Study of hot flow anomalies using Cluster multi-spacecraft measurements

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Abstract

Hot flow anomalies (HFAs) were first discovered in the early 1980s at the bow shock of the Earth. In the 1990s these features were studied, observed, and simulated very intensively and many new missions (Cluster, THEMIS, Cassini, and Venus Express) focused the attention to this phenomenon again. Many basic features and the HFA formation mechanism were clarified observationally and using hybrid simulation techniques. We described previous observational, theoretical, and simulation results in the research field of HFAs. We introduced HFA observations performed at the Earth, Mars, Venus, and Saturn in this paper. We share different observation results of space missions to give an overview to the reader.

Cluster multispacecraft measurements gave us more observed HFA events and finer, more sophisticated methods to understand them better. In this study HFAs were studied using observations of the Cluster magnetometer and the Cluster plasma detector aboard the four Cluster spacecraft. Energetic particle measurements (28.2-68.9 keV) were also used to detect and select HFAs. We studied several specific features of tangential discontinuities generating HFAs on the basis of Cluster measurements in the period February-April 2003, December 2005-April 2006, and January-April 2007, when the separation of spacecraft was large and the Cluster fleet reached the bow shock. We have confirmed the condition for forming HFAs, that the solar wind speed is higher than the average. This condition was also confirmed by simultaneous ACE magnetic field and solar wind plasma observations at the L1 point 1.4 million km upstream of the Earth. The measured and calculated features of HFA events were compared with the results of different previous hybrid simulations.

During the whole spring season of 2003, the solar wind speed was higher than the average. Here we checked whether the higher solar wind speed is a real condition of HFA formation also in 2006 and 2007.

At the end we gave an outlook and suggested several desirable directions of the further research of HFAs using the measurements of Cluster, THEMIS, incoming Cross Scale and other space missions.

Key words: Hot flow anomaly, tangential discontinuity, Earth’s bow shock, solar wind

1. Introduction

Hot flow anomalies (HFAs) were discovered in the early 1980s using AMPTE and ISEE measurements (Schwartz et al. 1985; Thomsen et al. 1986). In the 1980s and the early 1990s they were studied very intensively. After 2000 researchers left this topic. In the last few years, however HFAs became being studied intensively again thanks for the Cluster, THEMIS, Mars Global Surveyor (MGS), Voyager, Venus Express (VEX) and Cassini missions. The purpose of this review is to present some of these results and give an overview to the reader about hot flow anomalies.

1.1. Observations

The fundamental properties of HFAs were clarified by Schwartz (1995). A tangential discontinuity (TD) interacts to the bow shock (BS) and a tenuous, hot bubble forms (See Fig. 1). The original name of HFAs was hot diamagnetic cavity (HDC) however they are also known as active currents sheets (AC) because the HFA extends alongside the discontinuity (Eastwood et al. 2008). See also Fig. 1). HFAs have significant influence on the magnetopause (MP) (Sibeck et al. 1999, 2000, 2001; Eastwood et al. 2008). The outer surface of the expanding cavity behaves as fast mode shock and the inner surface of the expanding region shows the features of a tangential discontinuity (Schwertz 1993; Paschmann et al. 1988; Lucek et al. 2004). See also Fig. 2). The electron distribution is an isotropic Maxwell distribution (Thomsen et al. 1986; Schwartz 1993) whose state is reached by fire hose instability (Eastwood et al. 2008). The proton distribution is Maxwellian (Thomsen et al. 1986; Schwartz 1995). The wave properties of the HFAs were studied by Tulin et al. (2008) in different stage of their evolution using k-filtering techniques and multispacecraft measurements from the Cluster fleet. The hot plasma of the expanding cavity can be considered turbulent and shows nonlinear properties (Kovács and Facskó 2009). The typi-
The relative position of the tangential discontinuity (TD) and the bow shock (BS) of the Earth during HFA formation; furthermore the direction of the convective electric field. This HFA was observed by THEMIS spacecraft. (Eastwood et al., 2008)

The change angle of the magnetic field through the discontinuity is 70° (Schwartz, 1995; Safránková et al., 2002; Facskó et al., 2009, 2008). HFA propagate into the magnetosheath (MS) (Safránková et al., 2002) and along the TD (Eastwood et al., 2008). The active current sheet expands farther in the upstream region (Safránková et al., 2002). The system is not in pressure balance so the events expand (Thomsen et al., 1986; Lucek et al., 2004). Sometimes double HFAs are observed (Safránková et al., 2000). Suprathermal particles may be present (Lucek et al., 2004) but energetic particle events are not observed in all cases. When they are observed then the flux increase starts before the magnetic signature and ends after the magnetic perturbations (Thomsen et al., 1986; Lucek et al., 2004). The beam generated by the interaction of the discontinuity and the bow shock is usually parallel to the TD surface (Lucek et al., 2004).

