interplanetary scintillation (IPS) of stellar radio sources showed that major interplanetary disturbances are originated from solar regions containing coronal holes. Thus interplanetary shocks may originate in changing coronal holes which suddenly emit faster solar wind. In this paper we present two examples of related solar and interplanetary observations corresponding to sudden commencement (SC) events at the Earth which show by different means that interplanetary shocks are, at least in some cases, related to an increase in the area of coronal holes. The events correspond to 6 June 1979 and 1 October 1991. A possible scenario at the Sun for the occurrence of an increase in the area of coronal holes and a mechanism for the formation of the shock are also presented.

KEY WORDS: Interplanetary shocks, coronal holes, coronal mass ejections.

INTRODUCTION

Interplanetary shocks, formerly associated with flares and eruptive filaments, are now widely believed to be caused by coronal mass ejections (CMEs) (e.g. Kahler, 1992). CMEs were first thought to be caused by these explosive events, but it is becoming clear that CMEs and flares or eruptive prominences are associated but not causally related events. It is believed now that coronal mass ejections are the result of the reconfiguration of the coronal magnetic field structure (see for instance Kahler *et al.*, 1988; St. Cyr and Webb, 1991). Observations and correlated studies of solar and interplanetary phenomena by Sheeley *et al.*, (1985) have shown that interplanetary shocks seem to be always associated with a CME, but CMEs are not always associated with interplanetary shocks. As there are many more CMEs than shocks, a selective association must be found. The natural association would be with the large and high-speed CMEs, but Sheeley *et al.*, found that even small and low-velocity CMEs may be associated with interplanetary shocks. Moreover, these authors also found that the velocity of the CMEs, as observed in the coronagraph, is poorly correlated with the velocities of the associated interplanetary shocks, and the shape and extension of the shock expected from the CME do not coincide with those observed in the interplanetary shocks.

On the other hand, the analysis of more than one year of observations of large-scale interplanetary disturbances by means of IPS, made by Hewish and Bravo (1986) showed that a coronal hole was *always* present in the solar source region of the disturbance. This led us to propose that interplanetary shocks may be formed by a sudden increase in the velocity of the wind emitted from the hole (see also Bravo *et al.*, 1991 a,b). The interaction of the high-speed wind with the previously emitted slow wind will give rise to a shock in interplanetary space, as shown by means of numerical simulations by Dryer *et al.*, (1980).

From a comparative study, a good spatial relation between coronal holes and the region of origin of CMEs associated with interplanetary shocks was found by Bravo and Pérez-Enríquez (1993). This finding strengthened the relationship between coronal holes and interplanetary shocks as found from the IPS survey. However, the mass involved in a CME cannot come from the magnetically open, low-density region of a coronal hole: therefore we did not conclude that coronal holes are the sources of the CMEs. Instead, we suggested that the interplanetary shock actually originates in the hole by a sudden increase of flux velocity due to the same cause which produces the CME from an adjacent magnetically closed region. Hence, CMEs and interplanetary shocks are not causally related (CMEs are not the pistons driving the shocks) but have the same solar origin in different but adjacent regions at the Sun: helmet streamers and coronal holes. In this paper we discuss the solar and interplanetary observations related to the SC events of 6 June 1979 and 1 October 1991 in order to bring more light into the shock formation problem.

THE OBSERVATIONS

(a) The 6 June 1979 event

On 6 June 1979, an SC occurred at 19: 27 UT due to the arrival at the magnetopause of a shock front traveling in the interplanetary medium. The speed and density profiles of this shock (King, 1983) are shown in Figure 1. Here we can see that large increases in velocity and density were present at the shock. Note that there is also a previous non-compressive major density increase which is not related to the shock. The shock density enhancement lasted for less than one hour. After the shock the velocity remained high, with some fluctuations, for several days while the density rapidly decreased and remained low for about the same period, as usually happens in high-speed streams. This disturbance was tracked by means of IPS observations by Hewish and Bravo (1986) and associated with something happening at the Sun about the 4th of June in a source region located near the equator and east of central meridian. This region is shown with a circle on the corresponding Carrington rotation map in Figure 2. The region contained a well-defined coronal hole (dashed in the figure) and we have indicated with stars several flares that took place in an active region near the hole on June 3 and 4. No observation of a coronal mass ejection was reported but this might be due to the fact that CMEs coming directly toward the Earth are very difficult to see in the coronagraph, which is especially suitable for observing CMEs out of the limbs.

