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Transport of open magnetic flux between solar polar regions

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Abstract. We present the observations of coronal hole that has originated at the polar hole in one hemisphere, extended to equatorial region, got disconnected and transported across the equator to polar region of opposite hemisphere.

Keywords. Sun: magnetic fields, Sun: activity, Sun: corona, Sun: photosphere

1. Introduction and data

Earlier studies of coronal holes (CHs) have found near rigid rotation, which initially was interpreted as the consequence of CHs magnetic field rooted deep in the convection zone. Later, Wang & Sheeley (2004) have introduced the footpoint switching (or interchange reconnection), when the rigid rotation is maintained by continuous reconnection between closed (bipoles) and open (CH) field lines. Karachik, Pevtsov, & Sattarov (2006) used coronal bright points (CBPs) to trace solar rotation inside of three coronal holes. They found no difference in solar rotation for CBPs inside and outside of CHs. At the same time, the average rotation of studied CHs did not show presence of the differential rotation in agreement with the interchange reconnection model. On the other hand, Jones (2005) had pointed out that the internal rotation derived by helioseismology methods indicates that CHs may be rooted as deep as the base of the convection zone. Harvey & Recely (2002) had classified CHs on three category: polar CHs (latitude $> 60°$), isolated non-polar CHs ($\pm$ 60°), and transient CHs. Their study had revealed that polar CHs evolve from high-latitude isolated CHs. During their evolution, polar CHs may connect to low latitudes through polar lobes – a narrow equatorward extension of polar CH. However, the previous studies indicate that although polar holes in opposing hemispheres may extend to low latitudes, there is no direct interaction between two polar regions. Here we provide the first observational evidence of a complete transport of one CH across the equator, from one solar polar region to the other.

The data used in this study include full disk observations from SOHO/EIT (286Å) and SOHO/MDI. Our observations cover period of nine solar rotations, starting from Carrington Rotation (CR) 1982. Figure 1-left shows evolution of the total magnetic flux at high latitudes ($>$70°) computed from MDI Carrington maps. Using the intersection of linear polynomial with zero flux line, one can estimate that the Northern (Southern) polar field had reversed its sign around CR1965 (CR1976). Reversal dates for N-Pole/S-Pole were also reported as CR1972/CR1976 (Pevtsov *et al.* 2003) and CR1975/CR1981 (Durrant & Wilson 2003). Despite some disagreement in dates, we conclude that the transport of open magnetic flux (CH) across solar equator described below had occurred after both solar poles had reversed their polarities.

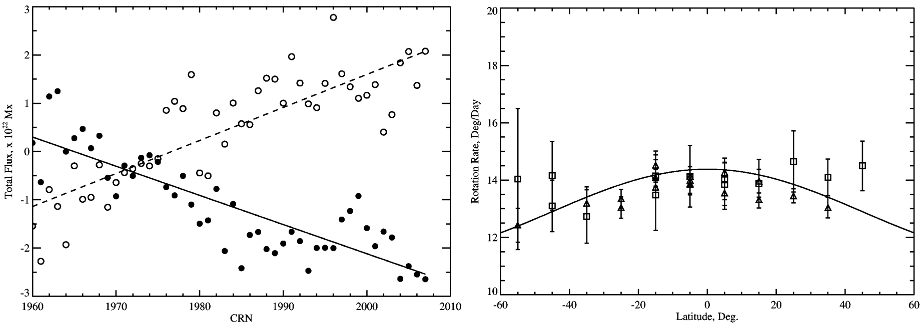

Figure 1. Left: Magnetic flux of polar regions at the time of polarity reversal. Open/filled circles corresponds to Southern/Northern polar regions. Dashed and solid lines are least squares best-fits to the data by first degree polynomial. Right: Mean rotation rate of CH boundaries. Triangles (squares) denote measurements with low (high) errors in rotation rates. Solid line is a typical sunspot rotation rate.

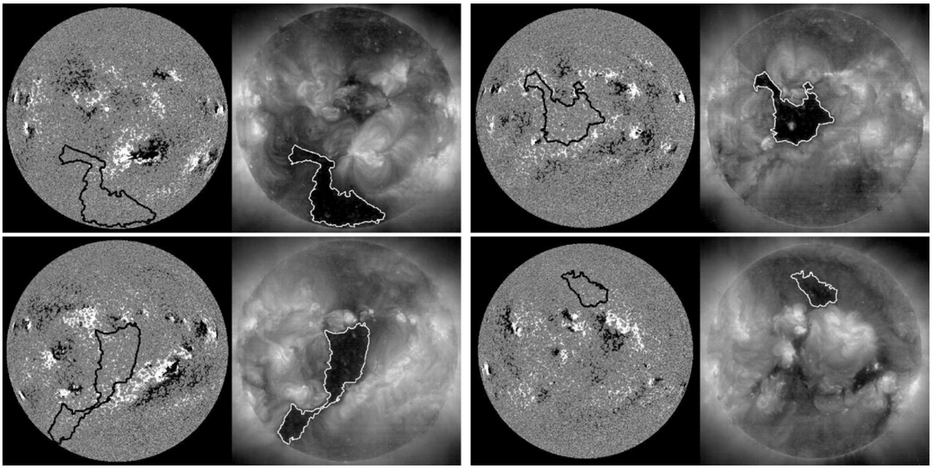

Figure 2. Coronal hole and its magnetic field. Left: CR1982, CR1985. Right: CR1987, CR1990.

