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Cone angle control of the interaction of magnetic clouds with the Earth’s bow shock

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Abstract We study the interaction of magnetic clouds (MCs) with the near-Earth environment. Recent works suggest that the bow shock crossing may modify significantly the magnetic structure of an MC, and thus its ability to drive geomagnetic storms. This change is largely controlled by the bow shock configuration, which depends on the upstream interplanetary magnetic field (IMF) orientation. From the distribution of the magnetic field orientation in 152 Earth-impacting MCs, we determine for the first time the typical shock configuration during MC events. We find that 56% (6.3%) of the time, the subsolar bow shock configuration is exclusively quasi-perpendicular (quasi-parallel). The rest of the time, both configurations coexist. Furthermore, using a subset of 63 MCs observed simultaneously in the solar wind and in the dayside magnetosheath, we determine the magnitude of the magnetic field alteration, how it depends on the shock configuration, and how it relates to the IMF cone angle.

1. Introduction

Magnetic clouds (MCs) are a subgroup of interplanetary coronal mass ejections, characterized by an enhanced and smoothly rotating magnetic field [Burlaga et al., 1981]. They are responsible for the strongest geomagnetic storms [Huttunen et al., 2005; Yermolaev et al., 2012] and are thus of particular importance for solar-terrestrial studies and space weather forecasting. In order to predict their geomagnetic effects, considerable effort has been put into analyzing correlations between the MCs’ properties in the solar wind and the level of magnetic disturbances on the ground [e.g., Gopalswamy et al., 2008; Ji et al., 2010; Hidalgo et al., 2011, and references therein]. However, one key process that is usually ignored is the MC’s interaction with the bow shock and the ensuing propagation into the magnetosheath.

Operating as the interface between the interplanetary and the planetary plasma, the magnetosheath regulates the solar wind-magnetospheric coupling. The large-scale structuring of the magnetosheath is largely controlled by the bow shock configuration. In turn, the shock configuration is defined by the angle $\Theta_{Bn}$ between the interplanetary magnetic field (IMF) and the local shock normal. For example, the Parker spiral IMF orientation leads to the quasi-perpendicular shock geometry on the dusk flank and the quasi-perpendicular geometry on the dawn flank, giving rise to considerable dawn-dusk asymmetries in the magnetosheath [e.g., Dimmock and Nykyri, 2013; Walsh et al., 2014; Dimmock et al., 2015, and references therein].

The orientation of an MC’s magnetic field can change significantly as it passes through the bow shock. The extent of this alteration depends on the shock configuration [Turc et al., 2014a, 2014b, 2015]. Therefore, it is important to know the encountered $\Theta_{Bn}$, to understand the geoeffectivity of MCs. The shape of the bow shock, and thus its normal, can be estimated through modeling, while the upstream magnetic field direction during MCs is currently primarily available from observations near the first Sun-Earth Lagrangian point (L1). However, in the context of space weather forecasting, this is, in general, too short to provide advance warnings, and the a priori knowledge of the MC’s magnetic field configuration is generally not available. Yet if there are preferred orientations of the MCs’ magnetic field, one can determine typical bow shock configurations the MCs encounter and hence better estimate their geomagnetic response.

In this paper, we will first examine 152 MCs observed in the solar wind upstream of Earth to check whether there are predominant orientations in their magnetic field. Using these statistical results in combination with a
bow shock model, we will then estimate the shock configuration during these MCs. Finally, we will use a subset of 63 MCs where simultaneous observations were available both in the solar wind and in the magnetosheath to examine how the change in the MCs’ magnetic field across the bow shock relates to the upstream magnetic field orientation.

2. Event List and Data Sets

This study is based on a catalog of 152 Earth-impacting MCs, extending from January 2000 to December 2014. The events were identified by visual inspection of spacecraft observations upstream of Earth and are listed in the table provided as supporting information to this paper. Because this catalog was initially compiled to facilitate the comparison of observations in the solar wind and in the Earth’s environment during MCs, the OMNI data set is used as a reference for the times. Note, however, that in the present paper, we will use primarily data from the Advanced Composition Explorer (ACE) [Stone et al., 1998] spacecraft, which remained in the vicinity of L₁ throughout the studied period. The reason for that is that most of our analysis does not require time-shifted data, except in section 3.3. We use the measurements from the Magnetic Field Experiment [Smith et al., 1998] and from the Solar Wind Electron, Proton and Alpha Monitor [McComas et al., 1998]. In case of large data gaps at ACE, the OMNI data set propagated to the Earth’s bow shock, or the Magnetic Field Investigation [Lepping et al., 1995] and the Solar Wind Experiment [Ogilvie et al., 1995] measurements from the Wind spacecraft [Acuña et al., 1995] are utilized instead. All data are obtained from the Coordinated Data Analysis Web (CDAWeb).