### 1.1.1. Statistical studies

Several statistical studies of HFAs were carried out before the Cluster mission. These studies were based on 9 to 20 events because it was very difficult to observe these dramatic perturbations of the solar wind plasma that can be clearly identified with the appropriate instruments. HFAs were considered as rare events after their discovery; later an average of 3 events was supposed to occur per day (Fuselier et al., 1997; Schwartz et al., 2000). This opinion did not have to be revised after the launch of Cluster, which revealed many HFA events (Kecskeméty et al., 2000; Facskó et al., 2008, 2009; Facskó et al., 2009). Now we know that HFAs appear very frequently and when several conditions are satisfied, like the large angle between the normal of the TD and the Sun-Earth direction (Schwartz et al., 2000; Safránková et al., 2002) and a high solar wind speed (Safránková et al., 2003; Facskó et al., 2008, 2009; Facskó et al., 2009). Besides of the higher solar wind speed the TD must sweep slowly past the surface of the BS (Schwartz et al., 2000; Facskó et al., 2009; Facskó et al., 2009). This feature is almost always coupled to high solar wind speed beams (downstream: Safránková et al., 2000; Facskó et al., 2008, 2009; Facskó et al., 2009; Facskó et al., 2009). HFA propagate and extend both in the magnetosheath and in the upstream region. The statistical study by Safránková et al. (2002) suggests that HFAs impact 10 $R_g$ into the magnetosheath and extend approximately 25 $R_g$ in the solar wind, where $R_g$ is the gyroradius. Facskó et al. (2004) discovered HFAs at a much larger distance from the bow shock. These HFAs are triggered by tangential but not rotational discontinuities (Safránková et al., 2002). Double HFAs can be observed both in the solar wind and the magnetosheath (Safránková et al., 2002). The convective electric field ($E = -v \times B$) is very important in the development of HFAs: the field focuses particles on the TD and the discontinuity leads them back to the perpendicular bow shock where they are accelerated (Thomsen et al., 1993). If the electric field is symmetric then the cavity is also symmetric. If the field is asymmetric then an asymmetric cavity is the result. If the electric field is not present at any side of the TD then HFAs cannot develop (Thomas et al., 1991; Thomsen et al., 1993). The associated energetic particles were studied by Louarn et al. (2003) using Cluster RAPID (Research with Adaptive Particle Imaging Detectors; Wilken et al., 2001) measurements in the magnetosheath. Particle acceleration was explained by first order Fermi acceleration. Nowadays the quasi-perpendicular bow shock is considered as the prime source of the energy of the energized particles (Lucek et al., 2004; Omidi and Sibeck, 2007; Németh, 2008).

### 1.1.2. Extra-Terrestrial HFAs

Fortunately these hot diamagnetic cavities do not occur only at the terrestrial bow shock. HFA would form wherever there is an appropriate interaction between an interplanetary tangential discontinuity and a collisionless shock as Lucek et al. (2004) proposed. Using measurements from MGS (Mars Global Surveyor; Albee et al., 1998) the Martian analogies were discovered.

Figure 1: The environment of the interaction zone: the cavity and its propagation observed by Cluster. (Lucek et al., 2004)
ical polar coordinates. The fourth and fifth panels are the el ectron
els show the magnitude and direction of the magnetic field in s pher-
Figure 3: A HF A analogy in the Kronian system. The top three pa n-
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ions to the discontinuity on both sides of the TD. During
ulated convective electric field points and focuses the
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comparable (Masters et al., 2008). Both must be gener-
units of km but in units of gyro radii their size may be
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crease inside the cavity instead of dropping. The ge-
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ment was unable to measure the solar wind ion distribu-
Fig. 3). Due to pointing constraints the CAPS instru-
Spectrometer; Young et al., 2004) measurements. Finally,
for example at Saturn using Cassini MAG (MAGnetome-
2006) to suggest looking for HFAs near other planets,
number density and temperature respectively and the sixth (bottom)
panel is a time-energy spectrogram of electron count. (Masters et al.
2008 Fig. 1)
by Øieroset et al. (2001) at the flank of Martian bow
shock. Two events were observed and analyzed which
looked like HFAs in the magnetic field and electron data,
however the dramatic ion heating, and bulk flow deflection,
typical of terrestrial HFAs were unable to be shown. This
result led Facskó et al. (2008, submitted on November 4,
2006) to suggest looking for HFAs near other planets,
for example at Saturn using Cassini MAG (MAGnetome-
ter; Dougherty et al. 2004) and CAPS (Cassini Plasma
Spectrometer; Young et al. 2004) measurements. Finally,
some events were discovered by Masters et al. (2008) (See: Fig. 3).
Due to pointing constraints the CAPS instrument
was unable to measure the solar wind ion distribution
so the plasma velocity had to be measured by the
electron instrument. The electron density was found to
increase inside the cavity instead of dropping. The ge-
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because the different features of the bow shock of Sat-
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remained perpendicular to the beam. The instability also plays an important role. A density wave starts from the center (Thomas, 1989).

