

Comparing 1-year GUMICS–4 simulations of the Terrestrial Magnetosphere with Cluster Measurements

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Key Points:

- The GUMICS–4 **code** provides realistic ion plasma moments and magnetic field in the solar wind and the outer magnetosheath.
- The code [...] predicts [...] realistic **bow shock** locations [...].
- An inner magnetosphere model should be added to the code to increase the accuracy of the simulation **in inner magnetosphere**.

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23 **Abstract**

24 We compare the predictions of the GUMICS-4 global magnetohydrodynamic
 25 model for the interaction of the solar wind with the Earth's magnetosphere
 26 to Cluster-3 measurements over the course of one year, from January 29, 2002
 27 to February 2, 2003. In particular, we compare [...] the north/south com-
 28 ponent of the magnetic field (B_z), the component of the velocity along the
 29 Sun-Earth line (V_x), and the plasma density as determined from a top hat
 30 plasma spectrometer and the spacecraft's potential. We select intervals in the
 31 solar wind, the magnetosheath and the magnetosphere where these instruments [...]
 32 provided good quality data and the **model correctly predicts the region in which**
 33 **the spacecraft is located**. We determine the location of the bow shock, the magnetopause
 34 and the neutral sheet **from** the spacecraft measurements and compare their **locations**
 35 **to those predicted by the simulation.**

36 The GUMICS-4 **model** provides quite good results in the solar wind however its
 37 accuracy is **worse** in the magnetosheath. The simulation results are not realistic in the
 38 magnetosphere. The bow shock location is predicted well however the magnetopause lo-
 39 cation is less accurate. The neutral sheet positions are located quite well thanks to the
 40 special solar wind conditions. [...]

41 **1 Introduction**

42 One of the most cost-effective way to study the interaction of the solar wind **with**
 43 planetary magnetospheres (or predict the conditions **in** near-Earth space) is **modeling**
 44 **this complex system** using a [...] magnetohydrodynamic (MHD) code. In the past,
 45 several [...] parallelized [...] codes were developed, which are used and applied to fore-
 46 cast the cosmic environment of the Earth; such as the Lyon-Fedder-Mobarry [LFM; *Lyon*
 47 *et al.*, 2004] code, **the Grid Agnostic MHD for Extended Research Applications**
 48 [**GAMERA**; *Zhang et al.*, 2019], the Open Geospace General Circulation Model [OpenG-
 49 GCM; *Raeder et al.*, 2008], the Block-Adaptive-Tree-Solarwind-Roe-Upwind-Scheme [BATS-
 50 R-US; *Powell et al.*, 1999; *Tóth et al.*, 2012]. In Europe only three global MHD codes
 51 were developed: the Grand Unified Magnetosphere–Ionosphere Coupling Simulation [GUMICS-4;
 52 *Janhunen et al.*, 2012], the Computational Object Oriented Libraries for Fluid Dynam-
 53 ics [COOLFluiD; *Lani et al.*, 2012] and the 3D resistive magnetohydrodynamic code Gor-
 54 gon [*Chittenden et al.*, 2004; *Ciardì et al.*, 2007]. The COOLFluiD is a general-purpose

plasma simulation tool. The Gorgon code was developed **to study** high energy, collisional plasma interactions and has been adapted to simulate planetary magnetospheres and their interaction with the solar wind [Mejnertsen *et al.*, 2016, 2018]. **Neither Gorgon nor COOLfluid have an ionospheric solver.** [...] **Almost all of** these codes are available at the Community Coordinated Modelling Center (CCMC; <http://ccmc.gsfc.nasa.gov/>) hosted by the NASA Goddard Space Flight Center (GSFC) **or** the Virtual Space Weather Modelling Centre (VSWMC; <http://swe.ssa.esa.int/web/guest/kul-cmpa-federated>; **re-**
quires registration for the European Space Agency (ESA) Space Situational Awareness (SSA) Space Weather (SWE) portal) hosted by the KU Leuven [Poedts *et al.*, 2020]. A comparison of the simulation results **with** spacecraft and ground-based measurements is necessary to understand the abilities and features of the developed tools. A statistical study using long term global MHD runs for validation [...] of the codes seems **is needed**. Because [...] providing long simulations **are** costly and time consuming [...], only a few studies **have been done**, **almost all for periods much less than a year except Liemohn *et al.* [2018]**.

Guild et al. [2008a,b] launched two months of LFM runs and compared the plasma sheet properties in the simulated tail with the statistical properties of six years Geotail magnetic field and plasma observations [Kokubun *et al.*, 1994; Mukai *et al.*, 1994]. The LFM successfully reproduced the global features of the global plasma sheet in **a** statistical sense. However, there were some differences. The sheet was too cold, too dense and the bulk flow was faster than the observed plasma sheet [Kokubun *et al.*, 1994; Mukai *et al.*, 1994]. The LFM overestimated the ionospheric transpolar potential. The transpolar potential correlated with the speed of the plasma sheet flows. Equatorial maps of density, thermal pressure, thermal energy and velocity were compared. The LFM overestimated the plasma sheet density close to the Earth, the temperature by a factor of ~ 3 **and** the global average flow speed by a factor of ~ 2 . The LFM reproduced many of the climatological features of the Geotail data set. The low-resolution model underestimated the occurrence of the fast earthward and tailward flows. Increasing the simulation resolution resulted in the development of fast, busty flows. **These flows influenced the statistics and contributed to a better agreement between simulations and observations.**

Zhang et al. [2011] [...] studied the statistics of magnetosphere-ionosphere (MI) coupling **using Guild et al.** [2008a]'s LFM simulation above. The polar cap po-

tential and the field aligned currents (FAC), the downward Poynting flux and the vorticity of the ionospheric convection were compared with observed statistical averages and the Weimer05 empirical model [Weimer, 2005]. The comparisons showed that the LFM model produced quite accurate average distributions of the Region 1 (R1) and Region 2 (R2) currents. The ionospheric **R2** currents in the MHD simulation seemed to **originate** from the diamagnetic ring current. The average LFM **R1** and **R2** currents were **small** compared with the values from the Weimer05 model. The average **Cross Polar Cap Potential (CPCP)** was higher in the LFM simulation than the measurements of the SuperDARN and the Weimer05 model. The average convention pattern was quite symmetric in the LFM simulation against the SuperDARN measurements and the Weimer05 model. The SuperDARN measurements and the Weimer05 model had **a** dawn-dusk asymmetry. In the LFM model, more Poynting flux flowed into the polar region ionosphere than in the Weimer05 model. It was the consequence of the larger CPCP in the LFM simulation. The larger CPCP allowed **a** higher electric field in the polar region. The statistical dependence of the high-latitude convection patterns on Interplanetary Magnetic Field (IMF) clock angle was similar to the SuperDARN measurements [Sofko *et al.*, 1995] and the Weimer05 model. The average ionospheric field-aligned vorticity showed good agreement on the dayside. However, the LFM model gave **a** larger nightside vorticity than SuperDARN measurements because the Pedersen conductance on the night side ionosphere was too low.

Wiltberger et al. [2017] studied the structure of [...] high latitude field-aligned current patterns using three resolutions of the LFM global MHD code and the Weimer05 empirical model [Weimer, 2005]. The studied period was a month long and contained two high-speed streams. Generally, the patterns agreed well with results obtained from the Weimer05 computing. As the resolution of the simulations increased, the currents became more intense and narrow. The ratio of the Region 1 (R1), the Region 2 (R2) currents and the R1/R2 ratio increased when the simulation resolution increases. However, both the R1 and R2 currents were smaller than the predictions of the Weimer05 model. This effect led to a better agreement of the LFM simulation results with the Weimer 2005 model results. The CPCP pattern became concentrated in higher latitudes because of the stronger R2 currents. The relationship of the CPCP and the R1 looked evident at higher resolution of the simulation. The LFM simulation could have reproduced the statistical features of the field aligned current (FAC) patterns.

121 *Hajducek et al.* [2017] simulated the month (**January,2005**) using the Space Weather
122 Modelling Framework [SWMF; *Tóth et al.*, 2005] and the OMNI solar wind data (<https://omniweb.gsfc.nasa.gov/>)
123 as input. The simulations were **compiled** with and without **an** inner magnetosphere model
124 and using two different grid resolutions. The model was very good in predicting the **ring**
125 currents [...] [SYM-H; <http://wdc.kugi.kyoto-u.ac.jp/aeasy/asy.pdf>; *Iyemori*, 1990]. The
126 K_p index (that measures the general magnetospheric convention and the auroral currents
127 [*Bartels et al.*, 1939; *Rostoker*, 1972; *Thomsen*, 2004]) was predicted well during storms
128 however the index was **overestimated** during quiet time periods. The AL index (that
129 describes the westward electro jet of the surface magnetic field introduced by *Davis and*
130 *Sugiura* [1966]) was predicted reasonably well **on** average. However the model reached
131 the highest negative AL value less often **it was reached in the** observations because
132 the model captured the structure of the auroral zone currents poorly. The overpredicting
133 of K_p index during quiet times might have had the same reason because that index
134 was also sensitive **to** auroral zone dynamics. The SWMF usually over predicted the CPCP.
135 These results were not sensitive to grid **resolutions, with the except of** the AL in-
136 dex, **whitch** reached the highest negative value more often when the grid resolution was
137 higher. Switching off of the inner magnetosphere model had **a negative effect on** the
138 accuracy of all quantities mentioned above, except the CPCP.

139 In this paper, the Cluster SC3 measurements are compared directly to a previously
140 made 1-year long GUMICS–4 simulation in the solar wind, magnetosheath and the mag-
141 netosphere along the Cluster SC3 orbit saved from the simulation results and measured
142 by the spacecraft [*Facskó et al.*, 2016]. **In this paper these parameters, namely the**
143 B_z , **the north/south component of the magnetic field in GSE coordinates, the**
144 **solar wind velocity GSE X component (V_x) and the solar wind density n are**
145 **compared to the Cluster SC3 measurements as well as the location of the bow**
146 **shock, magnetopause and the neutral sheet. These parameters are selected**
147 **because [...] B_z controls the magnetosphere, [...] V_x is the main component**
148 **of the solar wind velocity [...] and [...] n is the ion plasma momentum that**
149 **is the easiest to calculate; furthermore more instruments could determine it**
150 **(see Section 2.2).** The structure of this paper is as follows. Section 2 describes the GUMICS–4
151 code, the 1-year simulation and **the considered measurements of the Cluster space**
152 **mission.** Section 3 gives comparisons between the simulations and observations. Results
153 of the comparison are discussed in Section 4. Finally, Section 5 contains the conclusions.

154 **2 The GUMICS–4 products and Cluster measurements**

155 Here we use two [...] very different [...] time series. The first type is derived from
 156 a previously 1-year **run of the GUMICS–4 simulation** [Facsikó *et al.*, 2016]. The sec-
 157 ond **time series were** measured by the magnetometer, ion plasma and electric field in-
 158 struments of the Cluster reference spacecraft.

159 **2.1 The GUMICS–4 code**

160 The GUMICS–4 has two coupled simulation domains, the magnetospheric domain
 161 outside of $3.7 R_E$ radius **sphere** around the Earth and a coupled ionosphere **module**
 162 **containing 2D height-integrated model of ionosphere**. The GUMICS–4 is not a
 163 parallel code however it **has been** extensively used for studying the energy propagation
 164 processes from the solar wind to the magnetosphere through the magnetopause and other
 165 features [Janhunen *et al.*, 2012, see the references therein]. The code has also been ap-
 166 plied **to study** forced reconnection in the tail [Vörös *et al.*, 2014]. Recently, **several**
 167 **hundred** synthetic two hours duration GUMICS–4 simulation **runs** were made to com-
 168 pare the simulation results to empirical formulas [Gordeev *et al.*, 2013]. The agreement
 169 was quite **good in general, but** the diameter of the magnetopause [...] in the sim-
 170 ulation **deviated significantly from** observations in the tail. The [...] GUMICS–4
 171 **simulation magnetotail** was smaller than **what the** spacecraft observed and measured.
 172 A 1-year long simulation was made using the GUMICS–4 code [Facsikó *et al.*, 2016]. Ju-
 173 usola *et al.* [2014] compared the ionospheric currents, fields and the [...] CPCP in the
 174 simulation **to observations from the** Super Dual Auroral Radar Network (SuperDARN)
 175 radars [Greenwald *et al.*, 1995] and CHAMP spacecraft [Reigber *et al.*, 2002] field aligned
 176 currents (FAC) measurements [Juusola *et al.*, 2007; Ritter *et al.*, 2004]. The [...] CPCP,
 177 [...] the FAC and other currents could not be reproduced properly. The possible cause
 178 of this **poor** agreement could be **due to low resolution in inner magnetosphere**
 179 **and/or** the lack of **an** inner magnetosphere model **incorporating the physics in this**
 180 **region**. This **hypothesis** is supported by the result of Haiducek *et al.* [2017]. Haiducek
 181 *et al.* simulated only a month-long period using a different spatial resolution and [...]
 182 tested the code **with** the inner magnetosphere model of the SWMF **switched off** for
 183 a special run. This run without **an** inner magnetosphere model made it clear that only
 184 the CPCP parameter of the simulation agreed quite well with the measurements. This
 185 fact explained why the agreement between the Cluster SC3 and the GUMICS-4 simu-

lations was so good as described by *Lakka et al.* [2018a,b] based on the CPCP in GUMICS–4 simulations. *Kallio and Facskó* [2015] determined **plasma and magnetic field** parameters along the **lunar** orbit **from** the *Facskó et al.* [2016]’s global MHD simulations. The [...] parameters differed significantly in the geotail **indicating a need for** future studies. *Facskó et al.* [2016] determined the footprint of [...] Cluster SC3 using the 1-year simulation and the Tsyganenko T96 empirical model [*Tsyganenko*, 1995]. [...] The agreement of the footprint **was** better in the Northern Hemisphere. The GUMICS–4 tail **was** shorter in the simulations than the observations. [...]