Our identification criteria were primarily (i) a magnetic field strength higher than in the ambient solar wind and (ii) a smooth rotation of the magnetic field direction [Burlaga et al., 1981]. Additional criteria were also used to define the front and rear boundaries of the MCs, such as the proton temperature and density, the Alfvén Mach number \(M_A\), and the plasma beta being lower than in the surrounding solar wind. Note that none of these signatures are a necessary condition, as they are not consistently, albeit frequently, observed during MCs [e.g., Jian et al., 2006; Lepping et al., 2006; Lavraud and Borovsky, 2008, Wu and Lepping, 2011]. Also, the events listed in our catalog are essentially the same as those listed in, for example, Wu and Lepping [2015] and by Richardson and Cane [2010; http://www.srl.caltech.edu/ACE/ASC/DATA/level3/icmetable2.htm], but the start and end times of the MC proper often differ. The main reasons for that are that we are not restricting our selection to events that can be modeled by flux ropes, as was done, for example, in Lepping et al. [2006] and Wu and Lepping [2015], and that we use the \(M_A\) as an additional criterion to define the MCs’ boundaries.

For each of these MCs, we have checked whether the following spacecraft sampled the dayside magnetosheath during the MC’s passage: Cluster [Escoubet et al., 2001], the Time History of Events and Macroscale Interactions during Substorms (THEMIS) [Angelopoulos, 2008], the Geomagnetic Tail Lab (GEOTAIL) [Nishida, 1994], Interball Tail [Galeev et al., 1996], and Double Star TC1 [Liu et al., 2005]. Magnetic field measurements in the magnetosheath are obtained from the FluxGate Magnetometers aboard Cluster [Balogh et al., 1997], THEMIS [Auster et al., 2008], and Double Star [Carr et al., 2005]; the Magnetic Field Experiment [Kokubun et al., 1994] aboard Geotail; and from the FM-3I and the Multicomponent Investigations of Fluctuations (MIF) magnetometers [Nozdrachev et al., 1995; Klimov et al., 1997] aboard Interball Tail.

3. Results

3.1. MC Properties at L₁

Using our event catalog, we analyze the properties of MCs at L₁ from 2000 to 2014, i.e., between the maxima of Solar Cycles 23 and 24. Our results may thus not be representative of other solar cycles. We calculate the distribution of the magnetic field and plasma parameters within MCs using 5 min average data. We have checked that using other window widths, from 1 min to averaging over an entire event, does not affect the results significantly. Note that we exclude here the sheath regions which precede a large number of MCs and whose properties differ strongly from the MC proper.

Our data set comprises > 43,000 samples. The average number of samples per event is 287, corresponding to a 23.9 h duration, with a standard deviation of 11.4 h (137 samples). This is comparable, for example, to the data set of Wu and Lepping [2015], in which the average MC duration is 18.8 h, with a standard deviation of 11.0 h. The event duration ranges from 4.25 h (51 samples) to 62.8 h (754 samples).

Figure 1 shows the distribution of (a) the magnetic field strength, (b) its cone angle \(\text{arccos}(B_x/B)\), (c) its clock angle \(\text{arccos}(B_z/\sqrt{B_y^2 + B_z^2})\) (with the magnetic field components in the geocentric solar magnetic (GSM))
Figure 1. Distribution of (a) the magnetic field strength, (b) the magnetic field cone angle arccos ($B_x/B$), (c) the magnetic field clock angle arccos ($B_z/\sqrt{B_y^2 + B_z^2}$) (with $B_x$, $B_y$, and $B_z$ in GSM coordinates), and (d) the Alfvén Mach number in the solar wind upstream of Earth, during 152 MC events. Also indicated in each panel are the mean and median values of the displayed parameter; the numbers in parentheses correspond to the mean and median values for the reduced data set used in section 3.3.

