J. Astrophys. Astr. (2006) **27**, 101–112

Evolving Coronal Holes and Interplanetary Erupting Stream Disturbances

Rajendra Shelke
Prof. Ram Meghe Institute of Technology & Research Badnera, Amravati, Maharashtra 444 607, India.

Abstract. Coronal holes and interplanetary disturbances are important aspects of the physics of the Sun and heliosphere. Interplanetary disturbances are identified as an increase in the density turbulence compared with the ambient solar wind. Erupting stream disturbances are transient large-scale structures of enhanced density turbulence in the interplanetary medium driven by the high-speed flows of low-density plasma trailing behind for several days. Here, an attempt has been made to investigate the solar cause of erupting stream disturbances, mapped by Hewish & Bravo (1986) from interplanetary scintillation (IPS) measurements made between August 1978 and August 1979 at 81.5 MHz. The position of the sources of 68 erupting stream disturbances on the solar disk has been compared with the locations of newborn coronal holes and/or the areas that have been coronal holes previously. It is found that the occurrence of erupting stream disturbances is linked to the emergence of new coronal holes at the eruption site on the solar disk.

A coronal hole is indicative of a radial magnetic field of a predominant magnetic polarity. The newborn coronal hole emerges on the Sun, owing to the changes in magnetic field configuration leading to the opening of closed magnetic structure into the corona. The fundamental activity for the onset of an erupting stream seems to be a transient opening of pre-existing closed magnetic structures into a new coronal hole, which can support high-speed flow trailing behind the compression zone of the erupting stream for several days.

Key words. Sun: coronal holes—interplanetary disturbances—interplanetary scintillation.

1. Introduction

Coronal holes play an important role in the occurrence of various kinds of solar events. It is well established that the geomagnetic activity is related to the development of coronal holes on the Sun. Coronal transients, most of which are associated with eruptive prominences, have a significantly higher rate of occurrence in the vicinity of coronal holes than at other locations on the Sun (Webb *et al.* 1978). Active regions that produce solar flares and associated type II radio bursts are found to exist in the neighbourhood of coronal holes, indicating that MHD – shock waves generating type II – burst emission migrate along open magnetic field lines of the coronal holes (Shelke & Pande 1985). Several large scale soft X-ray blowouts are seen to erupt from or near the boundary of coronal holes (Bhatnagar 1996). There are some observations that show that transient coronal holes (sometimes now called 'X-ray dimming' or "coronal depletions") frequently form subsequent to eruptive prominences, coronal mass ejections or both (Rust 1983; Watanabe *et al.* 1992; Hudson 1996; Sterling & Hudson 1997).

The interplanetary scintillation (IPS) measurements at 81.5 MHz detect the enhancement in the density turbulence at distances greater than or equal to 0.7 AU. The large-scale structures of enhanced density turbulence in interplanetary medium are termed interplanetary disturbances. Hewish & Bravo (1986) used IPS measurements at 81.5 MHz and coronal hole images to study the solar cause of interplanetary disturbances. The proximity of mid-latitude coronal holes near the sources of interplanetary disturbances on solar disc led them to conclude that perhaps some coronal hole activity was to be blamed for interplanetary disturbances and interplanetary shocks.

In IPS maps of large-scale structures of higher or lower than average plasma density in the solar wind at 0.6–1.5 AU, Hewish & Bravo (1986) observed two kinds of typical interplanetary disturbances during August 1978–September 1979, namely: (1) most stable Co-rotating Interaction Regions (CIRs), and (2) transient erupting streams. The erupting stream disturbance has a roughly spherical compressed shell of enhanced plasma density, which is driven by the high-speed flow of low-density plasma trailing behind for several days. Hewish's team mapped 73 erupting stream disturbances, derived their origins by back projecting the disturbances onto the solar disk and plotted their sources on the synoptic maps using Carrington coordinates as circles of about 90° wide. The positional agreement between coronal holes and 90° circles led them to conclude that mid-latitude coronal holes are the sources of erupting stream disturbances.

Although coronal hole is a source of an excess kinetic energy flux in the solar wind (Steinitz & Eyni 1980), it is difficult to understand how a stable coronal hole can trigger a transient erupting stream, unless it is evolving. A coronal hole evolves, owing to the changes in its magnetic field configuration. It is plausible that changes in the field configuration of an evolving coronal hole can onset the erupting stream. In this paper, an attempt has been made to investigate a possible association between evolutionary changes in coronal holes and sources of erupting streams on the solar disk to probe into this possibility. Here, section 2 describes the observational material and the subtraction method used to delineate evolutionary changes in coronal holes. These evolutionary changes are categorized in different types in section 3 and their association with erupting streams is established in section 4. The magnetic configuration of coronal regions overlying the eruption sites of erupting streams is examined in section 5. Section 6 discusses and concludes the results of the present study.