Lin (2002) studied numerically the interaction for different orientations and configurations of the tangential discontinuity at the bow shock. She noted that the magnetopause had a bulge as Sibeck et al. (2001) and Eastwood et al. (2008) observed. The angle $\gamma$ between the Sun direction is large and HFA cannot form if this cone angle is less than 43° or larger than 83° in her simulation. The angle between the directions of the magnetic field vectors on the two sides of the discontinuity (so called change angle, $\Delta \Phi$) was large approximately 70° as it was observed by Schwartz (1995), Safránková et al. (2002), Facskó et al. (2008, 2009). She also found the ion-beam instability to be the source of the energy. The electric field points to the discontinuity and depends on the change angle. If the change angle is larger then the size of the cavity also increases. This size increases with solar wind speed and also depends on $\gamma$. She found a maximum size when $\gamma = 80^\circ$.

Finally it seems that HFAs appear at the boundary surface of the quasi-parallel and quasi-perpendicular region of bow shocks. At the quasi-perpendicular bow shock particles are accelerated and the escaping ions are trapped and focused by the tangential discontinuity. A faction of them are accelerated many times. This process ends when the TD reaches the quasi-parallel region (Omidi and Sibeck, 2007, Fig. 5). A beam is then ejected and its energy is dissipated by electromagnetic ion-beam instabilities if the size of the beam is limited. Alfvén waves generate a cavity and the rest of the energy heats the plasma (Thomas and Brecht, 1988, Thomas, 1989). The interaction of the TD and the bow shock led us to discover a new type of the shock called solitary shock, where the TD changes the behaviour of the shock and magnetosheath.

2. Cluster multi-spacecraft measurements

Only few HFA studies were carried using multispacecraft measurements. Safránková et al. (2000) used the observations of INTERBALL-1 and its subsatellite, MAGION-4. These measurements however cannot suffer from the fact that both satellites had different instruments. The first real multispacecraft HFA observations were made by Lucek et al. (2004), using Cluster measurements. The advantage of four spacecraft was used in their work. The normal of the TD was calculated from the relative observation time and positions of the Cluster fleet. They could determine the transition speed of the intersection line of the TD and the bow shock ($\sim 110 \text{ km/s}$) which was according to the previous observations and theory (Schwartz et al., 2000). The different spacecraft really observed the motional electric field calculated from the measured magnetic field and solar wind velocity vectors. The compression and propagating direction and speed of the cavity boundaries were also observed by the Cluster fleet. The CIS (Cluster Ion Spectrometry, Réme et al., 2001) measured the velocity distributions of the HFAs and they observed two particle populations coupled to the solar wind and the ions streaming away from the terrestrial bow shock. Using these observations they determined the age of the observed HFAs.
Kecskeméty et al. (2006) concentrated on energized particles measured by RAPID. Kovács and Facskó (2009) studied the turbulence inside the cavity. Tjulin et al. (2008) used Cluster as a wave telescope to investigate the wave properties of HFAs. Actually the Cluster mission (Escoubet et al., 1997) seems to be good platform for wave studies because four spacecraft measures simultaneously from different points. This enables to identify wave vectors directly in 3D. In Tjulin et al. (2008)’s study k-filtering technique was used (Pincon and Lefeuvre, 1991). The events studied in Tjulin et al. (2008) were also studied previously in Lucek et al. (2004) particularly. One of them was considered young and the other event was a more developed HFA. The k-filtering technique observed two particle populations in the less developed event and only one population in the older HFA. The first population was associated to the solar wind and the second particle population was specularly reflected at the bow shock. The older HFA has only one, hot and deflected particle population. Naturally the presence of the two populations was unstable so they developed and united into one population heating the plasma in the cavity. Only special wavelengths were observed so using the CIS solar wind measurements the size of the HFA could be estimated. It was only 1400 km however this size does not contradict the simulations (Lin, 2002) and the other size estimations (Facskó et al., 2009) of developed HFAs because this event was quite young. The plasma parameters may have influence for the periodicity so the gyroradius was calculated using the mean magnetic field inside the HFA measured by FGM (Fluxgate Magnetometer; Balogh et al., 2001). The result (2200 km) is the maximum that can be accepted as scaling factor of the periodicity. This might mean that the HFA size and the plasma parameters together determine and filter the wave length inside the cavity.