During undisturbed times, the IMF is expected to follow on average the orientation of the so-called Parker spiral [e.g., Borovsky, 2010]. At Earth, it makes a 45° angle with the Sun-Earth line and lies roughly in the ecliptic plane. This would translate into a 45° cone angle and 90° clock angle. During MCs, however, we find that the magnetic field orientation often departs strongly from that direction, as evidenced in Figures 1b and 1c. The cone angle distribution (Figure 1b) peaks at 90°, i.e., $B_x = 0$. The average cone angle is 88°, and its values range between 70° and 110° about 45% of the time during MCs. Therefore, the magnetic field of MCs lies generally close to the plane perpendicular to the Sun-Earth line, and its $B_z$ component is small. The extreme cone angle values, corresponding to quasi-radial magnetic field orientations, are mostly due to a few events.

Overall, the clock angles are much more evenly distributed than the cone angles (Figure 1c), suggesting that MCs do not have a strong predominance of their orientations in the plane perpendicular to the Sun-Earth line. However, there seems to be a tendency for clock angles to occur between $-130^\circ$ and $-50^\circ$ and 60° and 140°. Yet the bin values remain essentially within one standard deviation from the average, as evidenced by the dashed black (mean) and blue (mean ± 1σ) circles in Figure 1c. Only the peak between 60° and 140° slightly exceeds one standard deviation and may stem from the fact that our data set contains more MCs with their axis oriented toward positive than toward negative $B_y$, as was, for example, the case in the data set of Li et al. [2011]. We also note that, in general, the clock angle tends to vary more than the cone angle during a given event (not shown).

The distribution of the $M_A$ (Figure 1d) shows that its values are typically much lower during MCs than during regular solar wind conditions, where $M_A$ usually ranges between 8 and 10. The distribution displayed in Figure 1d peaks between 3 and 4 and has a mean value of 4.7, consistent with the results presented, for example, in Lavraud and Borovsky [2008].
3.2. Bow Shock Configuration During MCs

As discussed in section 1, the shock configuration can affect the interaction of MCs with the Earth's environment. In particular, the crossing of the quasi-parallel shock leads to significant modifications of the MCs' magnetic field orientation [Turc et al., 2014b, 2015]. It is therefore of particular importance to know the details of the shock configuration the MC encounters upon entering the magnetosheath. Because the magnetic field of MCs rotates slowly, while the other solar wind parameters remain fairly constant, the passage of an MC can be regarded as a succession of quasi steady states. Since the upstream conditions are stable on time scales far greater than the kinetic scales associated with the bow shock physics, the bow shock has sufficient time to adapt to them. In particular, the foreshock should reform upstream of the quasi-parallel region as it moves along the bow shock's surface, as shown in Turc et al. [2015] using hybrid simulations. Therefore, the shock geometry is dictated by the MC's magnetic field and progressively evolves during its passage.

The values of the angle $\Theta_{Bn}$ can be estimated using a bow shock model. We utilize here the Ježáb et al. [2005] model, which has been shown to be more reliable than other models in the low $M_A$ regime [Turc et al., 2013]. As the inputs for the model, we use the mean magnetic field and plasma parameters during the MC events analyzed in section 3.1, i.e., $B = 12.4$ nT, $n = 6.5 \, \text{cm}^{-3}$, and $V = 482 \, \text{km} \, \text{s}^{-1}$.

The values of $\Theta_{Bn}$ along the bow shock's surface are calculated for three different IMF orientations: due northward (Figure 2a), Parker spiral like (Figure 2b), and radial (Figure 2c) IMF. Each of the panels displays a polar map of the dayside bow shock surface, as if it were observed from the Sun, with the colors indicating the $\Theta_{Bn}$ values. The distance from the center of the plot corresponds to the zenith angle, relative to the Sun-Earth line, ranging here from 0 to 90°, while the azimuthal direction is the angle in the plane perpendicular to the Sun-Earth line. According to the distribution of the upstream magnetic field cone angle (see Figure 1b), Figure 2a illustrates the most common situation during MCs, with a cone angle equal to 90°. We show here an example with a 0° clock angle, but other values of this angle would result in a similar shock configuration, only rotated about the Sun-Earth axis so that the area where $\Theta_{Bn} = 90°$ (in black) would remain at 90° from the upstream magnetic field.