A 1-year global MHD simulation was produced with the GUMICS–4 code using the OMNI solar wind data from January 29, 2002 to February 2, 2003 as input [*Facskó et al.*, 2016]. The creation and analysis of the simulation was wased on a workpackage of the European Cluster Assimilation Technology (ECLAT) project (https://cordis.europa.eu/result/rcn/165813_en.html; <http://www.eclat-project.eu/>). The GUMICS-4 is a serial code [*Janhunen et al.*, 2012] hence the 1-year simulation was made in 1860 independent runs. This interval covered 155 Cluster SC3 orbits and each orbit lasted 57 hours. The FMI supercomputer **at the time** had 12 **cores** on each node hence the 57 hours were divided into 4.7 hours simulation time with one hour initialisation period. Each **sub-interval** used its own **individual** average Geocentric Solar Ecliptic (GSE) IMF magnetic field X component B_x component and dipole tilt angle. All data gaps **in solar wind** were **interpolated linearly**. If the data gap of the input file was at the beginning (or the end) **of the interval then** the first (or last) good data **from** the input file was used to fill the gap. The initialisation of each **simulation run** was made using constant values. These values were the first valid data of the input file repeated 60 times (60 minutes) in the input file of the sub-interval. The simulation results were saved [...] every five minutes. Various simulation parameters, for example, the density, particle density, temperature, magnetic field, solar wind velocity (29 different quantities) were saved from the simulation results along the Cluster reference spacecraft’s **orbit** in the GSE coordinates. [...]

2.2 The Cluster SC3 measurements

The Cluster-II spacecraft of the European Space Agency (ESA) were launched in 2000 and study the geospace [...] [*Credland et al.*, 1997; *Escoubet et al.*, 2001]. The four spacecraft form a tetrahedron **in space** however here we use only the measurements

of the reference spacecraft, [...] Cluster SC3. The spacecraft were stabilised [...] and their period is ~ 4 s. Hence, the **intrinsic time** resolution of the plasma instruments is 4 s and we use 4 s averaged magnetic field data. The **highest** resolution of the Cluster FluxGate Magnetometer (FGM) magnetic field instrument is 27 Hz [Balogh *et al.*, 1997, 2001]. The ion plasma data **are** provided by the Cluster Ion Spectrometry (CIS) Hot Ion Analyser (HIA) sub-instrument [Reme *et al.*, 1997; Rème *et al.*, 2001]. The CIS HIA instrument is calibrated using the Waves of HIgh frequency Sounder for Probing the Electron density by Relaxation (WHISPER) wave instrument onboard Cluster [Décréau *et al.*, 2001; Trotignon *et al.*, 2010; Blagau *et al.*, 2013, 2014]. **The results of these calibrations can appear** as sudden non-physical jumps in the CIS HIA data. The CIS HIA had different modes to measure in the solar wind and the magnetosphere. When the instrument switched from **one** mode to another mode it appeared as a non-physical **jumps also appear** in the **measurements** [...]. These features **impair** the accuracy of [...] data **analyses**.

We protect our results from these non-physical jumps [...] using a density determination based on different principles. We use the spacecraft potential of the Electric Field and Wave Experiment [EFW ; Gustafsson *et al.*, 1997, 2001] to determine the electron density. This quantity can be calculated using the empirical density formula

$$n_{EFW} = 200(V_{sc})^{-1.85}, \quad (1)$$

where n_{EFW} is the calculated density and V_{sc} is the Cluster EFW spacecraft potential [Trotignon *et al.*, 2010, 2011]. The EFW and the WHISPER were used for the calibration of the CIS HIA and the Plasma Electron and Current Experiment [PEACE; Johnstone *et al.*, 1997; Fazakerley *et al.*, 2010a,b]. Both instruments were still working onboard all Cluster spacecraft. Their stable operation reduced the number of data **gaps**, **and it also** made the data analysis easier.

3 Comparison of measurements to simulation

The [...] parameters **saved** from the GUMICS–4 simulations and the Cluster SC3 magnetic field, solar wind velocity and density measurements are compared in **different regions, namely** the solar wind, magnetosheath and magnetosphere using cross correlation calculation. The **temporal** resolution of the simulated Cluster orbit data is mostly five minutes because the **results of the simulations** are saved [...] every five

248 minutes [Facsikó *et al.*, 2016]. However, the time difference between points **can** be more
 249 than five minutes at the boundary of the subintervals, because the length of **the** sim-
 250 ulation intervals is determined in minutes. To facilitate analysis of the simulation results,
 251 all simulation data were interpolated to one minute resolution. This method does not
 252 provide extra information to the cross correlation calculation. The data gaps are elim-
 253 inated using **linear** interpolation [...] and extrapolation when the gap is at the start
 254 or the end of the selected interval. The spin resolution (4 s) of Cluster SC3 magnetic field
 255 measurements is averaged over one minute around ($\pm 30\text{ s}$) the time stamps of the saved
 256 data.

257 For the correlation calculation, intervals are selected carefully in the solar wind (**see**
 258 **Section 3.1**), the magnetosheath (**see Section 3.2**), the dayside and the night side mag-
 259 netosphere (**see Section 3.3**). In these intervals, the parameters did not vary a lot and
 260 **we require** neither [...] Cluster nor the virtual probe **to cross** any boundaries. To
 261 compare [...] the B_z magnetic field, V_x solar wind speed and the n_{CIS} and the n_{EFW}
 262 curves we [...] cross **correlate** selected intervals. [...] We carefully examine **such** cases
 263 and remove [...] intervals **which are too short for the ± 60 minutes correlation**
 264 **calculation** (shorter than four hours) [...] and large data gaps from the correlation
 265 calculation. [...] Those intervals are also neglected where the plasma instrument has
 266 a calibration error or **a change in its recording mode as it moves from the mag-**
 267 **netosphere to solar wind** (for example). The electron density is also calculated using [...]
 268 Equation 1 and [...] **correlated** [...]. We want to avoid **the** calibration errors and sud-
 269 den non-physical jumps mentioned previously. The **correlation results for the den-**
 270 **sity derived from the electric field potential** results do not differ significantly **from**
 271 **those for the top hat plasma instrument**, however the n_{EFW} does not have any
 272 mode change and it is applicable in the magnetosphere too (against the CIS HIA instru-
 273 ment).

274 3.1 Solar wind

275 We use OMNI IMF and solar wind velocity, density and temperature data as in-
 276 put **to** the simulation. **There is a reason why we** compare **parameters in the** so-
 277 **lar wind region in the simulation and the measurements.** The IMF X component can-
 278 not be given to the GUMICS-4 as input [Janhunen *et al.*, 2012; Facsikó *et al.*, 2016]. How-
 279 ever, the magnetic field of the solar wind has **an** X component in the simulations. Ad-

ditionally, the solar wind structure might change from the simulation domain boundary at $+32 R_E$ to the sub-solar point of the terrestrial bow shock where all OMNI data is shifted. Almost the same solar wind **time** intervals are used as in [...] Table 1 of *Facskó et al. [2016]*. The number of these intervals is small because [...] Cluster fleet instruments were calibrated in 2002, just after **launch** (Table 1). Hence we do not have a satisfactory ion plasma data coverage for this year. Additionally, to improve the accuracy of the correlation calculation (see below) we delete the intervals that were too short (shorter than five hours) or the CIS HIA instrument changed its mode. The Cluster fleet is located in the solar wind only from December to May and only for a couple of hours during each orbit near [...] apogee. We double check whether the Cluster SC3 stays in the solar wind in both the simulation and reality. We also check the omnidirectional CIS HIA ion spectra on the Cluster Science Archive (CSA; <https://www.cosmos.esa.int/web/csa/csds-quicklook-plots>). **The spectra must contain one narrow band in the solar wind region.** Hence 17 intervals are left in the solar wind to study (Figure 1).

The selected intervals **occur for** quiet solar wind conditions (Figure 2). The GUMICS-4 simulation results have five minutes resolution and the Cluster SC3 measurements have one minute resolution (Figure 3). The measurements vary significantly. In spite of the quiet conditions the solar wind density often changes and deviates from the simulation. [...] Figure 4c **shows that** both densities deviate significantly. The CIS HIA density deviation is larger as [...] expected **given** the complexity and the large number of working modes of the CIS instrument. The magnetic field and the solar wind velocity fit better. [...] Figure 5a **shows that** the correlation of the magnetic fields is very good; furthermore on Figure 5c, 5e, 5f the correlation of the solar wind velocity and density is excellent (Table 1). The time shift on Figure 5b, Figure 5d, Figure 5f is about five minutes for the magnetic field and the CIS data. On Figure 5h for the EFW data the time shift is **less stable**. It is not **as well** determined as **in case of** the other parameters.

3.2 Magnetosheath

The Cluster SC3 spent only a little time in the solar wind from December, 2002 to May, 2003. However, the [...] spacecraft **enters** the magnetosheath each orbit (Figure 6). We selected intervals when the value of the magnetic field is around 25 nT. The field should be fluctuating because of the turbulent **deflected** flow of the **shocked** solar wind [...] the **temperature should be greater than that in the solar wind** [...].

312 The velocity should decrease to values ranging from 100-300 km/s. The density
 313 of the plasma should increase and reached values of $10\text{-}20 \text{ cm}^{-3}$. The narrow band
 314 on the omnidirectional CIS HIA ion spectra from the CSA (<https://www.cosmos.esa.int/web/csa/csds-quicklook-plots>) widens from the solar wind to the magnetosheath. 15–30 minutes
 315 from each bow shock crossing we considered the Cluster SC3 to have entered into
 316 the magnetosheath. At the inner magnetopause boundary of the magnetopause the
 317 flow speed [...] and the density drop. The magnetic field strength increases and the
 318 magnetic field becomes less turbulent than in the magnetosheath. The wide band on
 319 the omnidirectional CIS HIA ion spectra disappears. 15–30 minutes before the appear-
 320 ance of these indicators of the magnetopause crossing our intervals end. All inter-
 321 vals contain large data gaps, non-physical jump in instrument modes [...] or lasting
 322 less than four hour are removed. Hence 74 intervals considered in our final selection (Ta-
 323 ble 2).

325 All intervals have quiet upstream (or input) solar wind conditions (Figure 7). Inspite
 326 of our selected [...] magnetic field and [...] plasma parameters and the calculated em-
 327 pirical density indicate that they vary significantly stronger than in the solar wind in-
 328 tervals (Figure 8). The deviation between the simulated and the observed data is also
 329 larger in this region [...]. The scatter plots of the magnetic field, plasma flow speed
 330 and the densities show that these parameters agree well, but with greater vari-
 331 ation than the scatter plots for the solar wind (Figure 9a, 9b, 9c). The correlation of
 332 the simulated and the observed data is good for the magnetic field (Figure 10a), very
 333 good for the ion plasma moments and the calculated density (Figure 10c, 10e, 10g). The
 334 timeshift of the magnetic field is within five minutes mostly (Figure 10b) however the
 335 timeshift of the ion plasma moments is scattered (Figure 10d, 10f). The timeshift of the
 336 calculated EFW density seems to be more stable (Figure 10h). Generally, the GUMICS–4
 337 is less accurate in the magnetosheath than in the solar wind. The modelled mag-
 338 netic field is closer to the observations than the modelled plasma parameters
 339 are. The calculated empirical EFW density (n_{EFW}) fits better than the CIS HIA den-
 340 sity (n_{CIS}).

341 3.3 Magnetosphere

342 To select intervals in the magnetosphere we looked for the CIS HIA omnidirectional
 343 ion flux spectrum. Where the band of the hot magnetosheath ion population (dis)appeared,

344 the magnetosphere started/finished. The **plasma density decreases toward zero**, the
 345 magnetic field **strength is large**. We left 15–30 min after/before the magnetopause transi-
 346 tion to **identify magnetosphere intervals**. This way we found 132 intervals in the mag-
 347 netosphere (Table 3) using Cluster SC3 measurements. [...] Cluster SC3 spends con-
 348 siderable time in the magnetosphere (Figure 11).

349 Here we show neither any correlation calculation nor comparison plot. In the mag-
 350 netosphere the GUMICS–4 does not work well. Neither the magnetic field nor the plasma
 351 moments nor the N_{EFW} fit well. The solar wind velocity does not reach zero in the sim-
 352 ulation. Instead, the solar wind enters to the night side magnetosphere. The solar wind
 353 CIS HIA ion plasma density and the calculated density from spacecraft potential increase
 354 closer to the Earth (plasmasphere). The GUMICS–4 density is low there. We calculated
 355 the dipole field in GSE using Tsyganenko geotool box [Tsyganenko, 1995] and substracted
 356 from both the observed and the simulated magnetic field B_z data. The correlation of these
 357 corrected magnetic field measurements and simulations is very low too.