2. Observational data

It is necessary to identify evolutionary changes in coronal holes over which sources of erupting stream disturbances overlie, so as to establish the association between them. As the coronal hole evolves, its size increases or decreases due to opening or closing of its magnetic fields respectively. Owing to the changes in magnetic field configuration, some parts of the evolving coronal hole disappear and/or are formed, that can be segregated by the 'Subtraction Method'. In this method, coronal hole images seen in synoptic maps of two consecutive Carrington rotations are superimposed on each other to eliminate the coronal hole areas that are static (i.e., unchanged), and thereby to delineate the parts of coronal holes that are formed and/or disappeared from one synoptic map to another. These delineated parts represent the evolutionary changes in coronal holes.

Using the subtraction method, the areas of coronal holes which get diminished and/or are formed have been delineated and new synoptic charts, hereafter called "Evolution or E-charts", are made by plotting these delineated parts of coronal holes in Carrington coordinates (cf. Fig. 1). Thirteen such E-charts are made for KPNO He I 10830 Å coronal hole images seen in synoptic maps of Carrington rotations 1671–1684 (August 1978–August 1979). Note that the E-chart does not incorporate static areas of coronal holes, as they will be eliminated in the subtraction. Data on coronal holes are taken from Solar Geophysical Data.

In the present study, about 68 events of transient erupting stream disturbances observed by Hewish & Bravo (1986) are analyzed. The data on their sources on the

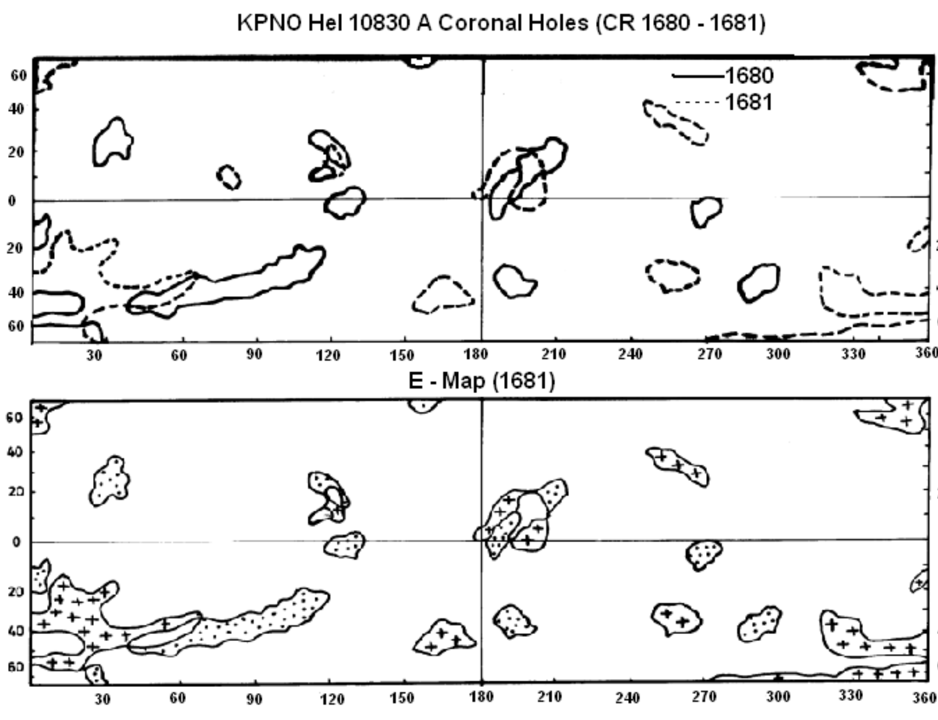

Figure 1. **(Top)** The superposition of coronal hole images seen in Carrington rotations 1680 and 1681. Solid and dashed lines represent the boundaries of coronal holes seen in rotations 1680 and 1681 respectively. **(Bottom)** The E-map (1681) derived from the above superposition. Crossed regions represent newly formed coronal hole areas (NFOCHA) formed due to the emergence of new coronal holes or the growth of existing coronal holes. Dotted regions correspond to the areas that have been coronal holes previously (POCHA). Note that E-chart does not incorporate static (i.e., unchanged) areas of coronal holes.

