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# Occurrence rate of magnetic holes between 0.72 and 1 AU: comparative study of Cluster and VEX data

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**Abstract.** Localised depressions in the magnetic field magnitude, or magnetic holes, are common features in many regions of solar system plasma. Two distinct mechanisms for their generation have been proposed. The first proposed that the structures are generated locally, close to the point of observation. The alternative has been proposed by Russell et al. (2008), who suggest that the observed magnetic holes represent nonlinear mirror structures that can be carried by the solar wind over vast distances of mirror stable plasma. According to Russell et al. (2008), magnetic holes are created in the vicinity of the sun and are convected by the solar wind outward. Periods of Cluster 1 and VEX data when both spacecraft were connected by the solar wind flow have been considered in this study, in order to determine the evolution of the magnetic holes occurrence rate. The comparison of the magnetic holes occurrence near the Venus and the Earth supports the Russell et al. (2008) premise that they are generated closer to the Sun most likely somewhere within the orbit of Mercury.

**Keywords.** Space plasma physics (Nonlinear phenomena)

## 1 Introduction

Localised nonlinear dips in the magnetic field were first referred to as "magnetic holes" by Turner et al. (1977) during their analysis of IMP6 data in the solar wind. Since this observation, it has been found that these structures are commonly observed in many regions of solar system plasma such as the solar wind (Turner et al., 1977; Fitzenreiter and Burlaga, 1978; Stevens and Kasper, 2007), planetary magnetosheaths (Balogh et al., 1992; Hubert et al., 1989; Tsurutani et al., 1982; Kaufmann et al., 1970), the Io wake, in cometary plasma (Russell et al., 1987) and even at the borders of the heliosphere (Tsurutani et al., 1984). An example of magnetic holes observed by the Venus Express magnetometer in the solar wind is shown in Fig. 1. A number of models have been proposed to explain the observations of magnetic holes, the most common and widely accepted of which attribute the majority of magnetic holes to the nonlinear stage of mirror instability (Southwood and Kivelson, 1993). The shape and duration of the magnetic holes seen in Fig. 1 is very similar to mirror wave structures observed in the magnetosheath (Balikhin et al., 2003, 2010; Chisham et al., 1999). Comprehensive theory of mirror instability that accounts for electron temperature (Pokhotelov et al., 2000), finite Larmor radius effects (Pokhotelov et al., 2004), plasma gradients (Pokhotelov et al., 2001), non-Maxwellian and multicomponent plasmas (Pokhotelov et al., 2008) has been developed. Analytical studies of the quasilinear and nonlinear stages of the instability (Pokhotelov et al., 2010) demonstrated how the mirror waves can be carried by the solar wind over long distances through the mirror stable plasma. However there are some arguments against attribution of all observed magnetic holes (dips) to the mirror instability (Tsurutani et al., 1992).

The region of magnetic hole generation is still unclear Russell et al. (2008) suggested that magnetic holes are created much closer to the Sun and survive for very long periods whilst being convected by the solar wind over huge distances in what is essentially a mirror stable plasma. Recently, THEMIS observations have been used to explain how magnetic holes can exist in the mirror stable plasma (Balikhin et al., 2009). If, as Russell et al. (2008) suggest, magnetic holes are generated closer to the Sun, they can be used for remote sensing of the plasma conditions in their region of generation. Plasma from the region in which the magnetic hole was generated will be trapped within the magnetic depression and carried along with the structure as it convects with the solar wind. Both the polarisation of a particular