358 3.4 Bow shock, magnetopause, neutral sheet

359 77 intervals are selected when [...] Cluster SC3 crossed the terrestrial bow shock
 360 once or multiple times (**Table 6**). When the spacecraft crosses the bow shock **inbound**
 361 the magnitude of the magnetic field and the solar wind density increases **by a factor**
 362 **of 4–5 times** (from 5 nT or 5 cm^{-3} , respectively), the solar wind speed drops from 400–
 363 600 km/s to 100–300 km/s; furthermore the narrow band on the omnidirectional Clus-
 364 ter CIS HIA ion spectra [...] widens. The Cluster measurements are 1-min averaged
 365 **whereas** the GUMICS–4 simulations have 5-min resolution. Hence all bow shock tran-
 366 sitions of the virtual spacecraft are slower and smoother. Additionally, the multiple bow
 367 shock transitions are not visible in the GUMICS simulations. The code reacts slowly for
 368 such sudden changes. The magnetic signatures fit better than the calculated plasma mo-
 369 ments. The jump of the ion plasma parameters and the derived Cluster EFW density
 370 of the simulations are shifted to the measurements. Generally, the density and the ve-
 371 locity of the simulations seem to be less accurate than the magnetic field of the simu-
 372 lations.

373 54 intervals are selected around magnetopause crossings [...] (**Table 7**). When
 374 the spacecraft crosses the magnetopause **inbound** the magnitude of the magnetic field

increases, the solar wind speed drops from 100–300 km/s to zero, the plasma density becomes zero; furthermore the wide band on the omnidirectional Cluster CIS HIA ion spectra disappears. [...] The location of the magnetopause is well determined by the Cluster SC3 measurements. However, it is very difficult to identify the magnetopause crossings in the simulation data. [...] The magnetopause crossings very often cannot be seen in the simulations. Or when the magnetopause crossings are clearly identified in both simulations and spacecraft measurements the events are shifted. The accuracy of the model is lower for the dayside magnetopause locations.

Nine intervals are chosen around Cluster SC3 neutral sheet crossings (Figure 12; Table 8). The neutral **sheet** locations **are** determined using the results of the Boundary Layer Identification Code (BLIC) Project [Facskó *et al.*, in preparation]. The BLIC code determines the neutral sheet crossing Cluster FGM magnetic field measurements using Wang and Xu [1994]’s method. When the solar wind speed is almost zero; furthermore the CIS HIA density and the EFW calculated density are almost zero too; finally the GSE Z component of the magnetic field changes is a sign of the code indicated neutral sheet crossing (Figure 19; red and blue curves). [...] The neutral sheet crossings are visible very well in the GUMICS simulations (Figure 19; black curves). For five events (from nine Cluster SC3 crossings) the GUMICS–4 also provides similar smoothed parameters and change of sign of the B_z component. This is a **outstanding** result because the tail in the GUMICS–4 simulations is significantly smaller than the observed reality [Gordeev *et al.*, 2013; Facskó *et al.*, 2016]; furthermore the solar wind enters the tail in MHD simulations generally [Kallio and Facskó, 2015].

4 Discussion

The agreement of [...] B_z , V_x and n_{EFW} **in the solar wind** with the similar GUMICS simulation **predictions** is very good (Figure 4a, 4b, 4c, blue). The agreement of [...] n_{CIS} is worse (Figure 4c, red). It was expected because the n_{EFW} depends on the spacecraft potential provided by the EFW instrument. However, the CIS instrument has many modes for measuring the plasma parameters and it needs **periodic** calibration too. The correlation of the solar wind V_x , n_{CIS} and n_{EFW} with the similar GUMICS simulation parameters is greater than 0.9 (Figure 5c, 5e, 5g). The correlation of the B_z is also greater than 0.8 (Figure 5a). [...] The **upstream boundary** of the GUMICS–4 code **lies** at $32 R_E$ [Janhunen *et al.*, 2012], the nose of the terrestrial bow shock is at about

407 $20 R_E$. If the solar wind speed is 400 km/s, then this spatial distance means less than
 408 **a 5 minutes delay, so it should not be visible in the time delays from the cross cor-**
 409 **relations.** 80% of the intervals support this theory but 20 % **do not.** In these cases, the
 410 one-minute resolution B_z , n_{CIS} or the n_{EFW} parameters have a sudden jump or vari-
 411 ation that the simulation cannot follow, or the resolution of the simulation **output** (5 minutes)
 412 is too small to see these variations. Therefore, the correlation calculation is not accu-
 413 rate in these cases. Previously the OMNI data was compared to the Cluster data and
 414 the Cluster measurements were compared to the GUMICS–4 [Facsikó *et al.*, 2016]. The
 415 comparison suggests that the GUMICS–4 results should be similar **for** the OMNI data.
 416 Furthermore, we calculate correlation functions in the solar wind, where there is no sig-
 417 nificant perturbation of the input parameters in the simulation box. Therefore, we get
 418 **the expected result** after comparing the two different correlation calculations.

419 In the magnetosheath we get worse agreement with the GUMICS simulation data
 420 (Figure 9a, 9b, 9c). **While the parameters are correlated, the scatter is greater.**
 421 The general reason **for** this larger uncertainty seems to be [...] **that the magnetosheath**
 422 **is turbulent.** This phenomena explains the higher variations of the B_z magnetic field
 423 on Figure 9a. The solar wind V_x , n_{CIS} and n_{EFW} agree better than the magnetic field
 424 component (Figure 9b, 9c). Here there is no deviation between the densities derived in
 425 different ways (n_{CIS} and n_{EFW}) on Figure 9c. Figure 10 seems to contradict these state-
 426 ments above. The larger uncertainty of the B_z is visible on Figure 10a. However, that
 427 correlation is still good on Figure 10b. The other parameters have larger (> 0.9) cor-
 428 relation in Figure 10c, 10e, 10g. However, the time shifts in Figure 10d, 10f, 10h seem
 429 to be worse. Actually here the time shifts are worse because the shape of the time se-
 430 ries in the magnetosheath looks very **smooth and similar hence there is not enough**
 431 **points to get a sharp and large maximum correlation as the function of timeshift.**
 432 **The difference between the minimum and the maximum of the correlation**
 433 **is small comparing with the uncertainty of the calculation. The maximum,**
 434 **the timeshift could be anywhere and the shape of the correlation vs. timeshift**
 435 **function is often neither symmetric nor has only one local maximum.** Hence,
 436 the correlation calculation provides larger time shifts for the ion plasma parameters and
 437 the n_{EFW} .

438 In the magnetosphere the GUMICS–4 does not work well. [...] GUMICS–4 uses
 439 a tilted dipole to describe the terrestrial magnetic field [Janhunen *et al.*, 2012]. After re-

440 moving the magnetic dipole from the magnetic field measurements of the Cluster SC3
 441 and the simulation we get very low correlations and unacceptable time shifts (not shown).
 442 [...] The tilted dipole is an insufficient description **of the inner magnetospheric mag-**
 443 **netic field.** [...] The plasma **moments** and the n_{EFW} do not fit either. **The single**
 444 **fluid, ideal MHD does not describe the inner magnetosphere well** therefore [...]
 445 V_x and [...] n in the simulations do not agree **with** V_x , [...] n_{CIS} and the n_{EFW} mea-
 446 **sured by the Cluster SC3.** Within the $3.7 R_E$ domain **ring current physics must be**
 447 **added, as it has been** in other global MHD codes [for example *Tóth et al., 2012*].
 448 This [...] can explain [...] the limited accuracy of the cross polar cap potential (CPCP)
 449 and geomagnetic indices of the GUMICS simulations [*Juusola et al., 2014*]. The CPCP
 450 [...] GUMICS **agrees well with** spacecraft measurements therefore this quantity could
 451 be used for [...] simulation studies [*Lakka et al., 2018a*]. *Haducek et al.* [2017] also [...]
 452 **compared** [...] geomagnetic indices and the CPCP. The Space Weather Modelling Frame-
 453 work (SWMF) was tested. When the inner magnetosphere model was switched off in the
 454 simulation only the comparison of the simulated and observed CPCP was good. There-
 455 fore, the reason of the discrepancy of the geomagnetic indices in the GUMICS simula-
 456 tions must be the missing inner magnetosphere model.

457 **The reason of why simulation results and [...] measurements disagree**
 458 **could be the code or the bad input parameters.** During the 1-year run the
 459 **distributions of the OMNI solar wind magnetic field B_x , B_y , B_z components**
 460 [...] ; **solar wind velocity V_x , V_y V_z components** [...] and the solar wind P dy-
 461 **namic pressure** are calculated [...] from January 29, 2002 to February 2, 2003
 462 in GSE reference frame. These distributions of the OMNI solar wind mag-
 463 **netic field B_x , B_y , B_z components** were overplotted by red in Figure 13a, 13d, 13g, 13j
 464 and Figure 16a, 16d, 16g, 16j; Figure 13b, 13e, 13h, 13k and Figure 16b, 16e, 16h, 16k;
 465 furthermore Figure 13c, 13f, 13i, 13l and Figure 16c, 16f, 16i, 16l. These dis-
 466 **dtributions of the OMNI solar wind velocity V_x , V_y , V_z components** were over-
 467 plotted by red in Figure 14a, 14d, 14g, 14j and Figure 17a, 17d, 17g, 17j; Fig-
 468 ure 14b, 14e, 14h, 14k and Figure 17b, 17e, 17h, 17k; furthermore Figure 14c, 14f, 14i, 14l
 469 and Figure 17c, 17f, 17i, 17l. These distributions of the P solar wind pres-
 470 **sure calculated from the OMNI solar wind parameters** were overplotted by
 471 red in Figure 15a, 15b, 15c, 15d and Figure 18a, 18b, 18c, 18d. The intervals
 472 when the GUMICS–4 simulations and the Cluster SC3 measurements dis-

473 agreed are collected for intervals in the solar wind (Table 4) and the mag-
 474 netosheath (Table 5). The averaged shifted OMNI parameters of the poorly
 475 agreeing intervals from the Tables 4 and 5 are saved. The distributions of the
 476 OMNI parameters belonging to the bad simulation results are calculated for
 477 the solar wind region (Figure 13, 14 and 15) and in the magnetosheath (Fig-
 478 ure 16, 17 and 18).

479 **1.** In the solar wind the distributions of the OMNI B_x , B_y and B_z can be
 480 compared in Figure 13a, 13d, 13g, 13j; Figure 13b, 13e, 13h, 13k; fur-
 481 thermore in Figure 13c, 13f, 13i, 13l.

- 482 (a) When the B_z disagrees in simulations and measurements in Figure 13a, 13b, 13c
 483 the black and red distributions of the OMNI B_x , B_y and B_z are not
 484 similar [...] . The reason of these strange spikes is that there is only
 485 one poorly correlated interval for the B_z in the solar wind according
 486 to Table 4.
- 487 (b) When the V_x disagrees in simulations and measurements in Figure 13d, 13e, 13f
 488 the black and red distributions of the OMNI B_x , B_y and B_z are sim-
 489 ilar [...] . The distributions do not agree perfectly because in Table 4
 490 the number of the poorly correlated intervals is only six for the V_x
 491 component.
- 492 (c) When the n_{CIS} disagrees in simulations and measurements in Figure 13g, 13h, 13i
 493 the black and red distributions of the OMNI B_x , B_y and B_z are sim-
 494 ilar [...] . The distributions do not agree perfectly because in Table 4
 495 the number of the poorly correlated intervals is only 12 for the n_{CIS} .
- 496 (d) When the n_{EFW} disagrees in Figure 13j, 13k, 13l the black and red
 497 distributions of the OMNI B_x , B_y and B_z are similar [...] . The dis-
 498 tributions do not agree perfectly because in Table 4 the number of
 499 the poorly correlated intervals is only nine for n_{EFW} .

500 The values of the OMNI B_x , B_y and B_z are not peculiar in the solar wind.

501 **2.** In the solar wind the distributions of the OMNI V_x , V_y and V_z can be
 502 compared in Figure 14a, 14d, 14g, 14j; Figure 14b, 14e, 14h, 14k; fur-
 503 thermore in Figure 14c, 14f, 14i, 14l.

- 504 (a) When the B_z disagrees in Figure 14a, 14b, 14c the black and red dis-
 505 tributions of the OMNI V_x , V_y and V_z are not similar [...] . The rea-
 506 son of these strange spikes is that there is only one poorly correlated
 507 interval for the B_z in the solar wind according to Table 4.
- 508 (b) When the V_x disagrees in simulations and measurements in Figure 14d, 14e, 14f
 509 the black and red distributions of the OMNI V_x , V_y and V_z are sim-
 510 ilar [...] . The distributions do not agree perfectly because in Table 4
 511 the number of the poorly correlated intervals is only six for the V_x
 512 component.
- 513 (c) When the n_{CIS} disagrees in Figure 14g, 14h, 14i the black and red
 514 distributions of the OMNI V_x , V_y and V_z are similar [...] . The dis-
 515 tributions do not agree perfectly because in Table 4 the number of
 516 the poorly correlated intervals is only 12 for the n_{CIS} .
- 517 (d) When the n_{EFW} disagrees in simulations and measurements in Fig-
 518 ure 14j, 14k, 14l the black and red distributions of the OMNI V_x , V_y
 519 and V_z are similar [...] . The distributions do not agree perfectly be-
 520 cause in Table 4 the number of the poorly correlated intervals is only
 521 nine for the n_{EFW} .