Sun are taken from Hewish & Bravo (1986). Other observed interplanetary disturbances are Co-rotating Interaction Regions (CIRs), which are forward–reverse MHD shock ensembles, together with the regions of enhanced density between them. They are produced in the interplanetary medium due to the interaction of fast solar wind streams with slower ones. Therefore it would seem that they do not originate on the Sun and hence they are not considered in this paper.

3. Evolutionary changes in coronal holes

The superimposition of coronal hole images seen in two consecutive rotations reveals that some coronal holes appear to grow bigger, and some appear to get smaller. Besides, the emergence of some new coronal holes and total disappearance of some existing coronal holes can also be seen. Interestingly, some existing coronal holes appear to grow to form new areas at the time when some areas of them are disappearing. These evolutionary changes in coronal holes have been classified into two categories, namely: (i) Previously Occupied Coronal Hole Area (POCHA) and (ii) Newly Formed Coronal Hole Area (NFOCHA). The former is related to the partial or complete disappearance of a coronal hole, whereas the latter is associated with the formation of new areas of coronal holes due to the birth of new holes or the growth of existing holes.

These two categories can be seen in Fig. 1. Here the regions filled with dots represent the areas of coronal holes, which existed in the preceding rotation 1680, but are seen to disappear in the succeeding rotation 1681. That is, these are the parts of coronal holes that have disappeared during the time between two synoptic maps. As they correspond to the locations that have been coronal holes previously, they are termed 'Previously Occupied Coronal Hole Areas (POCHA)'. Similarly, regions filled with crosses are the areas of coronal holes, which did not exist in the synoptic chart of the preceding rotation 1680, but are seen to appear only in the synoptic chart of succeeding rotation 1681. In other words, they are the new areas of the coronal holes that are formed due to the emergence of entirely newborn coronal holes or the growth of coronal holes that existed in the preceding rotations. They are termed 'Newly Formed Coronal Hole Area (NFOCHA)'.

4. Association of erupting stream disturbances with evolutionary changes in coronal holes

Hewish & Bravo (1986) have indicated the probable locations of the back projected erupting stream disturbances on the Sun as 90° wide circles on the synoptic maps. Using their data in the present study, the centers of these circles that ought to be the locations of origins of disturbances on the solar disk have been marked by bullets (•). These sources of erupting streams have been plotted on corresponding E-charts and their positions have been compared with the locations of delineated evolutionary changes in coronal holes in the form of POCHA and NFOCHA.

Distinct cases of newborn coronal holes over which the sources of erupting stream disturbances superimpose, have been identified. The classic example is erupting streams Nos. 7, 8 and 9 that came from the same source on rotation 1672, as indicated by the event numbers against the same Hewish's circle (cf. Fig. 2d). The sections of 10830 Å-synoptic maps of rotations 1671 and 1672 reveal that an isolated new coronal

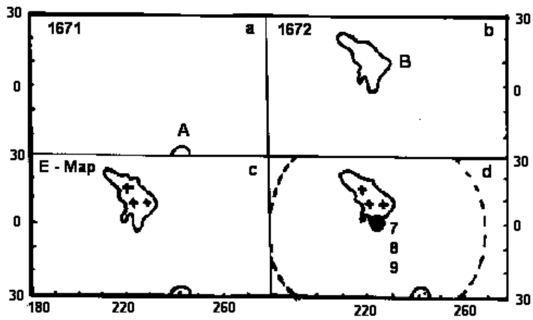

Figure 2. **(a & b)** Sections of 10830 Å synoptic maps of rotations 1671 and 1672, illustrating coronal holes A and B. **(c)** E-map (1672), derived from superposition of **(a)** and **(b)**, shows a newborn coronal hole 'B' (crossed region) and a small area 'A' that has been coronal hole previously (dotted region). **(d)** The dashed-circle represents the back-projected erupting stream disturbance onto the Sun. The center of the circle, as shown by bullet (•), corresponds to the source of erupting stream on solar disc. The event numbers 7, 8 and 9 refer to Table 1 of Hewish & Bravo (1986). Note the existence of source of the disturbances on the newborn coronal hole 'B'.