**Figure 2.** Color maps of the $\Theta_{Bn}$ angle along the surface of the dayside bow shock, calculated for three upstream magnetic field orientations: (a) due northward, (b) Parker spiral, and (c) radial IMF. The center of the plot corresponds to the subsolar point. The distance from the center of the plot is proportional to the zenith angle.
Figure 3. (a) $\Theta_{Bn}$ as a function of the upstream magnetic field cone angle. The thick dashed black lines show the maximum and minimum values of $\Theta_{Bn}$ in the bow shock geoeffective region as obtained from the 
{\citet{Jebral05}} model. The crosses correspond to 5 min samples of spacecraft observations in the magnetosheath (red: downstream of the bow shock geoeffective region; blue: not linked to the geoeffective region) during MCs. The dotted line marks $\Theta_{Bn} = 45^\circ$. (b) $\psi$ as a function of the upstream magnetic field cone angle for each of the 5 min magnetosheath samples. Color coded are the values of $\Theta_{Bn}$ associated with each of these data points. The black circles indicate the mean $\psi$ in each 20$^\circ$ cone angle bin.

clock angle. This map shows that for a 90$^\circ$ cone angle, the entire dayside bow shock is quasi-perpendicular. Conversely, in the case of a radial upstream magnetic field (Figure 2c), the bow shock configuration is exclusively quasi-parallel. When the cone angle is equal to 45$^\circ$, as is the case for the Parker spiral orientation, both quasi-parallel and quasi-perpendicular regimes coexist (Figure 2b). Note that contrary to typical solar wind conditions during which the quasi-parallel region is generally found on the dawnside bow shock, it can be found at any clock angle during MC events, since there is essentially no predominant clock angle for the magnetic field of MCs.

We now define the bow shock geoeffective region as the part of the bow shock through which passes the solar wind which directly impacts the dayside magnetosphere. To estimate the extent of this area, we use a magnetosheath model [{\citet{TURC14a}}] to relate the magnetosheath flow lines to their origin at the bow shock. We find that for average MC conditions the flow lines passing within 2$R_E$ of the dayside magnetopause originate from a region of the bow shock within 45$^\circ$ of the Sun-Earth line, which we set as the limit of the bow shock geoeffective region. This area is delineated by white circles in Figure 2.

We calculate the minimum and maximum values of $\Theta_{Bn}$ inside the bow shock geoeffective region as a function of the upstream magnetic field cone angle, the clock angle being set to 90$^\circ$. The value of the clock angle does not affect the extrema of $\Theta_{Bn}$ (variation $\leq 2^\circ$) because the shape of the 
{\citet{Jebral05}} bow shock model is almost axisymmetric about the Sun-Earth line. The obtained upper and lower limits of $\Theta_{Bn}$ are displayed in Figure 3a as dashed black lines; the colored crosses will be discussed later. We find that for a given cone angle, only a restricted range ($<40^\circ$) of $\Theta_{Bn}$ values are encountered in the bow shock geoeffective region and that
these values vary as a function of the cone angle. For example, for a 90° cone angle, $\Theta_{Bn}$ ranges between 60° and 90°.

We calculate that the bow shock geoeffective region is entirely quasi-perpendicular ($\Theta_{Bn} > 45°$) for cone angles between 64° and 116°. According to the analysis of the MCs’ properties (see Figure 1b), such cone angles are observed 56% of the time. On the contrary, an exclusively quasi-parallel shock ($\Theta_{Bn} < 45°$) will be encountered when the cone angle is below 25° or above 155°, that is, 6.3% of the time. The rest of the time, the $\Theta_{Bn}$ values straddle the two regimes, so that both quasi-parallel and quasi-perpendicular configurations coexist on the bow shock geoeffective region.