Photospheric magnetograms were used by Kaigorodov and Fainshtein (1991) to calculate the daily evolution of coronal magnetic fields by means of a potential field method. They measured the area (SMT) for the dashed hole on consecutive days and their results are shown in Figure 3. A sudden large increase in the area of the hole can be seen between the 3rd and the 4th of June, the time of the origin of the interplanetary disturbance at the Sun estimated from the velocity of the wind behind the shock and from IPS observations. The area eventually decreased to its original size on the 7th of June.

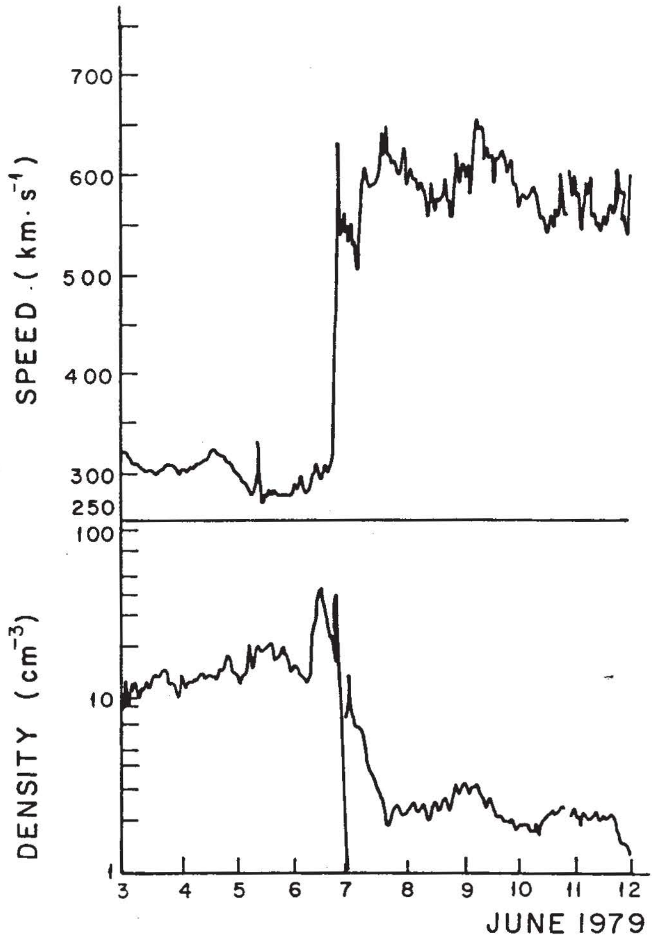

Fig. 1. Bulk speed and ion density profiles of the solar wind at ISEE-3 for June 1979. (After King, 1983).

(b) The 1 October 1991 event

The growth of coronal holes associated with interplanetary disturbances has also been directly observed in soft X-ray images of the Sun. Recently Watanabe *et al.*, (1993) reported on solar observations made with YOHKOH SXT related to the disappearance of a system of quiescent filaments on 28 September 1991 near the solar disk centre. This was accompanied by an X-ray flare of C2.1 class observed by GOES. Associated with this event, a small coronal hole was newly formed in the region immediately to the west of the site of the filament disappearance as a sudden extension of a pre-existing low-latitude coronal hole. They mention an aerial growth rate of the coronal hole of about 3 x 10^5 km^2/sec, which implies a diffusion rate about 20 times faster than that of the coronal magnetic field in the normal condition. This "extension" of the hole lasted for about three days. Watanabe *et al.*, (1993) also reported a solar wind disturbance with a plasma speed of 400-570 km/s observed by IPS at about 0.7 AU from the Sun on early October 1 associated with the SC of a geomagnetic storm at 18:13 UT on the same date. They consider that these observations suggest the presence of a disturbance in the inner heliosphere immediately after the filament disappearance.

In the following section we discuss these observations and we propose a possible scenario at the Sun in which all these related events could find a place.