522 The values of the OMNI V_x , V_y and V_z are not peculiar in the solar wind.

523 **3. In the solar wind the distributions of the solar wind P calculated from**
 524 **OMNI parameters can be compared in Figure 15a, 15b, 15c, 15d.**

- 525 (a) When the B_z disagrees in Figure 15a the black and red distributions
 526 of the OMNI P are not similar [...] . The reason of these strange spike
 527 is that there is only one poorly correlated interval for the B_z in the
 528 solar wind according to Table 4.
- 529 (b) When the V_x disagrees in simulations and measurements in Figure 15b
 530 the black and red distributions of the OMNI P are similar [...] . The
 531 distributions do not agree perfectly because in Table 4 the number
 532 of the poorly correlated intervals is only six V_x component.
- 533 (c) When the n_{CIS} disagrees in simulations and measurements in Figure 15c
 534 the black and red distributions of the OMNI P are similar [...] . The
 535 distributions do not agree perfectly because in Table 4 the number
 536 of the poorly correlated intervals is only 12 for the n_{CIS} .

537 (d) When the n_{EFW} disagrees in simulations and measurements in Fig-
 538 ure 15d the black and red distributions of the OMNI P are similar
 539 [...] . The distributions do not agree perfectly because in Table 4 the
 540 number of the poorly correlated intervals is only nine for the n_{EFW} .

541 The values of the OMNI P are not peculiar in the solar wind.

542 4. In the magnetosheath the distributions of the OMNI B_x , B_y and B_z can
 543 be compared in Figure 16a, 16d, 16g, 16j; Figure 16b, 16e, 16h, 16k; fur-
 544 thermore in Figure 16c, 16f, 16i, 16l.

- 545 (a) When the B_z disagrees in simulations and measurements in Figure 16a, 16b, 16c
 546 the black and red distributions of the OMNI B_x , B_y and B_z are sim-
 547 ilar [...] .
- 548 (b) When the V_x disagrees in simulations and measurements in Figure 16d, 16e, 16f
 549 the black and red distributions of the OMNI B_x , B_y and B_z are sim-
 550 ilar [...] .
- 551 (c) When the n_{CIS} disagrees in simulations and measurements in Figure 16g, 16h, 16i
 552 the black and red distributions of the OMNI B_x , B_y and B_z are sim-
 553 ilar [...] .
- 554 (d) When the n_{EFW} disagrees in Figure 16j, 16k, 16l the black and red
 555 distributions of the OMNI B_x , B_y and B_z are similar [...] .

556 The distributions agree quite well because in Table 5 the number of the
 557 poorly correlated intervals 18, 50, 33 and 30 for the B_z , the V_x , the n_{CIS}
 558 and n_{CIS} components, respectively. The number of cases are higher and
 559 the values of the OMNI B_x , B_y and B_z are not peculiar in the magne-
 560 tosheath.

561 5. In the magnetosheath the distributions of the OMNI V_x , V_y and V_z can
 562 be compared in Figure 17a, 17d, 17g, 17j; Figure 17b, 17e, 17h, 17k; fur-
 563 thermore in Figure 17c, 17f, 17i, 17l.

- 564 (a) When the B_z disagrees in Figure 17a, 17b, 17c the balck and red dis-
 565 tributions of the OMNI V_x , V_y and V_z are similar [...] .
- 566 (b) When the V_x disagrees in simulations and measurements in Figure 17d, 17e, 17f
 567 the black and red distributions of the OMNI V_x , V_y and V_z are sim-
 568 ilar [...] .

569 (c) When the n_{CIS} disagrees in Figure 17g, 17h, 17i the black and red
 570 distributions of the OMNI V_x , V_y and V_z are similar [...] .

571 (d) When the n_{EFW} disagrees in simulations and measurements in Fig-
 572 ure 17j, 17k, 17l the black and red distributions of the OMNI V_x , V_y
 573 and V_z are similar [...] .

574 The distributions agree quite well because in Table 5 the number of the
 575 poorly correlated intervals 18, 50, 33 and 30 for the B_z , the V_x , the n_{CIS}
 576 and n_{CIS} components, respectively. The number of cases are higher and
 577 the values of the OMNI V_x , V_y and V_z are not peculiar in the magne-
 578 tosheath.

579 **6. In the magnetosheath the distributions of the solar wind P calculated
 580 from OMNI parameters can be compared in Figure 18a, 18b, 18c, 18d.**

581 (a) When the B_z disagrees in Figure 18a the black and red distributions
 582 of the OMNI P are similar [...] .

583 (b) When the V_x disagrees in simulations and measurements in Figure 18b
 584 the black and red distributions of the OMNI P are similar [...] .

585 (c) When the n_{CIS} disagrees in simulations and measurements in Figure 18c
 586 the black and red distributions of the OMNI P are similar [...] .

587 (d) When the n_{EFW} disagrees in simulations and measurements in Fig-
 588 ure 18d the black and red distributions of the OMNI P are similar
 589 [...] .

590 The distributions agree quite well because in Table 5 the number of the
 591 poorly correlated intervals 18, 50, 33 and 30 for the B_z , the V_x , the n_{CIS}
 592 and n_{CIS} components, respectively. The number of cases are higher and
 593 the values of the OMNI P are not peculiar in the magnetosheath.

594 The inaccuracy of the GUMICS-4 simulations does not depend on the OMNI
 595 parameters in the solar wind and magnetosheath regions. The same study
 596 does not need to be done for the magnetosphere because the deviation of the
 597 measurements and the simulations is so large that it cannot be caused by the
 598 wrong OMNI solar wind parameters.

599 The bow shock positions agree in the GUMICS simulations and the Cluster SC3
 600 measurements. However, the magnetopause locations do not fit well as the bow shock

in simulations and observations. In simulations the location of the magnetopause is determined **from peaks in currents density, particle density gradient, or changes in flow velocity** [Siscoe *et al.*, 2001; García and Hughes, 2007; Gordeev *et al.*, 2013, see references therein]. In this paper the previously saved simulation parameters along the virtual Cluster SC3 orbit are analysed. **The J_y current density component cannot be calculated from only the Cluster SC3 measurements.** Therefore, the above mentioned methods cannot be applied. [...] This discrepancy of the magnetopause location agrees with the results of Gordeev *et al.* [2013] and Facskó *et al.* [2016]. Gordeev *et al.* [2013] compared synthetic GUMICS runs with an empirical formula for the magnetopause locations. Facskó *et al.* [2016] used OMNI solar wind data as input and got the same result as Gordeev *et al.* [2013] and this paper. [...] The neutral sheets are visible in both simulations and observations (Figure 19, Table 8). This experience is exceptional because the night side magnetosphere of the GUMICS–4 simulations is small and twisted [Gordeev *et al.*, 2013; Facskó *et al.*, 2016]. However, in these cases the IMF has no large B_y component. From Facskó *et al.* [2016] we know that the GUMICS has normal long tail (or night side magnetosphere) if the B_y is small.

5 Summary and conclusions

Based on the previously created 1-year long GUMICS–4 run global MHD simulation results are compared with Cluster SC3 magnetic field, solar wind velocity and density measurements along the spacecraft orbit. Intervals are selected when the Cluster SC3 and the virtual space probe are situated in the solar wind, magnetosheath and the magnetosphere and their correlation are calculated. Bow shock, magnetopause and neutral sheet crossings are selected and their visibility and relative position are compared. We achieved the following results:

1. **In the solar wind the correlation coefficient of the B_z , the V_x , the n_{EFW} and the n_{CIS} are larger than 0.8, 0.9, 0.9 and 0.9, respectively.** [...] The agreement of the B_z , the V_x and the n_{EFW} is very good, furthermore the agreement of the n_{CIS} is also good.
2. **In the magnetosheath the correlation coefficient of the B_z , the V_x , the n_{EFW} and the n_{CIS} are larger than 0.6, 0.9, 0.9 and 0.9, respectively.** [...] The agreement of the magnetic field component, the ion plasma moments and the calculated empirical density is a bit worse than in the solar wind. The V_x ,

633 the n_{EFW} and the n_{CIS} fits better than the B_z component in the magnetosheath.
 634 Their agreement is still good. The reason of the deviation is the turbulent behav-
 635 ior of the slowed down and thermalised turbulent solar wind.

636 3. In neither the dayside nor the nightside magnetosphere can the GUMICS-4 pro-
 637 vide realistic results. The simulation outputs and the spacecraft measurement dis-
 638 agree in this region. The reason of this deviation must be the missing coupled in-
 639 ner magnetosphere model. The applied tilted dipole approach is not satisfactory
 640 in the magnetosphere at all.

641 **4. Disagreement between GUMICS-4 and observations does not seem to
 642 be due to upstream solar wind.**

643 5. The position of the bow shock and the neutral sheet agrees well in the simulations
 644 and the Cluster SC3 magnetic field, ion plasma moments and derived electron den-
 645 sity measurements in this study. The position of the magnetopause does not fit
 646 that well. [...]

647 The GUMICS-4 has [...] scientific and strategic importance for the European Space
 648 Weather and Scientific community. This code developed in the Finnish Meteorological
 649 Institute is the most developed and tested, widely used tool for modelling the cosmic en-
 650 viroment of the Earth in the **Europe**. [...] **An inner magnetosphere model should**
 651 **be two way coupled to the existing configuration of the simulation tool to improve the**
 652 **accuracy of the simulations.**