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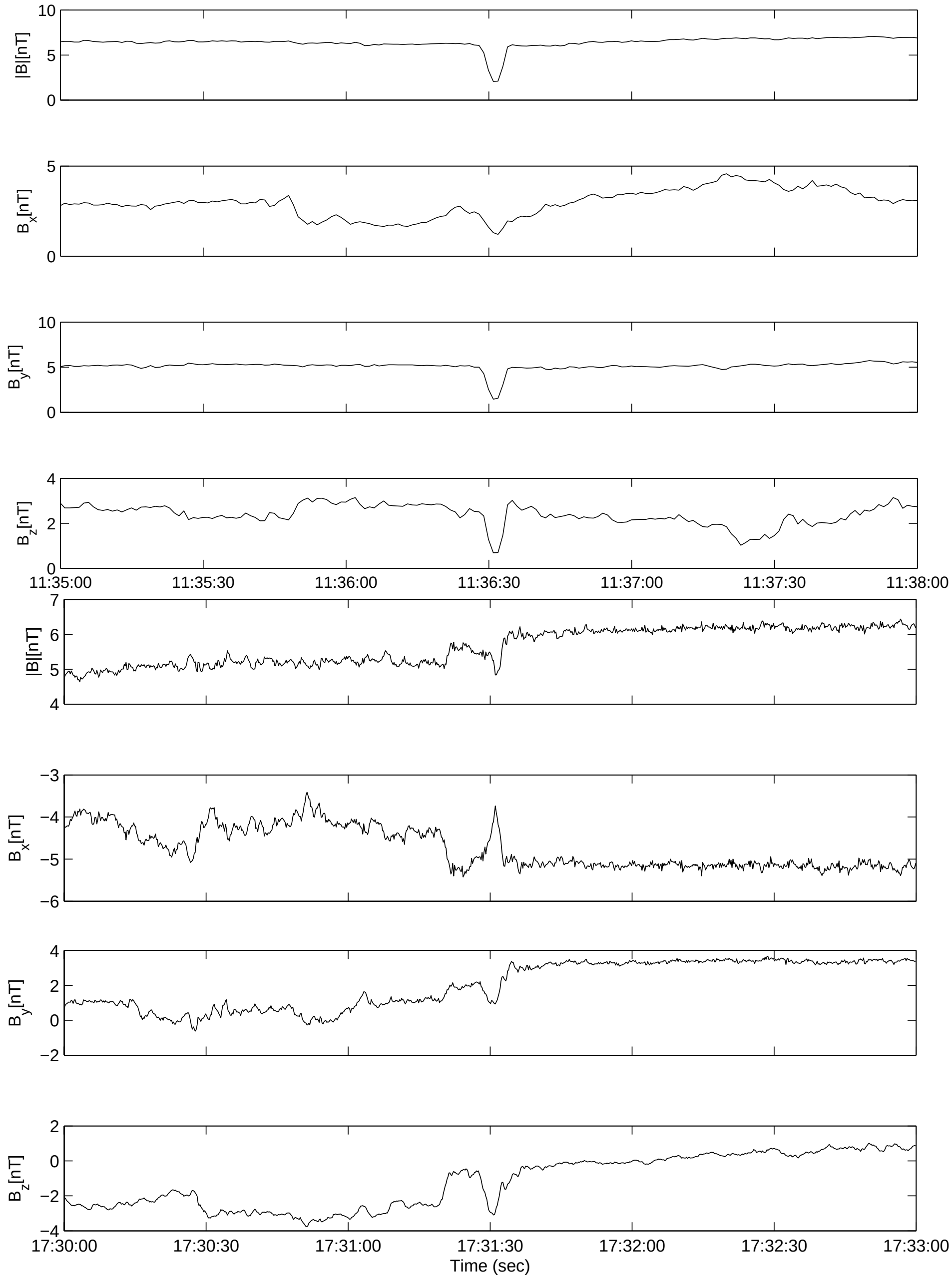


**Fig. 1.** Magnetic holes observed by Venus Express (top panel) and Cluster C1 (bottom panel). Each panel is 3 min long showing time of the day.

holes and the distribution of plasma trapped within them can provide valuable information about conditions in the region in which the magnetic hole was generated. As a analysis of Russell et al. (2008) suggestion regarding the generation region, the present paper exploits a conjunction between Venus and Earth (using observations by VEX and Cluster) that took place on 27 March 2009. Since the two spacecraft are separated by a distance of over 0.3 AU the probability for the spacecraft to detect the same magnetic hole, which size is of the order of $10^1$–$10^2$ ion Larmor radii, is very unlikely. Therefore a statistical study of the occurrence of magnetic holes around this conjugation period has been conducted and its results are presented in this paper.