CORONAL HOLE GROWTH AND INTERPLANETARY SHOCKS

From the analysis presented in the Introduction, we see that there are problems in thinking of coronal mass ejections as the direct cause of interplanetary shocks. However, the fact that a coronal hole is always present in the solar source region of the shock is not sufficient for thinking of coronal holes as the sources of the shocks. To support this point of view it is also necessary to envisage a mechanism capable of abruptly increasing the velocity of the flux from

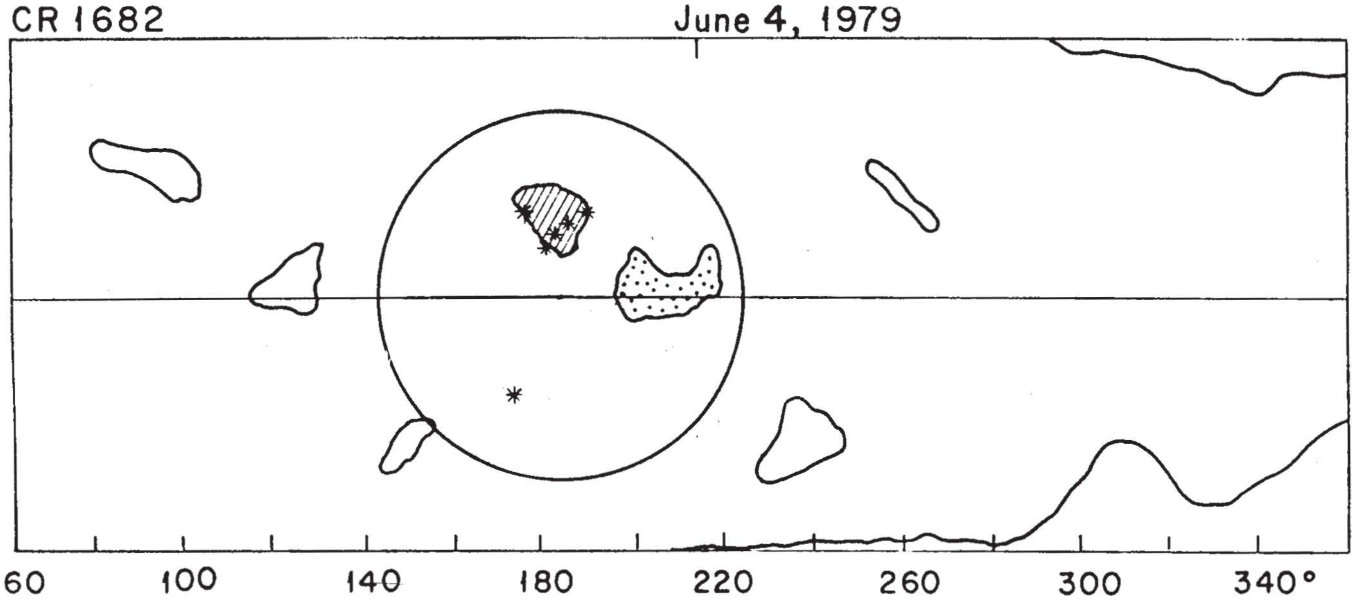

Fig. 2. Carrington rotation 1682 showing the source region estimated from IPS for the disturbance causing the 6 June 1979 SC event. The coronal hole is dotted and the flares on June 3 and 4 are indicated with stars.

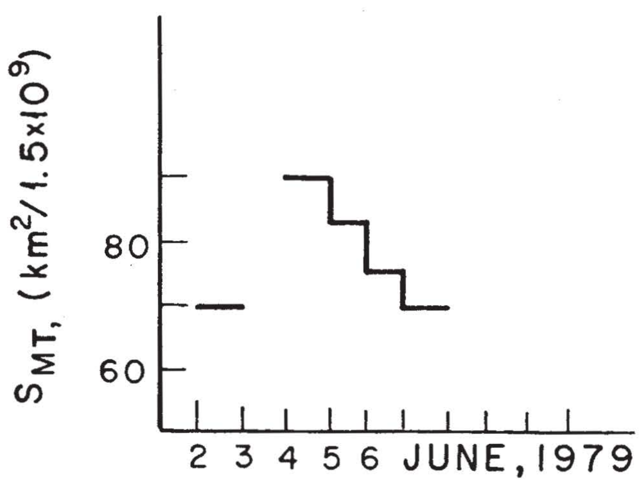

Fig. 3. The estimated area of the dotted coronal hole in figure 2 for consecutive days in June 1979 (after Kaigorodov and Fainshtein, 1991).

the hole in order to produce the shock and to show that such a mechanism is actually operating. It is also necessary to explain why CMEs are always accompanying interplanetary shocks and why they are often related to flares or eruptive filaments.