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 669 use the archive of the Community Coordinated Modelling Center (<https://ccmc.gsfc.nasa.gov/publications/posted>)
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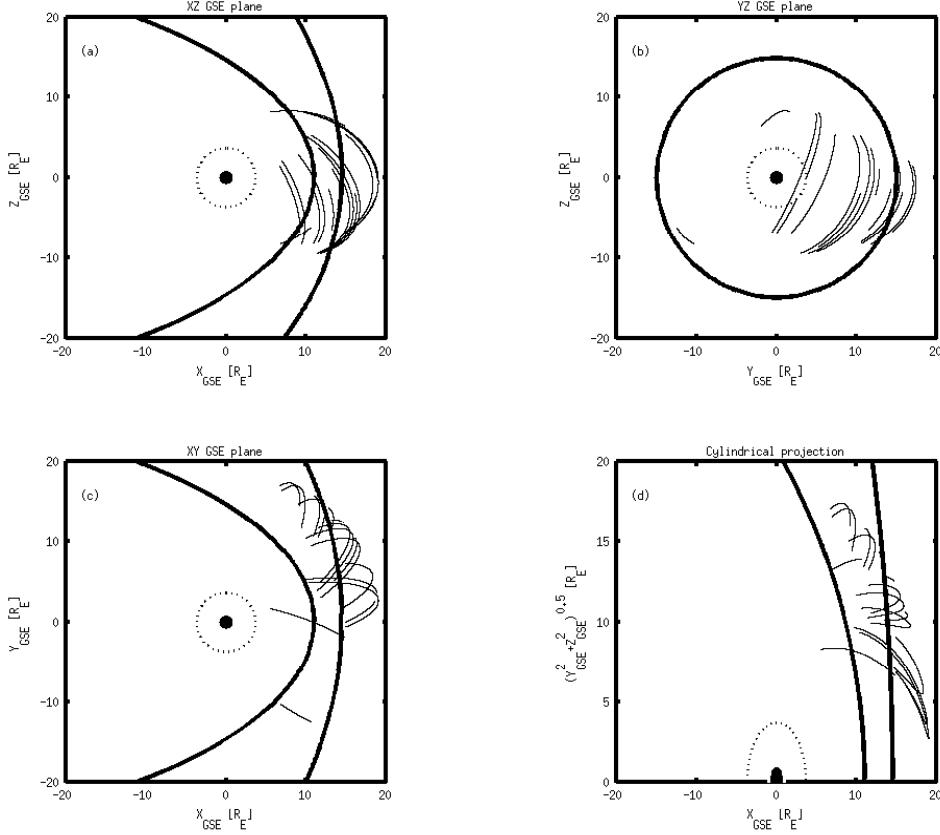
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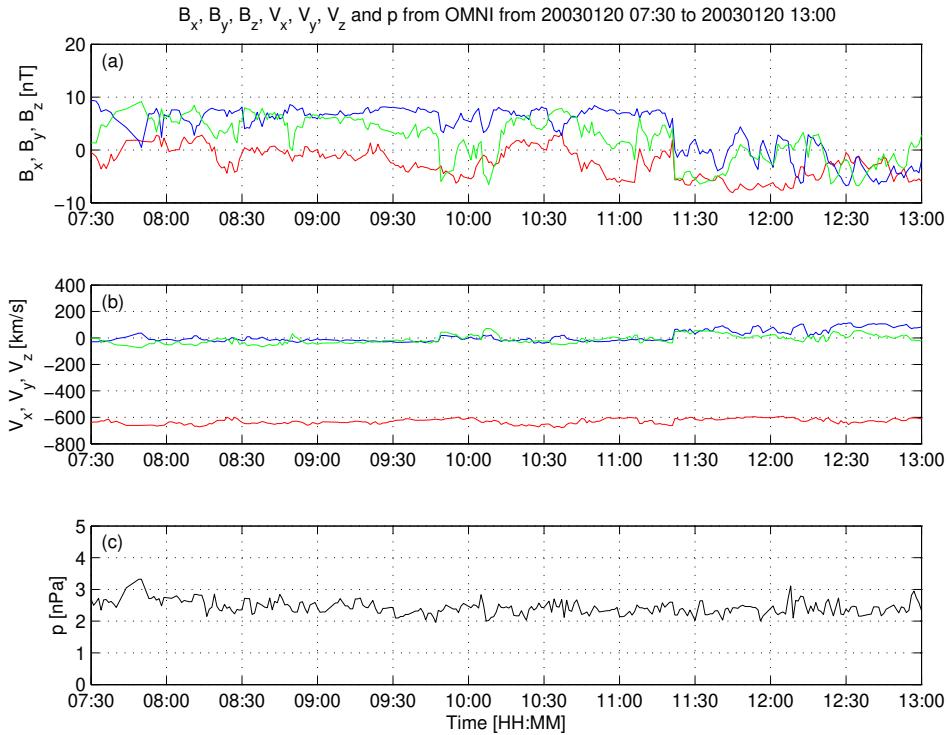
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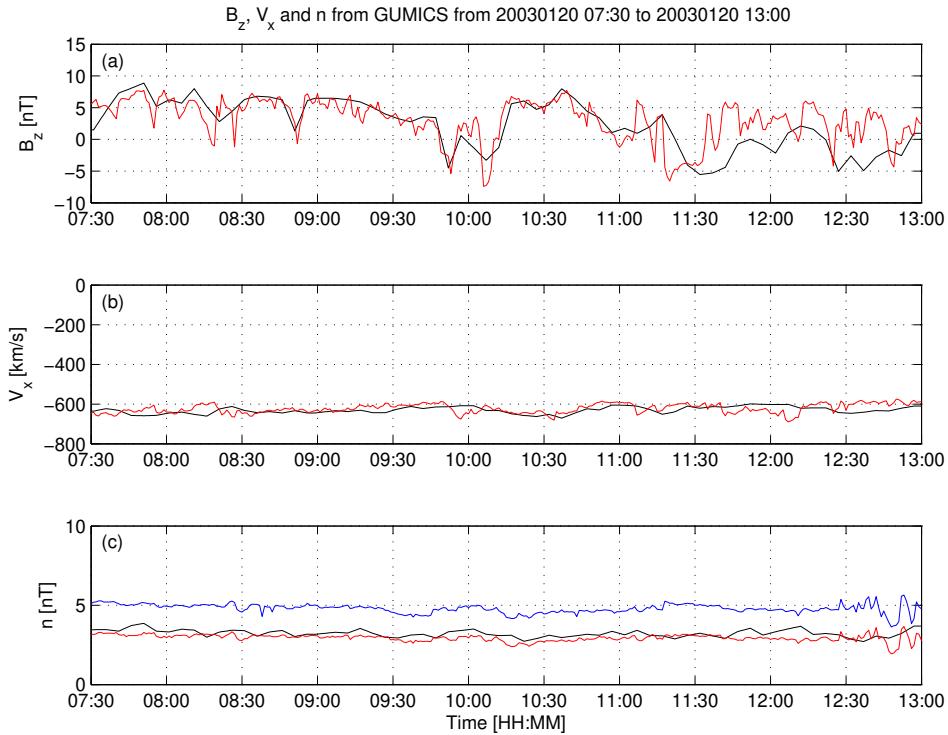
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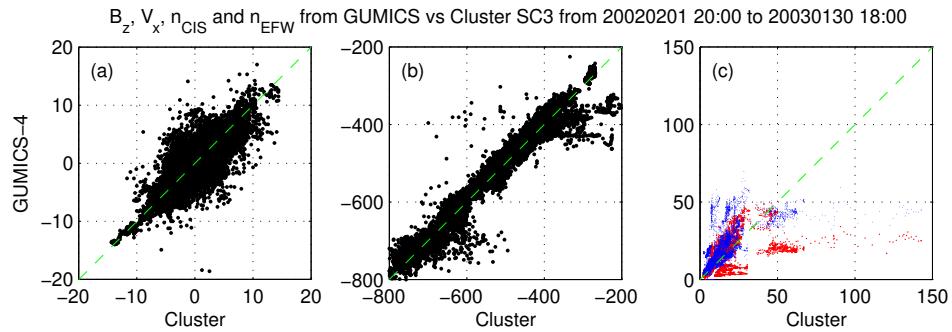
925 **Figure 1.** Cluster SC3 orbit in the solar wind in GSE system for all intervals (see Table 1).
926 (a) XZ (b) YZ (c) XY (d) Cylindrical projection. Average bow-shock and magnetopause po-
927 sitions are drawn on all plots using **thick** solid lines [Perego *et al.*, 1995; Tsyganenko, 1995,
928 respectively]. The black dots at $3.7 R_E$ show the boundary of the GUMICS-4 inner magneto-
929 spheric domain. The black circle in the origo of all plots shows the size of the Earth.



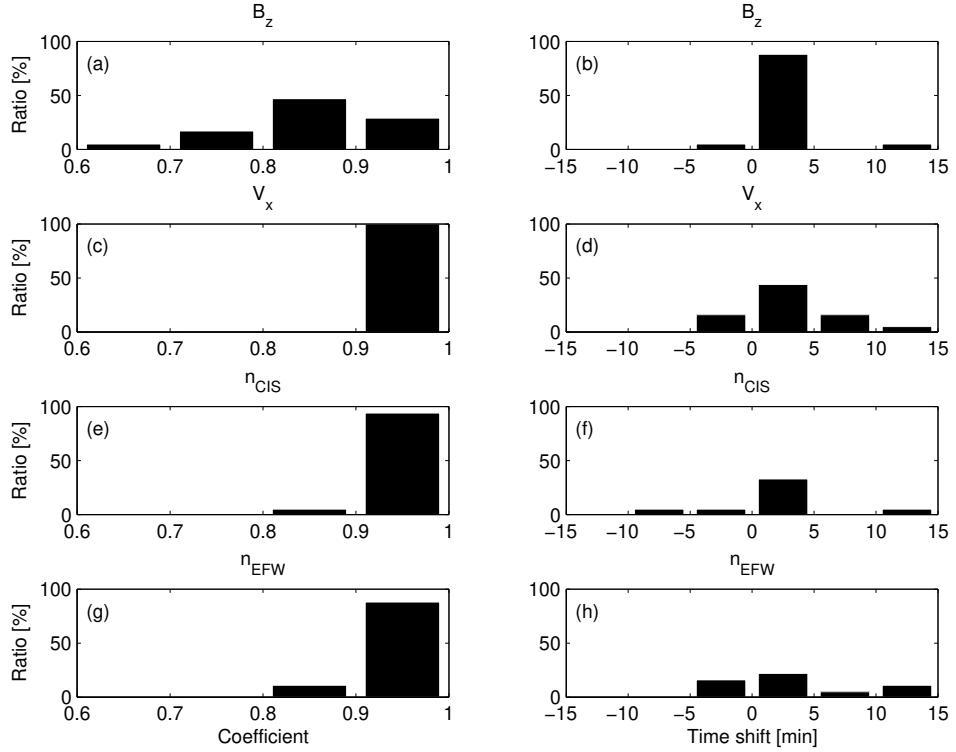
930 **Figure 2.** OMNI solar wind data in GSE system from 7:30 to 13:00 (UT) on January 20,
 931 2003. (a) Magnetic field B_x (red), B_y (green) and B_z (blue) components. (b) Solar wind velocity
 932 V_x (red), V_y (green) and V_z (blue) components. (c) The P pressure of the solar wind (black).



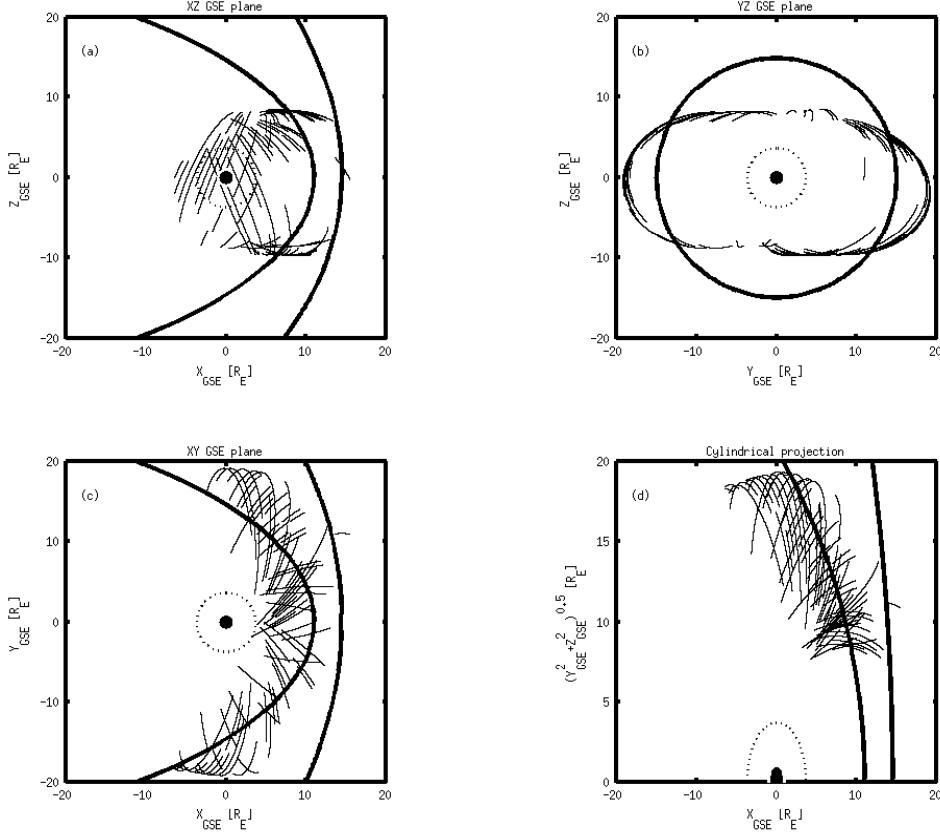
933 **Figure 3.** GUMICS-4 simulation results (black) and Cluster SC3 magnetic field Z component,
 934 ion plasma moments (red) and electron density calculated from spacecraft potential (blue) from
 935 January 20, 2003 from 7:30 to 13:00 (UT) in the solar wind in GSE system. (a) Magnetic field Z
 936 component. (b) Solar wind velocity X component (c) Solar wind density.



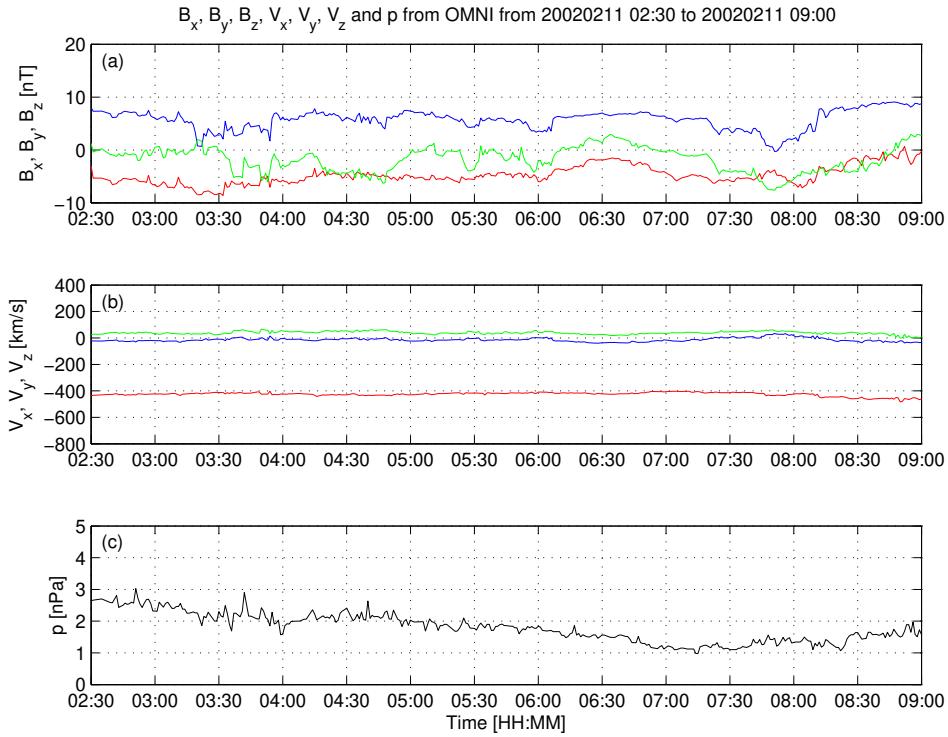
937 **Figure 4.** Scattered plots of the Cluster SC3 and GUMICS-4 simulations for all intervals in
 938 the solar wind. The dashed line is the $y=x$ line. (a) Magnetic field Z component in GSE system.
 939 (b) Solar wind velocity X component in GSE system. (c) Solar wind density measured by the
 940 CIS HIA instrument (red) and calculated from the spacecraft potential (blue).