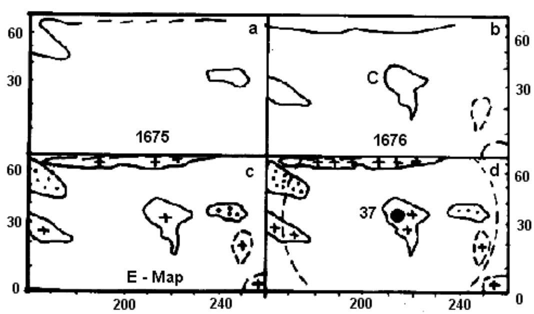

Figure 3. **(c)** E-map (1676) derived from superposition of **(a)** and **(b)** shows 5 newborn coronal holes (crossed regions) and 2 previously occupied coronal hole areas (dotted regions). **(d)** The source of back-projected erupting stream disturbance No. 37 on the solar disk, as shown by bullet (•), appears to exist on the newborn coronal hole 'C'. Note the existence of 4 NFOCHA and 2 POCHA within the circle that represents the back-projected disturbance onto the Sun.

hole 'B' (longitude 225–latitude N10; Fig. 2b) emerges on the solar disk in rotation 1672 and a small coronal hole 'A' (longitude 240–latitude S30) seen in rotation 1671 disappears subsequently in rotation 1672. The bullet (•) that indicates the source of the disturbances is seen to overlie on the newborn coronal hole 'B' (cf. Fig. 2d). It is interesting to note that there is no other coronal hole inside the Hewish's circle than the newborn coronal hole 'B' and a small area 'A' of about 10 degrees wide that has been a coronal hole previously (POCHA). However, 'A' is located far-off from the source location and thereby is unlikely to be linked to the erupting stream disturbances. Another example is erupting stream disturbance No. 37 (longitude 215–latitude N35; rotation 1676, Fig. 3d). The source of this disturbance appears to superimpose on the newborn coronal hole 'C' that emerges at longitude 230–latitude N35 in 1676 and resides with other 3 NFOCHA and 2 POCHA inside the Hewish's circle (cf. Fig. 3d). These examples demonstrate that the occurrence of erupting stream disturbances is related to the emergence of newborn coronal holes on the solar disk.

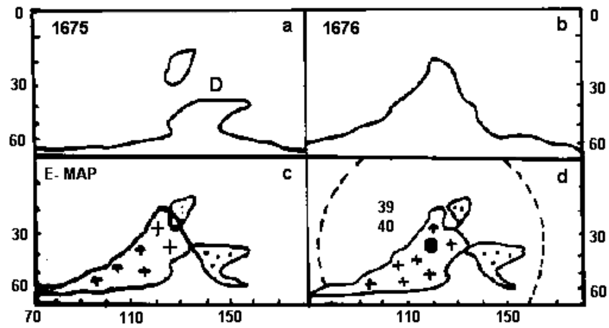

Figure 4. **(a) and (b)** Sections of 10830 Å synoptic maps showing polar coronal hole 'D' in preceding and succeeding rotations. **(c)** E-map (1676), showing concurrent growth and contraction of coronal hole D, forming NFOCHA (crossed region) on east side and POCHA (dotted region) on west side. **(d)** The source of back-projected erupting stream disturbances Nos. 39 and 40 on the Sun, as shown by bullet (•), appears to exist on newly formed coronal hole area. The dashed circle represents the back-projected disturbance on the Sun. Note the existence of both NFOCHA and POCHA within the circle.

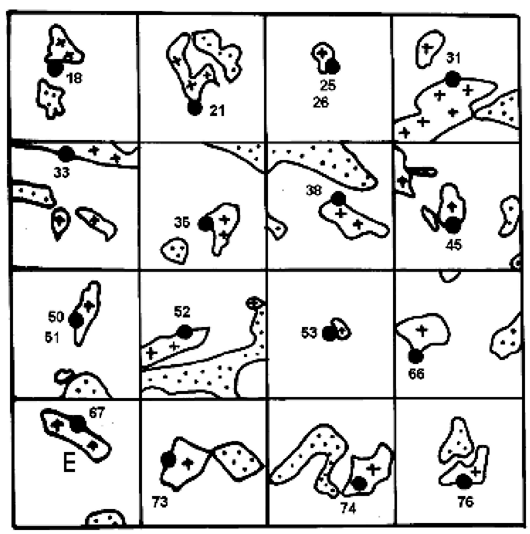

Figure 5. Striking examples of erupting stream disturbances demonstrating their association with NFOCHA (crossed regions). Dotted regions represent POCHA. Note the existence of sources of erupting streams (as shown by bullets) on NFOCHAs.