Eastwood et al. (2008) performed the first multi-spacecraft HFA study based on THEMIS measurements, in which HFAs were observed in the magnetosheath and in the upstream region simultaneously. Cluster has the advantage of having fully identical spacecraft, with instruments covering a wide range of conditions. The analyzing and processing of the Cluster magnetic, plasma and energized particle observations led to the largest statistical study of HFAs (Facskó et al., 2008, 2009). Facskó et al., 2009).

2.1. Selection of HFA events

Based on the above-mentioned observational studies (Facskó et al., 2008, 2009; Facskó et al., 2009; Schwartz et al., 1985; Thomsen et al., 1986, 1993; Sibeck et al., 1990, 2002) See also Fig. 3, HFAs can be selected based on the following criteria:

1. The rim of the magnetic cavity must be visible as a sudden increase in the magnetic field magnitude. Inside the cavity the magnetic field value drops and its direction turns around.
2. The solar wind slows down and its direction always turns away from the Sun-Earth direction.
3. The solar wind temperature increases and its value reaches up to several ten million degrees inside the cavity.
4. The solar wind particle density also increases on the rim of the cavity and drops inside the HFA.
5. The tangential discontinuity must appear in the upstream magnetic field.

Often but not always energized particles are present mostly in the range of 28.2-68.9 keV however sometimes in the range of 68.9-96.1 keV and 96.1-169.3 keV. Particle events start before the magnetic signatures appear and end after them (Kecskeméty et al., 2006). The convective electric field must point towards the discontinuity on both sides of the TD (Thomsen et al., 1993).
Using the criteria listed above 124 HFA events were found: between 2003 February and April 33 events, from 2005 December to 2006 April 41 events and finally between 2007 January and April another 50 events were identified (Fig. 7). After plotting the ACE SWEPAM (Solar Wind Electron, Proton, and Alpha Monitor; McComas et al., 1998) 1-hour averaged solar wind speed measurements and indicating the HFA events it seems that the HFAs appear when the solar wind speed is higher than the average (Fig. 8). This assumption is confirmed by the distribution of the solar wind speed and fast-magnetosonic Mach-numbers calculated using ACE MAG (MAGnetometer; Smith et al., 1998) and SWEPAM measurements (Fig. 9). The solar wind speed is approximately 130 km/s higher than the average during the HFA formation phase and the fast-magnetosonic Mach number is also higher than average. The difference is between 2.7-3.7 $M_f$ depending the year (Facskó et al., 2009). This condition was also observed by Safránková et al. (2000) but they observed HFAs in the magnetosheath where the differences are not as significant as in the solar wind. Based on measurements made in 2003 it seems that a higher solar wind pressure can be also a condition of HFA formation. Finally after analyzing the events of two additional years (2006 and 2007) the solar wind pressure seems to be not a condition for HFA formation; furthermore it is lower then the average however the average particle density is similar (Facskó et al., 2009).

2.2. The results of the statistical study

The most important result of the statistical study using Cluster multi-spacecraft is the discovery of the higher solar wind speed as a condition of HFA formation (Sec. 2.1). This result is unexpected because the original purpose of the statistical study was to compare with Lin (2002)’s results. She performed global hybrid simulation of HFAs and presented size estimation, angle estimations and size-angle functions (See: Sec. 1.2). The predicted size was confirmed by the study $(1 - 2 R_{Earth})$, the average value of $\Delta \Phi$ change angle was 70°, the $\gamma$ angle between the solar direction and the TD normal was larger than 45° as predicted (See Fig. 10). This large gap around the Sun-Earth direction has been observed by Schwartz et al. (2000) before. Finally, the previously described size-angle dependencies were also confirmed. The results by Schwartz et al. (2000) on the condition of HFA formation was also confirmed because several part of their result was used for the size estimation. (Facskó et al., 2009)