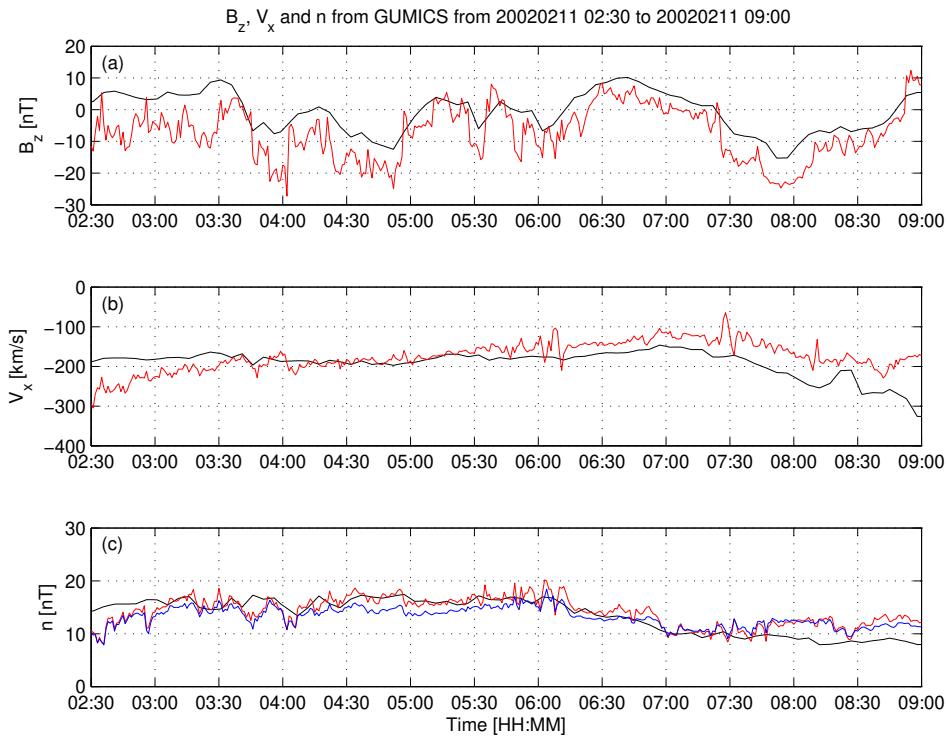
941 **Figure 5.** The distributions of the **highest** correlation coefficients (a, c, e, g) of the magnetic
 942 field Z component (B_z) in GSE system, solar wind velocity X component (V_x) in GSE system,
 943 the solar wind density measured by the CIS HIA (n_{CIS}) instrument and calculated from the
 944 spacecraft potential (n_{EFW}), respectively, for all intervals in the solar wind. The distributions of
 945 the **corresponding** time shifts (b, d, f, h) of the B_z , the V_x , the n_{CIS} and the n_{EFW}), respec-
 946 tively, for all intervals in the solar wind.



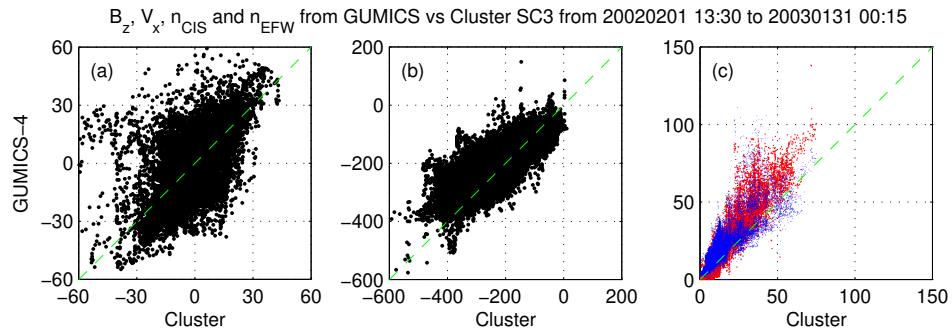
947 **Figure 6.** Cluster SC3 orbit in the magnetosheath in GSE system for all intervals (see Ta-
 948 ble 2). (a) XZ (b) YZ (c) XY (d) Cylindrical projection. Average bow-shock and magnetopause
 949 positions are drawn on all plots using **thick** solid lines [Peredo *et al.*, 1995; Tsyganenko, 1995,
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 951 spheric domain. The black circle in the origo of all plots shows the size of the Earth.



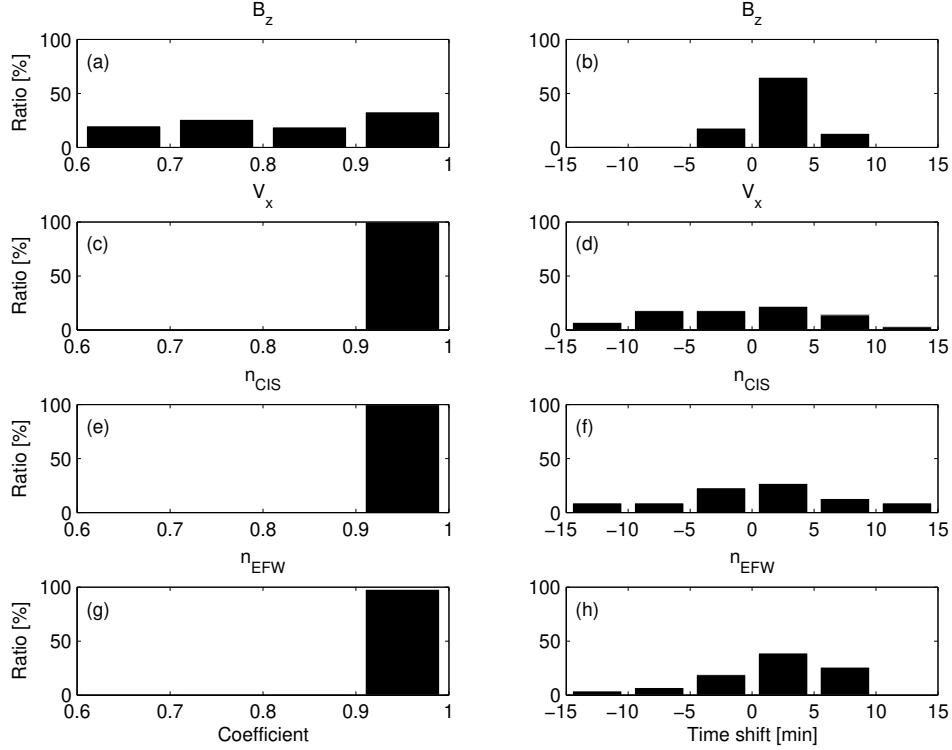
952 **Figure 7.** OMNI solar wind data in GSE system from 2:30 to 09:00 (UT) on February 11,
953 2002. (a) Magnetic field B_x (red), B_y (green) and B_z (blue) components. (b) Solar wind velocity
954 V_x (red), V_y (green) and V_z (blue) components. (c) The P pressure of the solar wind (black).



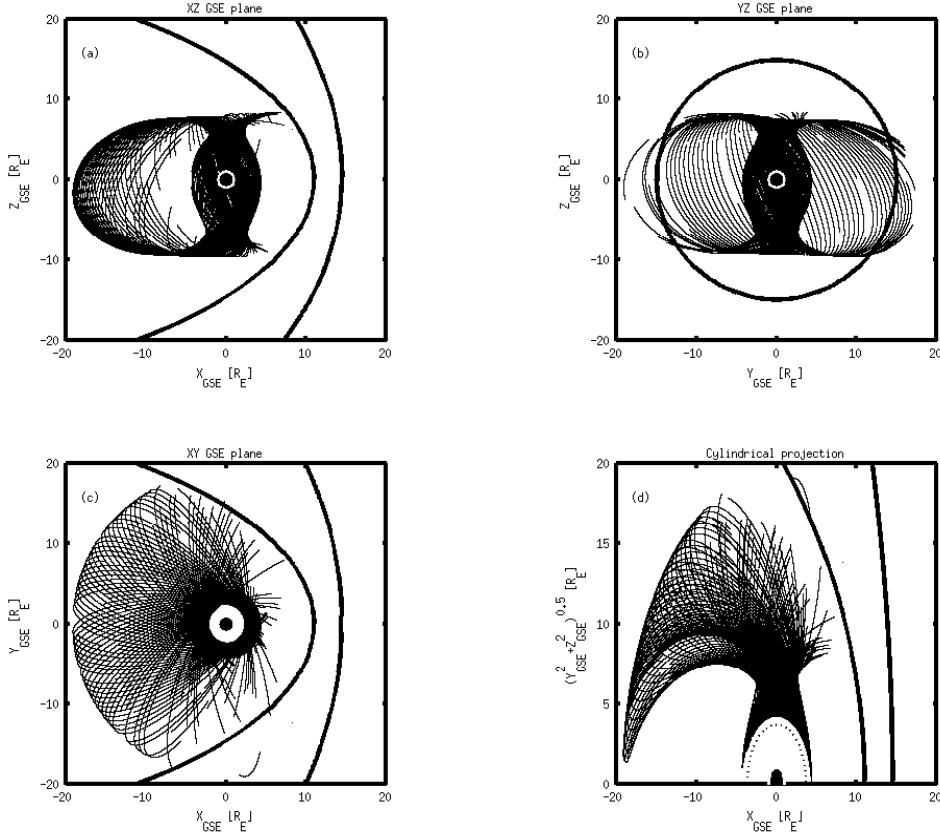
955 **Figure 8.** GUMICS-4 simulation results (black) and Cluster SC3 magnetic field Z component,
 956 ion plasma moments (red) and electron density calculated from spacecraft potential (blue) from
 957 February 11, 2002 from 2:30 to 9:00 (UT) in the magnetosheath in GSE system (a) Magnetic
 958 field Z component. (b) Solar wind velocity X component (c) Solar wind density.



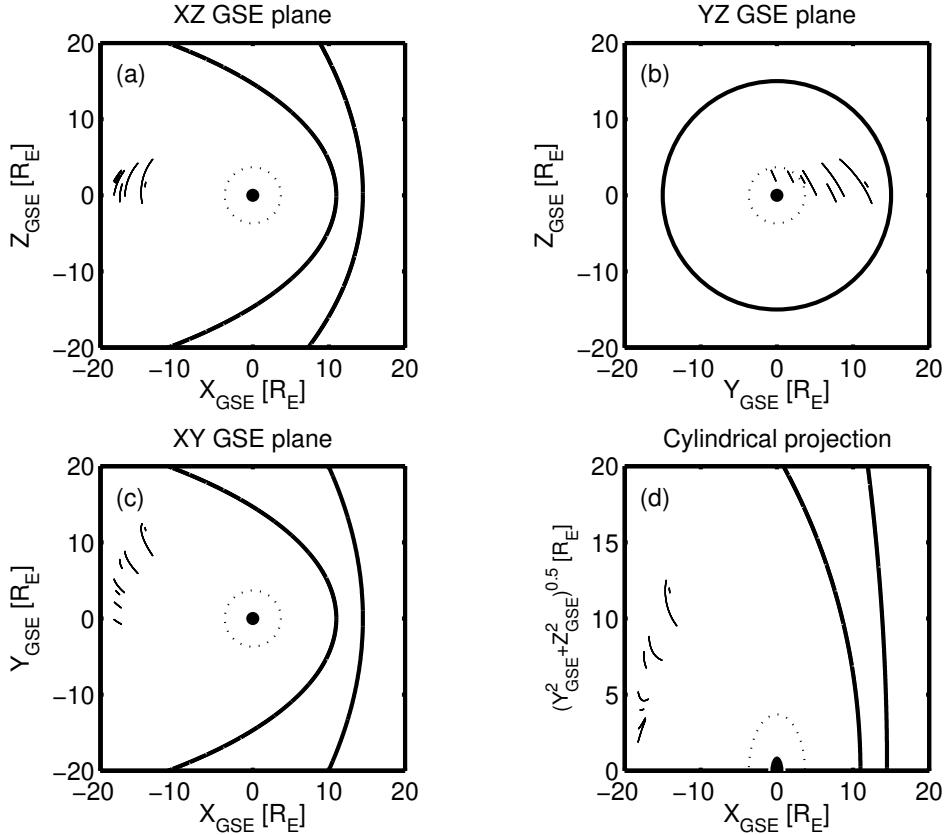
959 **Figure 9.** Scattered plots of the Cluster SC3 and GUMICS-4 simulations for all intervals in
 960 the magnetosheath in GSE system. The dashed line is the $y=x$ line. (a) Magnetic field Z com-
 961 ponent. (b) Solar wind velocity X component. (c) Solar wind density measured by the CIS HIA
 962 instrument (red) and calculated from the spacecraft potential (blue).