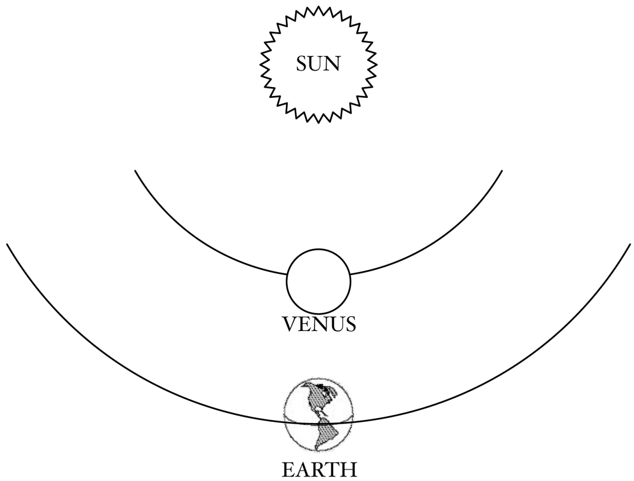


**Fig. 2.** Schematic representation of Venus-Sun inferior conjunction, that took place on 27 March 2009.

## 2 Data and analysis

### 2.1 Instrumentation

Data used in this statistical study were collected in the solar wind by the magnetometer instruments onboard the Venus Express (VEX) and Cluster spacecraft. Operating since April 2006, the VEX (Titov et al., 2006; Svedhem et al., 2007) is in a polar orbit with a period of 24 h. Since the pericentre/apocentre distances are 250/66 000 km and that the periapsis occurs at around 78° N, the satellite spends most of its time in the solar wind. Since VEX is a magnetically unclean spacecraft, VEX magnetometer instrument (Zhang et al., 2006) uses a dual sensor arrangement to enable the removal of stray magnetic fields generated by the operation of the spacecraft. The time resolution of the data used in this study is 1 s and for every each orbit we have excluded the periods when magnetic field was perturbed by the planet. The Cluster (Escoubet et al., 1997) satellites also occupy polar orbits. However, the orbit differs from that of VEX in that the line of apsides lies close to the equatorial plane. As a result, Cluster measurements in the solar wind are typically limited to a period from December to May. Cluster is a magnetically clean spacecraft and so the generation of stray magnetic fields due to spacecraft operations is minimised. The data from the Cluster fluxgate magnetometer (FGM) instrument (Balogh et al., 1997) used in this study has a 5 Hz sampling rate. Only the data when Cluster and VEX are outside the bow shock, in the solar wind have been considered. We have examined a period of 3 months of data, centred in the only Venus-Sun conjunction that has occurred in 2009. An inferior conjunction, when the two planets (Earth and Venus) lie in a line on the same side of the Sun (Fig. 2), occurs approximately once every 9 months. Due to the limited time when the Cluster satellites are in solar wind, and considering that Vex mission has only started in 2006, March 2009 is the only time interval that could be considered.

### 2.2 Methodology

One of the first computational methods proposed for the identification of the magnetic holes (Winterhalter et al., 1994) proposed a sliding window based method. Each data point is compared to the mean field magnitude in a 300 s window centred in the data point. The ratio $B_{\mathrm{min}}/B_{\mathrm{mean}}$ is calculated and compared to a threshold value determined on a trial and error basis. A second selection condition limits the field rotation observed across each event to less than 10°. Later studies had a more flexible approach on the numerical values of the thresholds and the detection method has been improved by considering the standard deviation in determining whether a candidate is indeed a magnetic hole, followed by visual inspection (Zhang et al., 2008).

In this paper we investigate the occurrence of magnetic holes over a period of 3 months using a wavelet based methodology. The proposed methodology has few advantages in comparison with the previous discussed studies, given by the variable scale and window length, a better correlation of the data set with the disturbance in the background and the ability to process automatically considerable amount of data.

Due to the quality and resolution of the data, the background, width, shape and structure of the magnetic dips, we have chosen "Morlet" wavelet to analyse the data. The length of the scales by which the function will be stretched reflects the maximum duration of a magnetic hole, ranging from few seconds to almost a minute (Winterhalter et al., 1994; Turner et al., 1977). By varying the wavelet scale and translating along the localised index of the time series, one can construct a representation showing both the amplitude of any features against the scale of the wavelet and how this amplitude varies in time. The wavelet function at each scale is normalised to have unit energy, so that the wavelet transforms at each scale are directly comparable to each other and to the transforms applied to subsequent sliding windows. The size of the cone of influence (COI) has been computed for a better detection accuracy. this results in a better measure of the decorrelation time for a single negative peak in the time series. By comparing the width of the peak in the wavelet power spectrum with this decorrelation time, one can distinguish between a dip in the data (possibly due to noise) and a harmonic component at the equivalent Fourier frequency. A 95 % confidence level was computed against a red noise background spectra. It has been used to initiate a null hypothesis for the significance of a peak in the wavelet power spectrum, offering extra reliability for the automatic detection.