3.3. Consequences for the Magnetic Structure of MCs Inside the Magnetosheath

We examine here the relationship between the variation of the MCs’ magnetic field direction across the bow shock and the magnetic field cone angle. Our catalog comprises 63 relevant MCs, with at least one spacecraft probing the dayside magnetosheath during more than 1 h. To relate the magnetosheath data to their counterparts in the solar wind, we use a magnetosheath model [Turc et al., 2014a] to trace back the flow lines to the bow shock and thus determine the convection delay from the bow shock to the spacecraft. The magnetosheath intervals are divided into 5 min samples during which the upstream solar wind parameters are averaged. This ensures that the flow pattern does not change while the solar wind flows from the bow shock to the spacecraft position, which takes of the order of a few minutes. The propagation time from $L_1$ to the Earth’s bow shock is calculated based on the average solar wind speed during each event. Applying a constant time shift per event results in errors of ±5 min on the time lag. The 5 min averages thus also contribute to reduce the influence of this uncertainty on the propagation time. For each of the parameters discussed in section 3.1, the mean and median values associated with the reduced data set are indicated in parentheses in Figure 1. They show that no bias is introduced when using this subset of MCs, except for the clock angle, which is not uniformly distributed in the reduced data set, due to the smaller number of samples. In the following, we only discuss the role of the cone angle.

The magnetosheath model also gives us an estimate of the $\Theta_{Bn}$ encountered at the bow shock’s crossing. The $\Theta_{Bn}$ values associated with each of the 5 min magnetosheath samples are plotted in Figure 3a as crosses, red when the flow line passing through the spacecraft originates from the bow shock geoeffective region (i.e., within 45° from the Sun-Earth line), and blue when it does not. We find that the data points associated with the bow shock geoeffective region fall within the range determined in section 3.2, although the lower and upper limits of $\Theta_{Bn}$ were there calculated for average MC conditions. We also note that most of the magnetosheath observations are made downstream a quasi-perpendicular shock, as was expected from the distribution of the magnetic field cone angle in the solar wind. Because of that and of our limited coverage of the magnetosheath, only a few of the blue points, which account for 35% of our data set, are found outside of the range of $\Theta_{Bn}$ associated with the bow shock geoeffective region.

We now focus on the modification of the MCs’ magnetic field. We define $\psi$ as the angle between the magnetic field in the solar wind and that in the magnetosheath, in order to quantify the variation of its direction. The values of $\psi$ calculated for each of the 5 min magnetosheath samples are displayed in Figure 3b, as a function of the upstream magnetic field cone angle. Color coded are the associated $\Theta_{Bn}$ values. They show that the larger $\psi$ values are associated to the quasi-parallel configuration (yellow to red), thus confirming statistically the results of previous cases studies [Turc et al., 2014b, 2015].

More interestingly, Figure 3b suggests that upper and lower limits of $\psi$ can be determined for a given cone angle, as was done for $\Theta_{Bn}$ in section 3.2. For cone angles around 90°, $\psi$ remains below 40°, while it ranges between 20° and 100° when the cone angle is below 30° or above 150°. Overall, the average $\psi$ increases as the upstream magnetic field becomes more radial, as evidenced by the black circles in Figure 3b which display the mean $\psi$ value in each 20° cone angle bin. Although the scarcity of the data for the more radial magnetic field orientations makes it difficult to establish a direct relationship between $\psi$ and the upstream cone angle, Figure 3b allows us to estimate whether the modification of the MCs structure across the bow shock will be significant and could thus alter its geoeffectivity.

4. Discussion and Conclusions

We have investigated the distribution of the magnetic field orientation during 152 Earth-impacting MCs and its consequence for their interaction with the Earth’s bow shock. Furthermore, using a subset of 63 MCs during
which magnetosheath observations were available, we have examined the relationship between their magnetic field orientation upstream of the bow shock and the alteration of its direction in the magnetosheath. The main results of this study are as follows:

1. The magnetic field of MCs lies predominantly near the plane perpendicular to the Sun-Earth line. The distribution of the clock angle, however, does not show any strongly prevailing orientation in this plane.

2. The magnetosheath flow lines which pass within $2R_E$ of the dayside magnetopause originate from a region of the bow shock within $45^\circ$ of the Sun-Earth line, which we term the bow shock geoeffective region. We find that the range of $\Theta_{\text{bow}}$ values in the bow shock geoeffective region for a given upstream magnetic field cone angle is relatively narrow ($< 40^\circ$). Hence, from the cone angle, we can predict whether the dayside magnetosphere will be downstream of a quasi-perpendicular or a quasi-parallel bow shock.