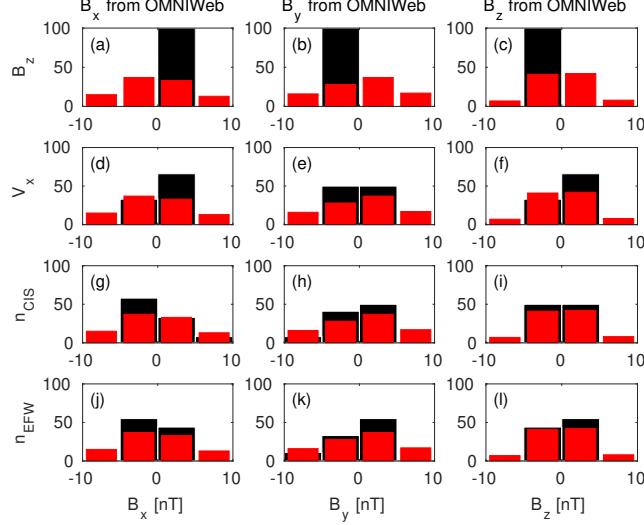
963 **Figure 10.** The distributions of the correlation coefficients (a, c, e, g) of the magnetic field Z
 964 component (B_z) in GSE system, solar wind velocity X component (V_X) in GSE system, the solar
 965 wind density measured by the CIS HIA (n_{CIS}) instrument and calculated from the spacecraft
 966 potential (n_{EFW}), respectively, for all intervals in the magnetosheath. The distributions of the
 967 time shifts (b, d, f, h) of the B_z , the V_X , the n_{CIS} and the n_{EFW}), respectively, for all intervals
 968 in the magnetosheath.



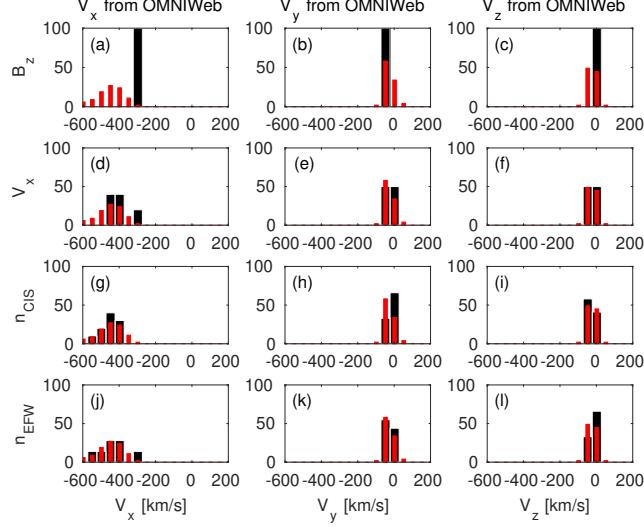
969 **Figure 11.** Cluster SC3 orbit in the magnetosphere in GSE system for all intervals (see Ta-
 970 ble 3). (a) XZ (b) YZ (c) XY (d) Cylindrical projection. Average bow-shock and magnetopause
 971 positions are drawn on all plots using **thick** solid lines [Peredo *et al.*, 1995; Tsyganenko, 1995,
 972 respectively]. The black dots at $3.7 R_E$ show the boundary of the GUMICS-4 inner magneto-
 973 spheric domain. The black circle in the origo of all plots shows the size of the Earth.



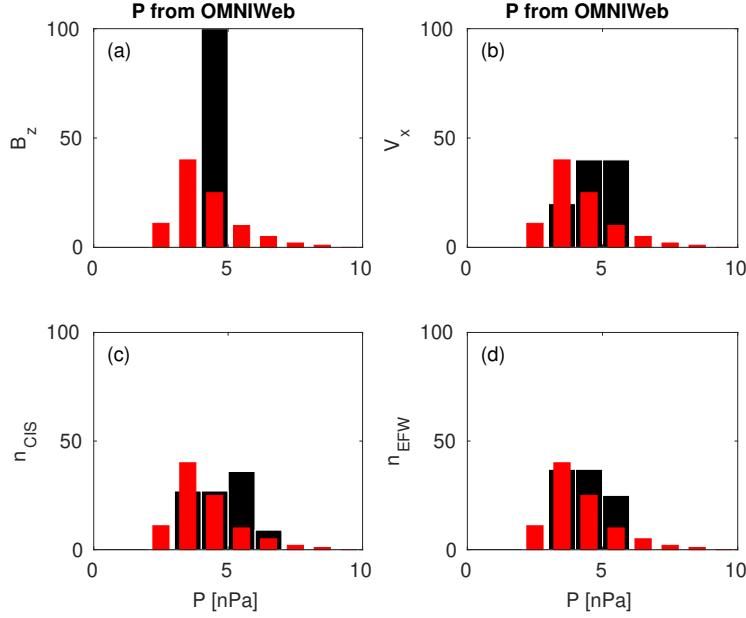
974 **Figure 12.** Cluster SC3 orbit in the tail in GSE system for all intervals (see Table 8). (a) XZ
 975 (b) YZ (c) XY (d) Cylindrical projection. Average bow-shock and magnetopause positions are
 976 drawn on all plots using **thick** solid lines [Perez et al., 1995; Tsyganenko, 1995, respectively].
 977 The black dots at $3.7 R_E$ show the boundary of the GUMICS-4 inner magnetospheric domain.
 978 The black circle in the origo of all plots shows the size of the Earth.



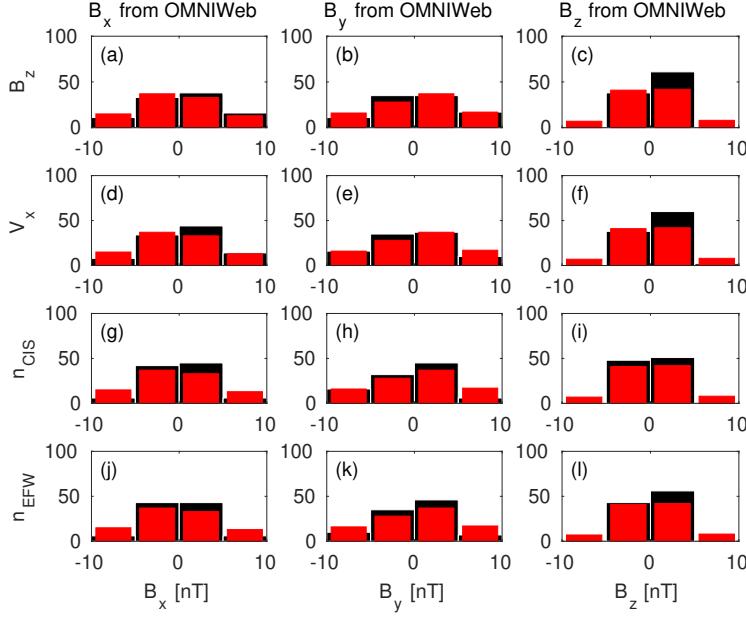
979 **Figure 13.** The **black** distributions of the B_x , the B_y and the B_z OMNI solar wind magnetic
 980 field components when the agreement of the Cluster SC3 measurements and the GUMICS-4
 981 simulations are poor in the solar wind (see Table 4). The B_z , the V_x , the n_{CIS} and the n_{EFW}
 982 are the magnetic field GSE Z component, the plasma ion velocity X GSE component, the solar
 983 wind density measured by the CIS HIA instrument and the calculated from the EFW spacecraft
 984 potential, respectively. (a, b, c) Distribution of OMNI B_x , B_y , B_z when the agreement of B_z
 985 is poor. (d, e, f) Distribution of OMNI B_x , B_y , B_z when the agreement of V_x is poor. (g, h, i)
 986 Distribution of OMNI B_x , B_y , B_z when the agreement of n_{CIS} is poor. (j, k, l) Distribution of
 987 OMNI B_x , B_y , B_z when the agreement of n_{EFW} is poor. The values are in percentage unit in
 988 the distributions. **The red distributions of (a, d, g, j), (b, e, h, k) and (c, f, i, l) are**
 989 **the distribution of the B_x , the B_y , and the B_z components of the OMNI solar wind**
 990 **magnetic field during the 1-year run from January 29, 2002 to February 2, 2003 in**
 991 **GSE reference frame, respectively.**



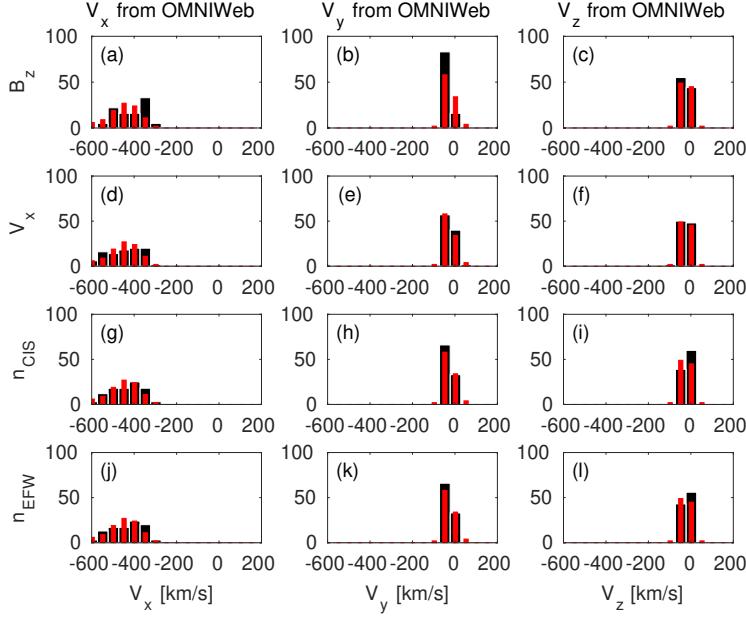
992 **Figure 14.** The **black** distributions of the V_x , the V_y and the V_z OMNI solar wind magnetic
993 field components when the agreement of the Cluster SC3 measurements and the GUMICS–4
994 simulations are poor in the solar wind (see Table 4). The B_z , the V_x , the n_{CIS} and the n_{EFW}
995 are the magnetic field GSE Z component, the plasma ion velocity X GSE component, the solar
996 wind density measured by the CIS HIA instrument and the calculated from the EFW spacecraft
997 potential, respectively. (a, b, c) Distribution of OMNI V_x , V_y , V_z when the agreement of B_z
998 is poor. (d, e, f) Distribution of OMNI V_x , V_y , V_z when the agreement of V_x is poor. (g, h, i)
999 Distribution of OMNI V_x , V_y , V_z when the agreement of n_{CIS} is poor. (j, k, l) Distribution of
1000 OMNI V_x , V_y , V_z when the agreement of n_{EFW} is poor. The values are in percentage unit in
1001 the distributions. **The red distributions of (a, d, g, j), (b, e, h, k) and (c, f, i, l) are**
1002 **the distributions of the V_x , the V_y and the V_z components of the OMNI solar wind**
1003 **velocity during the 1-year run from January 29, 2002 to February 2, 2003 in GSE**
1004 **reference frame, respectively.**



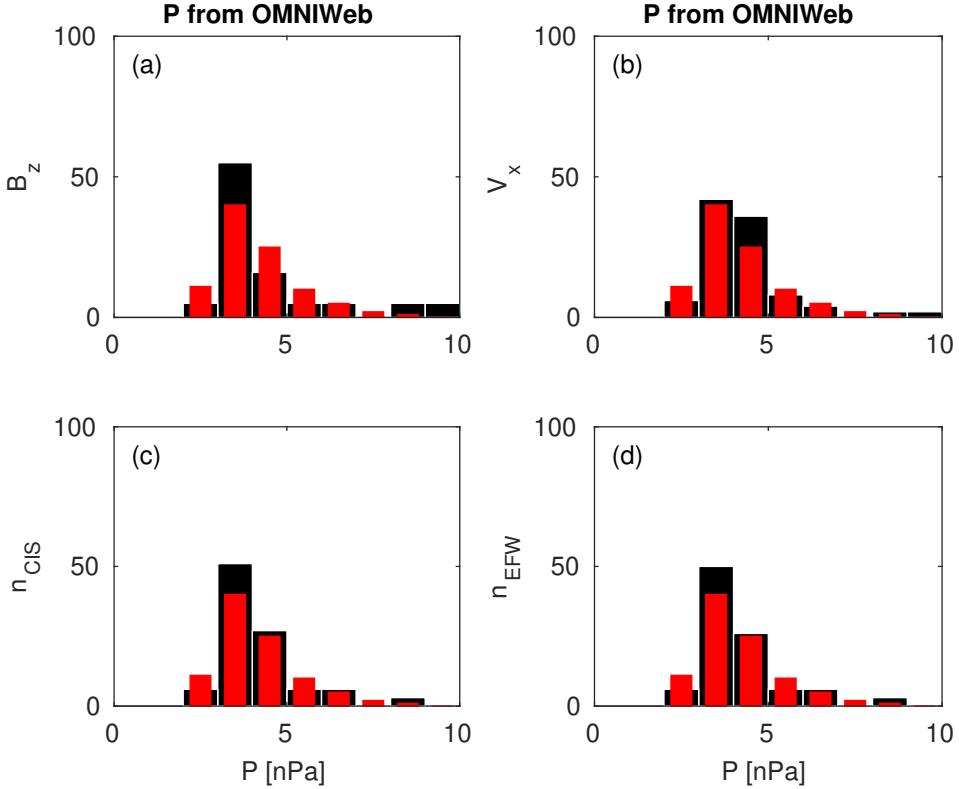
1005 **Figure 15.** The **black** distributions of the P solar wind dynamic pressure calculated from
 1006 OMNI parameters when the agreement of the Cluster SC3 measurements and the GUMICS-4
 1007 simulations are poor in the solar wind (see Table 4). The B_z , V_x , n_{CIS} and n_{EFW} are the mag-
 1008 netic field GSE Z component, the velocity X GSE component, the solar wind density measured
 1009 by the CIS HIA instrument and calculated from the EFW spacecraft potential, respectively.
 1010 (a, b, c, d) The distribution of the P calculated from OMNI data when the agreement of the B_z ,
 1011 the V_x , the n_{CIS} or the n_{EFW} are poor. The values are in percentage unit in the distributions.
 1012 **The red distributions of (a, b, c, d) are the distributions of the P solar wind dy-**
 1013 **namic pressure calculated from the OMNI solar wind parameters during the 1-year**
 1014 **run from January 29, 2002 to February 2, 2003 in GSE reference frame.**