Additionally, erupting stream disturbances can also be related to new areas of coronal holes that are formed due to the growth of existing coronal holes. The best examples are erupting streams Nos. 39 and 40 that came from the same source located at longitude 120–latitude S35 in rotation 1676 (cf. Fig. 4d). Let us examine the evolution of a coronal hole 'D' (longitude 140–latitude S45; rotation 1675; Fig. 4a). It appears to grow eastward, but concurrently shrink westward in rotation 1676 (cf. E-map; Fig. 4c). Consequently, a new coronal hole area (crossed region) is developed into a large portion on the east side of 'D', when some of its west side area, shown by dotted region, is disappearing. The source location of erupting streams Nos. 39 and 40 appears to

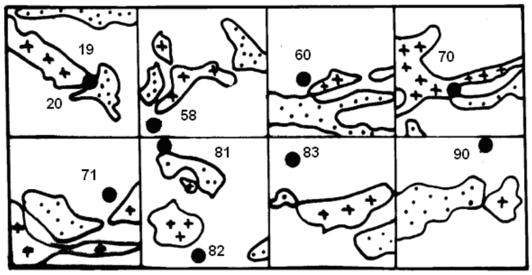

Figure 6. Classic examples of erupting stream disturbances showing a bit feeble association with NFOCHA. Note the existence of the sources of erupting streams (as shown by bullets) in close proximity to both NFOCHA (crossed regions) and POCHA (dotted regions).

exist inside this large, newly formed coronal hole area (NFOCHA) developed due to the growth of existing coronal hole (cf. Fig. 4d).

Some more striking examples are shown in Fig. 5. It can be seen that sources of erupting stream disturbances are located within the layout of NFOCHA. These NFOCHA cover both totally newborn coronal holes and new coronal hole areas formed due to the growth of existing coronal holes. All these examples demonstrate the association between source locations of erupting stream disturbances and newborn coronal holes on the solar disk (NFOCHA) formed due to the birth or growth of coronal holes.

However, there are some cases that exhibit a bit feeble association with NFOCHA. Figure 6 shows that the sources of erupting streams are located in close proximity to both NFOCHA and POCHA and thereby the possibility of their association with NFOCHA and POCHA is 50:50. The examples are event Nos. 19 and 20 (E-map 1673), 70 (E-map 1681) and 71 (E-map 1682). Besides, about 05 sources of the erupting stream disturbances appear to exist over or near the locations that have been coronal holes previously (POCHA) and hence are exceptions.

The histogram for the sources of erupting stream disturbances associated with NFOCHA or POCHA or both is plotted in Fig. 7. It can be seen that in a sample of 68 events of erupting streams, a large number of about 40 sources (plus 10 that are located within 20+ degrees as shown in Fig. 10) have shown their association with NFOCHA, with an exception of 5 events. About 13 sources have shown their alliance with both POCHA and NFOCHA. The sharp maximum for NFOCHA demonstrates a strong association between sources of erupting streams with newly formed coronal hole areas (NFOCHA). The critical examination of associated 40 NFOCHA reveals that all are not exclusively newborn coronal holes. Nearly half of them are new areas of coronal holes formed due to the growth of existing coronal holes. Their statistics are shown in Fig. 8.

There are some sources of erupting stream disturbances that do not overlie precisely on NFOCHAs, but reside close to them. This can be seen in Fig. 9. The classic example is event No. 64 (E-map 1680). The source is located about 10 degrees (in longitude) away from the border of the nearest NFOCHA. The histogram for the angular separation between the source locations and the border of associated NFOCHA or POCHA is shown in Fig. 10. Much closer positional agreement between sources of erupting streams and NFOCHA is apparent. This confirms the argument for a strong association between erupting stream disturbances and newborn coronal holes formed due to the birth or growth of coronal holes.

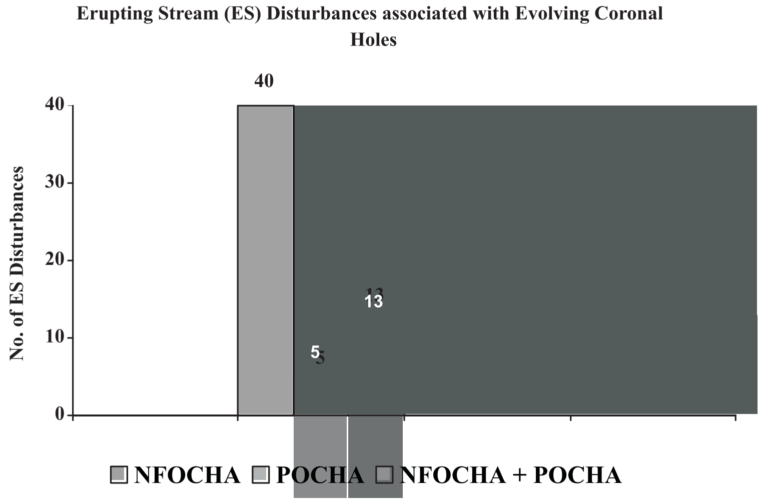

Figure 7. Histogram for sources of back-projected erupting stream disturbances associated with NFOCHA or POCHA or both. Note the sharp maximum for NFOCHA demonstrating their strong association with erupting stream disturbances.