3. Using the distribution of the magnetic field cone angle upstream of the shock obtained from the spacecraft measurements and the \textit{Jiřáček et al.} [2005] bow shock model, we estimate that an exclusively quasi-perpendicular (quasi-parallel) configuration is encountered 56% (6.3%) of the time in the bow shock geoeffective region during the passage of MCs. During the remaining 37.7% of the time, both quasi-parallel and quasi-perpendicular configurations coexist.

4. For a given cone angle, we obtain an estimate of the range of $\psi$, the angle between the solar wind and the magnetosheath magnetic fields. For cone angles around $90^\circ$, the values of the $\psi$ angle are relatively modest, about $20^\circ$ on average, while the variation of the magnetic field orientation is much higher, up to $100^\circ$, and has a large scatter when the magnetic field is quasi-radial.

Our results regarding the bow shock configuration have strong implications for the large-scale structuring of the Earth's environment. In the most common magnetic field orientation within MCs, that is, a cone angle close to $90^\circ$, asymmetries related to the shock geometry should be mild because the bow shock geoeffective area is entirely quasi-perpendicular. However, MCs are low-plasma $\beta$ structures, and during such conditions, the draping of the field lines around the magnetopause gives rise to accelerated flows on the flanks of the magnetosphere [see, e.g., \textit{Chen et al.}, 1993; \textit{Lavraud et al.}, 2007, 2013; \textit{Turc et al.}, 2015]. The flows should be most efficiently accelerated when the upstream cone angle is equal to $90^\circ$ because the piling up of the field lines in front of the magnetopause is then highest. The position of the high-speed flows depends on the upstream magnetic field clock angle and can therefore be found at any latitude. This may have implications for the triggering of the Kelvin-Helmholtz instability [\textit{Lavraud and Borovsky}, 2008].

For intermediate cone angle values, when the geoeffective region of the bow shock features both quasi-parallel and quasi-perpendicular regimes, asymmetries in the magnetosheath parameters arise, as is the case for the Parker spiral IMF orientation. The plasma properties will thus vary from one region of the magnetosheath to another, depending on the position of the quasi-parallel region. The impact of such asymmetries on the solar wind-magnetospheric coupling is still poorly constrained.

For cone angles below $25^\circ$ or above $155^\circ$, observed 6.3% of the time, the whole bow shock geoeffective region is in a quasi-parallel geometry. Though rarer than the fully quasi-perpendicular scenario, its occurrence rate is still not negligible. Moreover, it is essentially due to a few events with long intervals of quasi-radial magnetic fields, sometimes exceeding 10 h. This configuration leads to a profoundly different interaction of the MC with the Earth's environment, over an extended period of time. The MC's magnetic structure in the magnetosheath radically differs from that in the solar wind and can no longer be approximated by the observations made upstream of the bow shock [\textit{Turc et al.}, 2014b]. The modification of its magnetic field orientation, depending on the direction of its variation, can then possibly either increase or decrease the geoeffectivity of the MC.

Furthermore, the foreshock will form upstream of the subsolar bow shock, thus maximizing the impact on the magnetosphere of foreshock transients, which can cause magnetic disturbances detected on the ground [\textit{Eastwood et al.}, 2011; \textit{Hartinger et al.}, 2013; \textit{Archer et al.}, 2015]. Other effects associated with the quasi-radial upstream magnetic field may also arise [see, e.g., \textit{Shue et al.}, 2009; \textit{Hietala et al.}, 2009, \textit{Peng et al.}, 2010; \textit{Samsonov et al.}, 2012 and references therein]. During the 37.7% of the time when both quasi-parallel and quasi-perpendicular configurations coexist on the bow shock geoeffective region, the quasi-parallel regime may also influence the magnetospheric driving, though less prominently.

In the framework of space weather forecasting, most efforts to understand and predict the geoeffectivity of MCs have focused so far on their magnetic field $B_z$ component, which is crucial for reconnection at the terrestrial magnetopause [e.g., \textit{Gopalaswamy et al.}, 2008; \textit{Kilpua et al.}, 2012, and references therein].
However, the present work suggests that taking into account the other magnetic field components, and in particular $B_z$, could help to refine our understanding of the impact of MCs on the Earth’s environment. Assessing the role played by the different shock configurations and quantifying their influence on the solar wind-magnetospheric coupling during MCs is an avenue worth exploring for events whose geoeffectivity is not fully understood.

References