Numerical solutions of the equations governing the solar wind flux from coronal holes have been made by varying different parameters to understand their role in the characteristics of the flux. In particular, coronal holes are known to show a greater than radial divergence near the Sun and the role of this divergence has been investigated numerically by several authors (see for instance Pneuman, 1973; Durney and Pneuman, 1975; Wang and Sheeley (1991). They found that the outflow velocity of the solar wind from the hole increases as the divergence decreases. The same result was found by means of a source-surface extrapolation of observed photospheric fields to study the origin of the interplanetary fields and wind streams made by Levine *et al.*, (1977) and more recently by Wang and Sheeley (1990) and Wang *et al.*, (1990). Thus, a sudden decrease of the divergence of a coronal hole will result in a sudden increase in the velocity of the flux.

When a rearrangement of the large-scale coronal magnetic fields occurs, giving rise to a CME, it may also include a coronal hole. The emergence of new photospheric material with different magnetic polarity might lead to the disconnection of some of the field lines of a closed region, for example a helmet streamer, thus giving rise to the "release" of the plasma previously trapped in them and producing a CME. If the streamer is adjacent to a coronal hole, the now open field lines will add to the open flux tube from the hole causing its area to increase at the base. The border of the hole above the helmet streamer is limited by the position of the neutral sheet which has no reason to change. Hence the upper area of the hole will remain the same. This would reduce the divergence of the hole's flux tube and increase the flow velocity of the solar wind from it. A diagram of the suggested process is shown in Figure 4. It is important to notice that with the movements of the field lines Alfvén waves should also be produced which may increase the velocity of the wind even more.

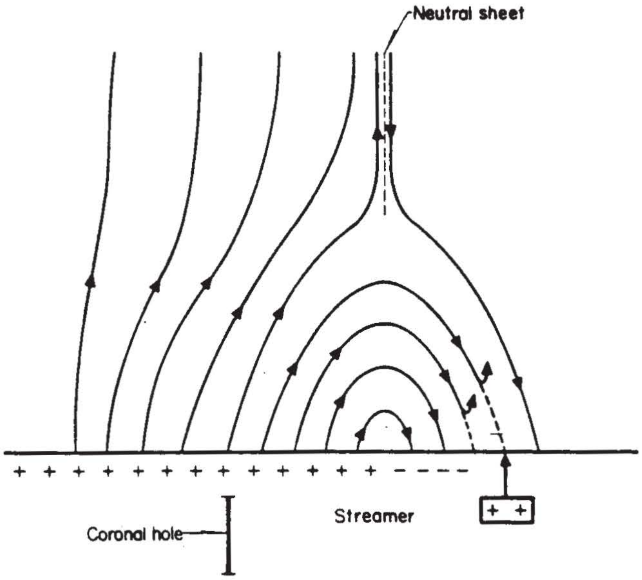

Fig. 4. Scheme showing the disconnection of some of the closed field lines of a streamer due to the emergence of a field of different polarity. The original border of the adjacent coronal hole will move to the right to include the newly open field lines and the divergence of the hole's flux tube will decrease.

In this scenario, the increase in the area observed for the holes associated with the SC events is due to the addition of open (newly disconnected) field lines, which release some mass (CME) not observed because the events took place near the solar central meridian. Increasing the area at the base of the hole will increase the solar wind velocity and thus form an interplanetary shock. Behind the shock, a high-speed, low-density, solar wind stream arises as observed for the 6 June 1979 event. The flares and the eruption of a filament near the hole might be triggered by the same large-scale magnetic rearrangement or directly by the emergence of the new material with the different polarity. In this scenario, a common cause produces different responses from different types of magnetic structures above the solar surface: a flare from an active region, the eruption of a prominence if present, the release of mass from a large scale closed region and the change of the velocity of the flux from a coronal hole. None of these are the cause of each other.

CONCLUSIONS

We present two cases where the increase of a coronal hole observed near the solar surface can be associated with the subsequent detection of an interplanetary shock. We conclude that, at least in some cases, coronal hole growing can lead to interplanetary shocks. We require more observations of short-term temporal changes in coronal holes and more IPS observations of interplanetary disturbances in order to establish whether rapid coronal hole changes are always the origin of interplanetary disturbances.

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