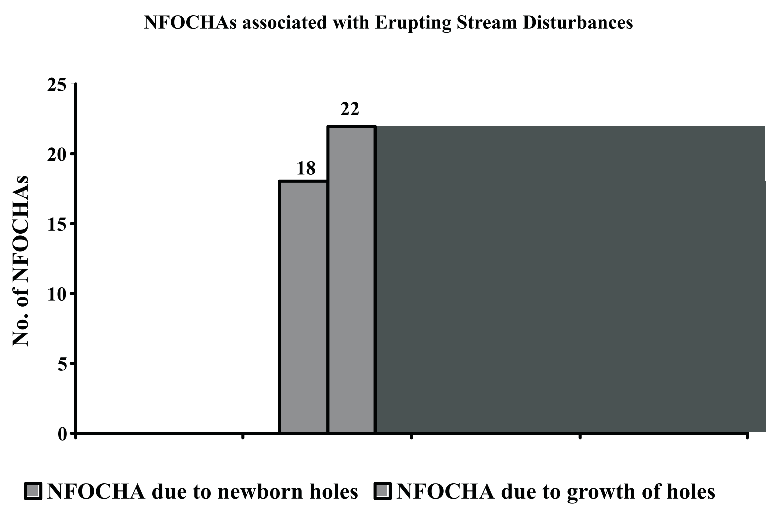

Figure 8. Statistics of newly formed coronal hole areas (NFOCHA) associated with erupting stream disturbances. About 18 NFOCHAs are exclusively newborn coronal holes and 22 are new areas of coronal holes formed due to the growth of existing coronal holes.

5. Magnetic configuration of coronal regions overlying the eruption site

It is interesting to examine the magnetic configuration of coronal regions in and around the eruption site of an erupting stream disturbance. This can be done by comparing daily maps of associated 10830 Å coronal holes before and after the date of eruption.

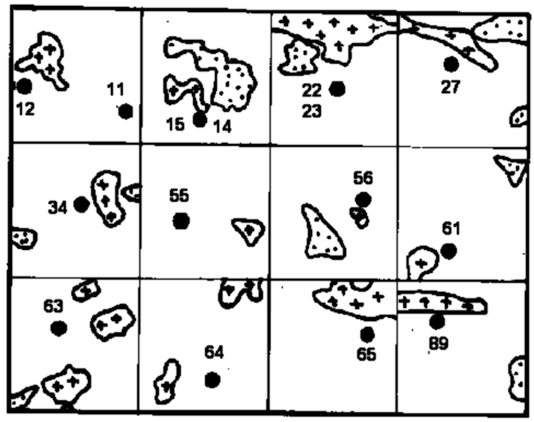

Figure 9. The classic examples of sources of back-projected erupting streams (shown by bullets) located close to NFOCHA (crossed regions) instead of overlying on them, as seen in preceding figures.

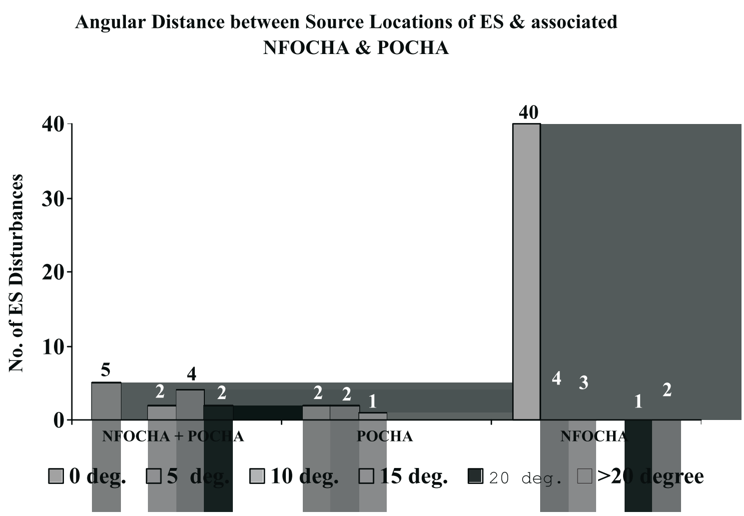

Figure 10. Histogram for sources of back-projected erupting stream disturbances (ES) associated with NFOCHA or POCHA or both for various angular separations (in degrees) between the source and border of nearest evolved part of coronal holes. Note the sharp maximum for NFOCHA for zero degree angular separation.