3. Discussion

Németh (2008) developed the following empirical criterion for the escape of energetic particle, after analyzing the geometry of escaping particles:

$$\sin \alpha \geq \frac{1}{B_1} \left(1 - \frac{u_v}{u_1}\right)^{-\frac{1}{2}},$$

(1)

where $\alpha$ is the angle of solar wind velocity and discontinuity normal, 1 and 2 are two possible positions of the discontinuity, $B_1$ and $B_2$ are the magnetic field at these positions, $u$ is the solar wind velocity and $v_\perp$ is the component of the particle velocity which is perpendicular to the magnetic field. If the solar wind speed is considered infinity and the rate of the magnetic field magnitude in the upstream and downstream region is set to the typical value (4) then this angle is $\alpha = 41.8^\circ$ which agrees well with simulation results (Lin 2002) and observations (Facskó et al., 2008, 2009, Schwartz et al., 2000). Unfortunately this formula does not explain why the observed speed is necessary for HFA formation. Further test particle and 3D hybrid simulations are needed to explain this condition theoretically.

4. Summary

The Cluster spacecraft have allowed us to observe HFAs with unprecedented resolution, providing a wealth of information and allowing us to compare the observations with simulations. Using a sample of 124 HFAs observed by Cluster we get the following general features:

1. The cone angle of the TD normal are high and the large gap around the Sun-Earth direction in the TD normal has no anisotropy.
2. Both the higher solar wind speed and Mach number are conditions of HFA formation. The velocity increase seems to be less than 200 km/s (measured in 2003) or 130 km/s (measured in 2006 and 2007). The relative increase is larger when measured in fast magnetosonic Mach number units.

3. We estimated the size and got good agreement with the simulations of $1 R_{\text{Earth}}$.

4. We constructed size-TD normal cone angle, Size-B direction change angle and Size-solar wind Mach number plots. All of them confirm the result of hybrid simulations.

5. Our theory presented in Sec. 3 develops the higher solar wind condition from fundamental geometrical features of HFA formation.

Further research is needed to explain more satisfactory the reason for condition (2). 3D hybrid simulations might give better insight here.
Currently HFAs are receiving wide interest again. We suggest some unsolved problems in the field of HFAs:

1. The Kronian HFA analogies do not agree with the geometric features based on terrestrial events. It would be useful to detect more events and perform a statistical study. Furthermore it is very disturbing that Kronian analogies exhibit an increase, rather than a decrease, in the particle density. The magnetic field signature however, is similar to that at Earth. Unfortunately it remained unclear what TD-bow shock interaction produces in a different region of parameter space; for example whether the much weaker electric field at Saturn leads to a different type of phenomenon. This problem and the fact that only HFA-like events have been reported to date, also might motivate further studies of HFAs at other planets.

2. HFA analogies were discovered at the Mars, Venus, Saturn and probably also in the inner heliosheath. It would be nice to detect them at bow shock of a fast moving star or extragalaxy. The beam formed by the interaction of the discontinuity interacts with the interstellar or intergalactic matter and this might observed. It would be nice to construct a model for this.

3. Since the launch of THEMIS, two multi-spacecraft fleets can observe HFAs. It would be most interesting to observe them simultaneously to study their temporal development. It is possible in 2007, 2008 and 2009. It would be interesting to observe the same event with two distant satellites: one (or more) might be one of the THEMIS or Cluster spacecraft and another may be Geotail or other satellite.

4. Finally it would be useful to observe simultaneously a hot flow anomaly at different scales to understand better the turbulence inside the cavity. The proposed Cross Scale mission may perform this observation.

After a short break the research on HFAs seems these structures again give exciting results. In spite of numerous papers and results we are only the beginning of understanding these complex features.

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Figure 10: Polar plot of the direction of the normal vectors of TDs. The azimuthal angle is measured between the GSE y direction and the projection of the normal vector onto the GSE yz plane. The distance from the center is the γ angle as determined by the cross-product method. The TD normal vector is in a special polar coordinate system in which we measure the γ angle from the center, and where the azimuth is the angle of GSE y and the projection of normal vector to GSE yz plane. The regions surrounded by dashed lines are the projection of error cones around the average normal vector marked by “X”. Circles and squares symbolize ACE and Cluster data, respectively. (Based on Facskó et al., 2009)

Figure 11: The configuration of the bow shock and the tangential discontinuity during a HFA event. The orbit of a trapped ion is shown. (From Németh, 2008)

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