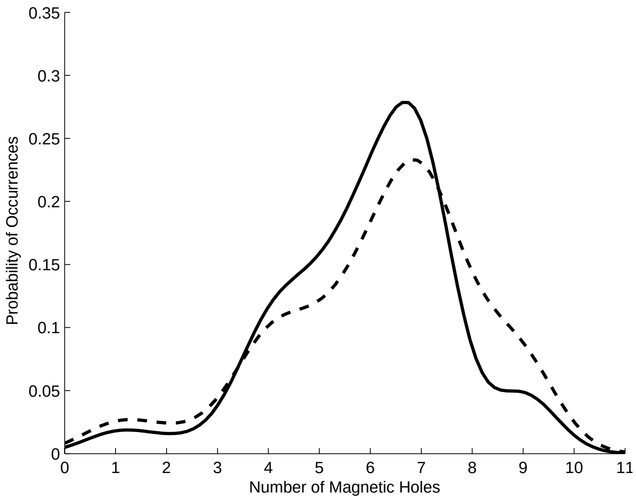


**Fig. 3.** VEX (dashed line) and Cluster (solid line) probability distribution functions of the occurrence rate.

### 2.3 Criteria and thresholds

For the purpose of our study, we characterise the mirror modes structures by: the depth of the corresponding depression of the magnetic field, the width of the magnetic hole and field rotation across the dip. The wavelet transform produces a matrix $\mathbf{W}(s,t)$ with the size $(s,x_n)$, where $s$ are the number of scales and $x_n$ is the length of the magnetic field time series. The level of correlation is reflected in the value of the corresponding term in the matrix of wavelets and it indicates the relative width of the magnetic hole and the index location of the dip in the magnetic field time series. Once the index of a candidate is known, a point by point algorithm was used to determine from the magnetic field magnitude data, the exact width by computing the difference between consecutive points $([x(2)-x(1) \quad x(3)-x(2) \quad \ldots \quad x(n)-x(n-1)])$, where $x(1)$ is the index of the dip, $x(n)$ is the maximum relative width determined by the wavelet transform. After determining the position and the width, we determine the linearity of the hole by computing the field rotation across the hole: $\theta = \arccos((\boldsymbol{B}_a \cdot \boldsymbol{B}_b)/(\|\boldsymbol{B}_a \times \boldsymbol{B}_b\|)) < 10°$. Only linear holes are considered to reduce the misidentification of structures generated by other processes associated with the interplanetary discontinuities. Each magnetic hole is considered to be a distinct event regardless of the proximity of other similar events. Our observed mirror mode structure occurrence rate is comparable with the results (Zhang et al., 2008; Soucek et al., 2008). It is likely that among the detected events there are also contributions from other types of discontinuities that produce field decreases but which are not commonly considered magnetic holes. It is difficult to classify the nature of the magnetic field drops based upon magnetic field alone due to the obvious variations in the structure of the magnetic hole (Fig. 1). However in studying the mirror mode waves, we are more interested in the relative value of the occurrence rate than the absolute one. In other words, we are interested in comparing the occurrence rate at various heliocentric distances in respect to time.

### 2.4 Statistics

Once the occurrence rate has been determined by the wavelet detection algorithm, for both date sets (VEX and Cluster), a probability distribution function (p.d.f.) is computed using a kernel smoothing density estimation technique. This method computes a probability density estimate of the occurrence over the 3 months for each of the data sets. The smoothness of the kernel density estimate is evident compared to the discreteness of the histogram provided by the two occurrence vectors. This discrete appearance is a result from the inherent statistical inefficiency of histograms as compared to kernel estimators. The estimate is based on a normal kernel function, using a window parameter that is a function of the number of points in the occurrence vector. The density is evaluated at one hundred equally spaced points that cover the range of the data.

The kernel density approximation of probability density function is defined by:

$$\hat{f}_b(x) = \frac{1}{mb}\sum_{i=1}^{m} K\left(\frac{x-x_i}{h}\right)$$

where $b$ is the bandwidth, $(x, x_1, \ldots, x_i)$ are the independent and identically distributed random variables sampled from the $K(x)$ distribution with an unknown density $f$ and kernel $K_b$ – the scaled kernel with the property: $K_b(x) = 1/b \cdot K(x/b)$, where $K$ is the standard normal distribution, described by the probability density function:

$$K(x|\mu,\sigma) = \frac{1}{\sigma\sqrt{(2\pi)}} e^{\dfrac{-(x-\mu)^2}{2\sigma^2}}$$

## 3 Results and conclusions

The two p.d.f. resulting from VEX (dashed line) and Cluster (solid line) data are shown in Fig. 3. Surprisingly they are very similar in overall shape and even some fine features. For example secondary maxima in Cluster data around 1 and 9 correspond to the secondary maxima in VEX around 1 and distinct change in the slope of the distribution at 9. The mirror instability is a kinetic instability, with some similarity to the plasma beam instabilities. However the role of resonance particles is played by ions with very small velocities (Southwood and Kivelson, 1993). The growth rate and subsequent nonlinear stage of evolution depends upon the peculiarities of distribution of these small portion of ions. So it is very unlikely and even impossible to explain the similarity of the p.d.f. in Fig. 3 by the generation mechanism. Such a similarity can only be explained if indeed as Russell et al. (2008)

assumed the magnetic holes are generated close to to the Sun and are carried by the solar wind further and further, passing on their way both the Venus and the Earth.

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