Let us examine an erupting stream disturbance No. 67 (cf. Fig. 5). This disturbance is unaccompanied by a flare or prominence activity anywhere on the disk. However, it is associated with the emergence of a new coronal hole 'E' on the Sun at latitude N 33–longitude 210 in rotation 1681. The daily maps of coronal hole 'E' arranged sequentially in Fig. 11 are examined to access the magnetic configuration of coronal regions in and around the eruption site of erupting stream disturbance No. 67. The critical examination of Fig. 11 reveals that coronal hole 'E' emerges on the solar disk at N 32 E 50

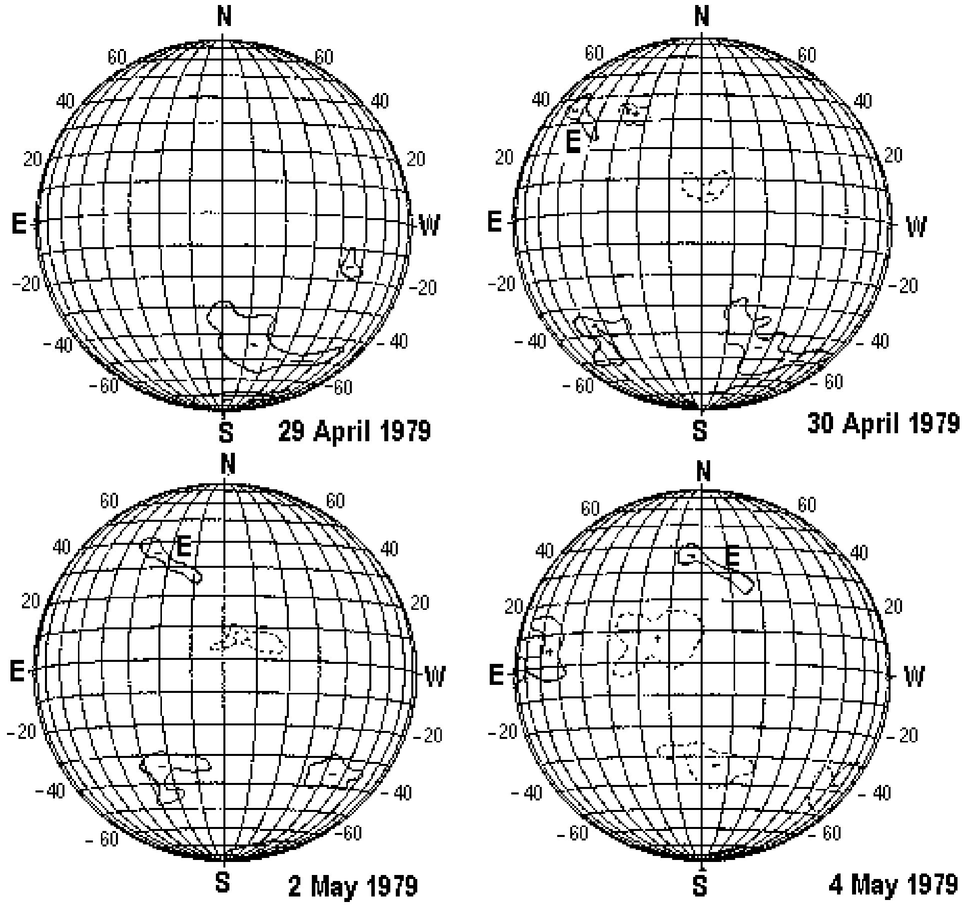

Figure 11. Day-to-day evolution of coronal hole 'E' associated with erupting stream No. 67. Note the formation of 'E' at N32–E50 on 30 April 1979. The arrival of leading edge of the erupting stream at 1 AU is 04 May 1979. There was neither flare nor disappearing prominence activity within the source area on the solar disc during a period $1 < \Delta t < 5$ days prior to the date of arrival.

on 30 April 1979 and can be seen in Fig. 11 till 4 May 1979. The leading edge of the disturbance has been reported to arrive at 1 AU on 4 May 1979 (cf. Hewish & Bravo 1986). The coronal hole 'E' should form within 90°-wide source area on the Sun during a period of 1–5 days prior to the arrival of the disturbance at 1 AU, if this newborn coronal hole was associated with erupting stream No. 67, which is indeed the case. This observation strengthens the argument for a close connection between transient erupting stream disturbances and newborn coronal holes lasting for days at the eruption site. It also suggests a conspicuous disruption of pre-existing closed magnetic structures in the corona during the onset of the erupting stream disturbance.