Table 1. Flux, area, and Mean Field of CH.

CRN	M-Flux, Mx	Area, Pix	B_{AVG}, G
1982	3.8×10^{21}	7.9×10^{5}	2.3
1983	9.9×10^{21}	11.9×10^{5}	4.0
1984	11.2×10^{21}	9.0×10^{5}	6.1
1985	11.0×10^{21}	6.4×10^{5}	8.3
1986	19.0×10^{21}	7.6×10^{5}	12.2
1987	9.4×10^{21}	4.9×10^{5}	9.3
1988	4.0×10^{21}	2.1×10^{5}	9.1
1989	9.6×10^{21}	4.4×10^{5}	10.5
1990	0.7×10^{21}	1.0×10^{5}	3.6

2. Evolution of the Coronal Hole over Nine Solar Rotations

Examination of SOHO/EIT images starting with CR1982 indicates that although both poles had reversed their polarity, no polar CHs had developed. On CR1982, southern polar CH is situated very asymmetrically in respect to S-pole, and later, (CR1991) it

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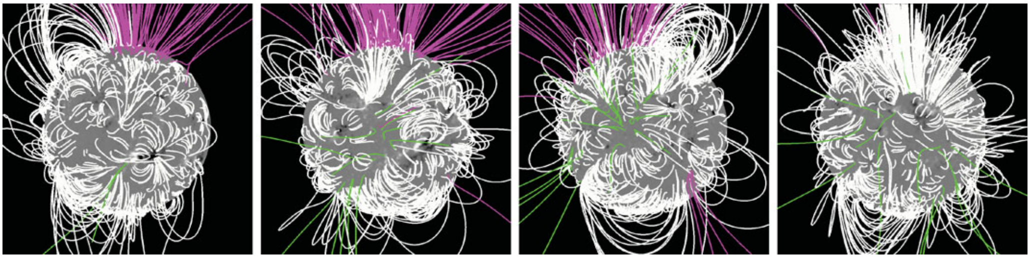

Figure 3. PFSS modelling of magnetic field shown on Fig. 2. White indicates closed filed lines; purple and green are opened field lines of opposite polarity.

disappears completely. CH on the North pole is also intermittent: it exists in CR1982, but is absent on later rotations. The studied coronal hole had originated as an extension of the South polar CH (Fig. 2). Once the extension reached the equator, the CH got disconnected from the southern polar hole. Next, it had travelled across the equator, and crossed to high latitudes in the Northern hemisphere. At the time of the event, the North polar region has had prevailing negative polarity field, while the newly transported CH was associated with the positive magnetic polarity. Table 1 and Fig. 2 demonstrate lack of continuity in total magnetic flux and area of the CH as it travels across the equator. Total magnetic flux associated with this CH varies between $\approx 4\%$ and 50% of total magnetic flux of polar field at the time of the event (2–$4{\times}10^{22}$ Mx). Significant variations in total flux and area indicate that these key properties of CH are largely determined by its photospheric roots. In that respect, the CH is analogous to a grass fire, which supports itself by continuously propagating from one patch of dry grass to the other. Such behavior is consistent with the interchange reconnection model. The lack of continuity and significant variations in flux and area of CH suggests that although morphologically it appears as the same coronal hole, its photospheric/magnetic footprint is constantly changing, thus suggesting that CHs are not a deep-rooted phenomena. Rotation profile of CH (Fig. 1, right) was computed by tracking the position of the mid-point between East and West boundaries of CH at a given latitude. Disregarding extreme latitudes, where the errors of this method are high, the average rotation profile is in a good agreement with the photospheric rotation. A gradual distortion of shape of CH (Fig. 2) also indicates that its photospheric footprint follows closely to the solar differential rotation profile. Travel "path" of the CH does not appear to be random. Despite the presence of weak magnetic fields of right polarity in vicinity of CH, it does not always move to these polarity patches. Analysis of EIT images suggests that CH avoids areas of closed magnetic fields, and its path follows the large-scale boundaries between separate flux systems. Potential Field Source Surface (PFSS, Fig. 3) modelling indicates that overall motions of the coronal hole are governed by location of magnetic separatrices in the corona.

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