Like source location on the Sun, precise onset time of an erupting stream disturbance is not known. Therefore it is difficult to find out whether the evolution of coronal holes causes the eruption of erupting streams or eruption triggers the changes in the coronal holes. However, this observation categorically demonstrates that the formation of new coronal holes and the onset of transient erupting streams are the manifestation of some mechanism that opens up the large-scale, closed magnetic structure overlying the eruption site.

6. Discussion and conclusions

Interplanetary disturbances are identified as an increase in the density turbulence compared with the ambient solar wind. Erupting stream disturbances are transient large-scale structures of enhanced density turbulence in the interplanetary medium driven by the high-speed flows of low-density plasma trailing behind for several days. The present study demonstrates a strong association between the emergence of newborn coronal holes on the solar disk and the occurrence of erupting stream disturbances in the interplanetary medium. The comparison of daily maps of associated coronal holes before and after the date of eruption of a disturbance confirms a conspicuous disruption of pre-existing closed magnetic structures overlying the eruption site in the corona during the onset of the disturbance.

A coronal hole signifies a region of radial magnetic fields. There must clearly be a predominant magnetic polarity for a coronal hole and perhaps a region of curl $B \neq 0$ at the photospheric boundaries of the hole. The association between newborn coronal holes and erupting streams is indicative of some mechanism that is responsible for both the phenomena. It is reasonable to conclude that the fundamental activity for the onset of an erupting stream seems to be a transient opening of closed magnetic structure of coronal fields into a newborn coronal hole, which can support high-speed flow trailing behind the compression zone of the erupting stream for several days. The spherical-shaped compression zone of an erupting stream is perhaps the 'curved-front' of the closed field structure that erupts into interplanetary medium during the opening process.

It is possible that the 90°-wide source circles may include active regions and strong solar eruptions, besides newborn coronal holes. For the erupting stream events studied in the present study, Hewish and Bravo (1986) found that

(1) flares and disappearing prominences may, on some occasion, be related to erupting streams as peripheral events and
(2) there are many occasions when erupting streams are unaccompanied by a flare or prominence activity anywhere on the disk.

For another data, Manoharan (1997) has shown that more than 80% of the interplanetary transients observed during 1986–1991 are associated with the eruptive prominences on the Sun, which are suggested to be the source of coronal mass ejections. Moreover, there are some observations that show that transient coronal holes frequently form subsequent to eruptive prominences, CMEs or both (Rust 1983; Watanabe *et al.* 1992; Hudson 1996; Sterling & Hudson 1997). In case of CMEs, the changes in the distribution of mass ejection latitudes with time do not correspond to those for solar features or activity related to small-scale magnetic structures such as sunspots, active regions, or H-α flares; they do resemble those of features related to large-scale magnetic structures, such as prominences and bright coronal regions (Hundhausen 1993). Thus, it is reasonable to conclude that erupting streams are generated either by several different mechanisms or alternately by some more fundamental process, which under suitable conditions, can also trigger eruptive prominences or CMEs and form new coronal holes at the eruption site. The sequence of onset timings of erupting streams, eruptive prominences and newborn coronal holes needs to be examined by investigating these three types of events together.

Acknowledgements

The author is grateful to Dr. Jack Harvey for providing daily maps of 10830 Å-coronal holes. Thanks are also due to the referee for his useful comments that helped to improve the quality of the paper.

References

Bhatnagar, A. 1996, *Astrophys. Space Sci.,* **243**, 105.
Hewish, A., Bravo, S. 1986, *Solar Phys.,* **106**, 185.
Hudson, H. S. 1996, In: IAU Colloq. 153, Magnetodynamic Phenomena in the Solar Atmosphere – Prototypes of Stellar Magnetic Activity (eds) Uchida, Y., Kosugi, T., Hudson, H. S. (Kluwer: Dordrecht), 89.
Hundhausen, A. J. 1993, *J. Geophys. Res.*, **98(A8)**, 13177.
Manoharan, P. K. 1997, *Geophys. Res. Lett.*, **24(21)**, 2623–2626.
Rust, D. M. 1983, *Space Sci. Rev.*, **34**, 21.
Shelke, R. N., Pande, M. C. 1985, *Bull. Astron. Soc. India,* **13**, 62.
Steinitz, R., Eyni, M. 1980, *Astrophys. J.*, **241**, 417.
Sterling, A. C., Hudson, H. S. 1997, *Astrophys. J.*, **491**, L55.
Watanabe *et al.* 1992, *PASJ*, **44**, L199.
Webb, D. F., McIntosh, P. S., Nolte, J. T., Solodyna, C. V. 1978, *Solar Phys.*, **58**, 389.