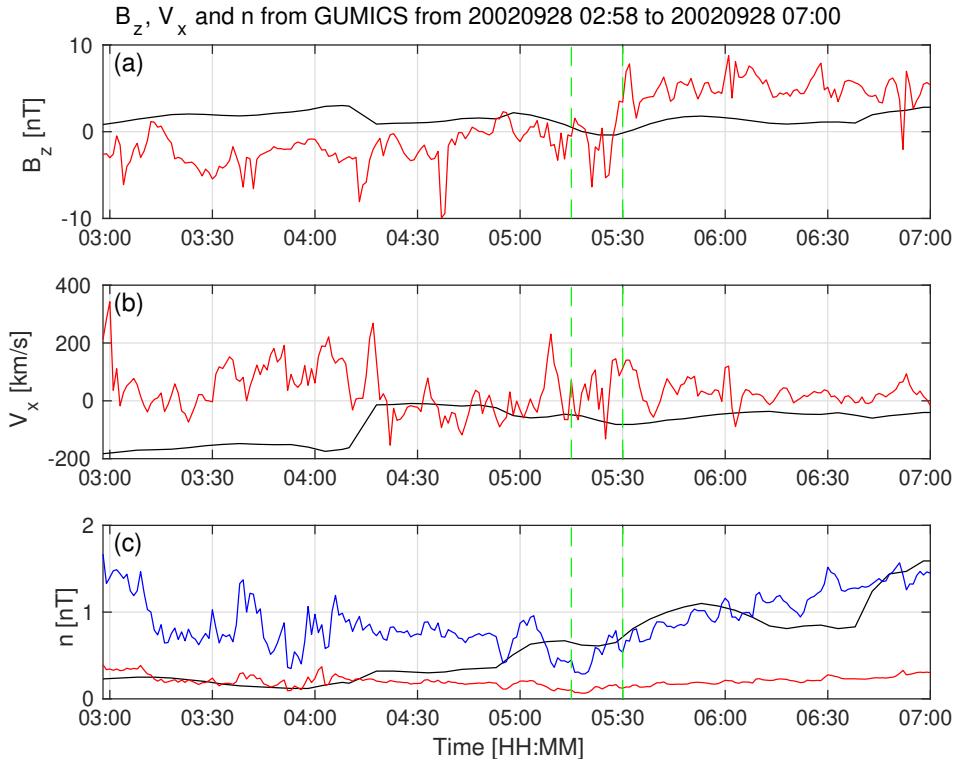
1015 **Figure 16.** The **black** distributions of the B_x , the B_y and the B_z OMNI solar wind magnetic
 1016 field components when the agreement of the Cluster SC3 measurements and the GUMICS–4
 1017 simulations are poor in the magnetosheath (see Table 5). The B_z , the V_x , the n_{CIS} and the
 1018 n_{EWF} are the magnetic field GSE Z component, the plasma ion velocity X GSE component,
 1019 the solar wind density measured by the CIS HIA instrument and the calculated from the EFW
 1020 spacecraft potential, respectively. (a, b, c) Distribution of OMNI B_x , B_y , B_z when the agree-
 1021 ment of B_z is poor. (d, e, f) Distribution of OMNI B_x , B_y , B_z when the agreement of V_x is poor.
 1022 (g, h, i) Distribution of OMNI B_x , B_y , B_z when the agreement of n_{CIS} is poor. (j, k, l) Distri-
 1023 bution of OMNI B_x , B_y , B_z when the agreement of n_{EWF} is poor. The values are in percentage
 1024 unit in the distributions. **The red distributions of (a, d, g, j), (b, e, h, k) and (c, f, i, l)**
 1025 **are the distribution of the B_x , the B_y , and the B_z components of the OMNI solar**
 1026 **wind magnetic field during the 1-year run from January 29, 2002 to February 2,**
 1027 **2003 in GSE reference frame, respectively.**



1028 **Figure 17.** The **black** distributions of the V_x , the V_y and the V_z OMNI solar wind magnetic
 1029 field components when the agreement of the Cluster SC3 measurements and the GUMICS–4
 1030 simulations are poor in the magnetosheath (see Table 5). The B_z , the V_x , the n_{CIS} and the
 1031 n_{EFW} are the magnetic field GSE Z component, the plasma ion velocity X GSE component, the
 1032 solar wind density measured by the CIS HIA instrument and the calculated from the EFW space-
 1033 craft potential, respectively. (a, b, c) Distribution of OMNI V_x , V_y , V_z when the agreement of
 1034 B_z is poor. (d, e, f) Distribution of OMNI V_x , V_y , V_z when the agreement of V_x is poor. (g, h, i)
 1035 Distribution of OMNI V_x , V_y , V_z when the agreement of n_{CIS} is poor. (j, k, l) Distribution of
 1036 OMNI V_x , V_y , V_z when the agreement of n_{EFW} is poor. The values are in percentage unit in
 1037 the distributions. **The red distributions of (a, d, g, j), (b, e, h, k) and (c, f, i, l) are**
 1038 **the distributions of the V_x , the V_y and the V_z components of the OMNI solar wind**
 1039 **velocity during the 1-year run from January 29, 2002 to February 2, 2003 in GSE**
 1040 **reference frame, respectively.**



1041 **Figure 18.** The black distributions of the P solar wind dynamic pressure calculated from
 1042 OMNI parameters when the agreement of the Cluster SC3 measurements and the GUMICS–4
 1043 simulations are poor in the magnetosheath (see Table 5). The B_z , V_x , n_{CIS} and n_{EFW} are
 1044 the magnetic field GSE Z component, the velocity X GSE component, the solar wind density
 1045 measured by the CIS HIA instrument and calculated from the EFW spacecraft potential, respec-
 1046 tively. (a, b, c, d) The distribution of the P calculated from OMNI data when the agreement of
 1047 the B_z , the V_x , the n_{CIS} or the n_{EFW} are poor. The values are in percentage unit in the dis-
 1048 tributions. **The red distributions of (a, b, c, d) are the distributions of the P solar**
 1049 **wind dynamic pressure calculated from the OMNI solar wind parameters during the**
 1050 **1-year run from January 29, 2002 to February 2, 2003 in GSE reference frame.**



1051 **Figure 19.** GUMICS-4 simulation results (black) and Cluster SC3 magnetic field Z compo-

1052 nent, ion plasma moments (red) and electron density calculated from spacecraft potential (blue)

1053 from September 28, 2002 from 2:58 to 7:00 (UT) in the tail in GSE system. (a) Magnetic field

1054 Z component. (b) Solar wind velocity X component (c) Solar wind density. From 05:15 to 05:30

1055 **between the green dashed vertical lines** both the Cluster SC3 and the virtual spaceprobe of

1056 the GUMICS-4 simulation cross the neutral sheet multiple times.

Start/End	C_{B_z}	δt_{B_z}	C_{V_x}	δt_{V_x}	$C_{n_{CIS}}$	$\delta t_{n_{CIS}}$	$C_{n_{EFW}}$	$\delta t_{n_{EFW}}$
	[min]		[min]		[min]		[min]	
20020201 20:00/0203 04:00	0.96	2	1.00	13	0.96	3	0.98	3
20020211 13:00/0212 12:00	0.82	2	1.00	0	0.99	18	0.99	18
20020218 09:00/0219 02:00	0.93	0	1.00	-3	0.94	-3	0.97	-3
20020219 06:30/0219 15:00	0.93	1	1.00	0	0.99	-60	1.00	-52
20020220 18:30/0222 00:00	0.87	4	1.00	4	0.93	-21	0.98	3
20020318 17:30/0319 02:30	0.89	1	1.00	21	0.98	50	0.99	5
20020412 20:30/0413 02:00	0.90	4	0.99	-54	0.94	60	0.98	12
20021227 12:00/1228 03:00	0.75	4	1.00	-3	0.99	-26	0.99	21
20021229 20:00/1230 16:00	0.68	1	1.00	1	0.99	-30	0.98	41
20030106 06:00/0106 19:00	0.79	4	1.00	6	0.99	4	0.99	-60
20030108 07:00/0109 03:30	0.55	10	1.00	41	0.99	10	0.97	-55
20030113 08:30/0113 18:00	0.91	3	1.00	5	1.00	3	0.97	-1
20030120 07:30/0120 13:00	0.82	2	1.00	9	1.00	-6	1.00	-3
20030122 12:00/0123 14:00	0.81	2	1.00	3	0.99	3	0.92	-60
20030124 18:00/0126 00:00	0.73	3	1.00	0	0.99	-60	0.99	60
20030127 16:00/0128 06:00	0.88	-1	1.00	-3	0.95	1	0.88	11
20030129 12:00/0130 18:00	0.90	2	1.00	4	0.94	-59	0.98	1

1057 **Table 1.** The studied solar wind intervals. The correlation coefficients (C_{B_z} , C_{V_x} , $C_{n_{CIS}}$,
1058 $C_{n_{EFW}}$) and time shift (δt_{V_x} , $\delta t_{n_{CIS}}$, $\delta t_{n_{EFW}}$) in minutes of the magnetic field GSE Z compo-
1059 nent (B_z), solar wind velocity X component (V_x), CIS and EFW densities (n_{CIS} , n_{EFW}).

Table 2: The studied magnetosheath intervals. The correlation coefficients (C_{B_z} , C_{V_x} , $C_{n_{CIS}}$, $C_{n_{EFW}}$) and time shift (δt_{V_x} , $\delta t_{n_{CIS}}$, $\delta t_{n_{EFW}}$) in minutes of the magnetic field GSE Z component (B_z), solar wind velocity X component (V_x), CIS and EFW densities (n_{CIS} , n_{EFW}). In the empty slots the correlation calculation gives invalid result.

Start/End	C_{B_z}	δt_{B_z}	C_{V_x}	δt_{V_x}	$C_{n_{CIS}}$	$\delta t_{n_{CIS}}$	$C_{n_{EFW}}$	$\delta t_{n_{EFW}}$
		[min]		[min]		[min]		[min]
20020201 13:30/0201 18:30	0.91	1	0.98	56	0.99	60	0.976	60
20020208 18:15/0209 00:00	0.73	2	0.95	60	0.98	-52	0.98	-54
20020211 02:30/0211 09:00	0.79	0	0.99	-20	0.99	-1	0.99	1
20020212 16:30/0212 21:00	0.80	3	0.99	54	0.99	31	0.99	30
20020219 17:30/0219 23:00	0.76	4	0.98	37	0.99	7	0.99	6
20020222 23:00/0223 06:30	0.64	0	0.97	-60	0.99	-47	0.98	-48
20020227 16:30/0227 23:15	0.48	59	0.98	-31	0.99	-39	1.00	-12
20020310 18:30/0311 00:30	0.97	3	0.98	19	0.99	8	0.99	-2
20020311 14:00/0311 19:00	0.86	5	0.97	36	0.99	-3	0.99	-40
20020406 19:00/0407 01:15	0.76	2	0.96	-60	0.98	-55	0.98	-56
20020410 17:30/0410 23:00	0.89	6	0.99	-50	0.99	3	1.00	5
20020411 11:30/0411 16:30	0.82	4	0.99	39	0.99	3	0.99	3
20020418 18:30/0418 22:45	0.92	60	0.99	-60	0.99	60	0.98	60
20020421 04:30/0421 07:45	0.96	47	0.99	-60	1.00	-60	1.00	-60
20020422 11:45/0422 15:45	0.73	-5	0.98	-17	0.99	-15	0.98	-16
20020423 08:30/0423 12:30	0.93	31	0.99	3	0.99	16	0.99	16
20020430 12:30/0430 17:00	0.79	59	0.98	22	0.98	-18		
20020505 07:00/0505 11:15	0.71	59	0.99	-58	0.98	-60		
20020506 19:15/0507 00:15	0.84	-27	0.98	-60	0.97	-37		
20020507 17:30/0507 23:00	0.93	2	0.98	-30	0.99	-49		
20020514 22:45/0515 03:00	0.79	49	0.99	35	0.99	38	0.99	43
20020517 07:00/0517 12:15	0.74	-5	1.00	-5	0.99	-4	0.99	-3
20020518 13:30/0518 19:30	0.70	1	0.99	9	0.97	-1	0.97	-1

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Table 2 – *Continued from previous page*

Start/End	C_{B_z}	δt_{B_z}	C_{V_x}	δt_{V_x}	$C_{n_{CIS}}$	$\delta t_{n_{CIS}}$	$C_{n_{EFW}}$	$\delta t_{n_{EFW}}$
		[min]		[min]		[min]		[min]
20020519 20:00/0520 03:30	0.98	2	1.00	-9	0.99	-5	0.99	-50
20020520 10:45/0520 20:15	0.77	1	0.99	-3	0.95	-1	0.99	-1
20020522 02:00/0522 08:45	0.49	52	0.99	4	0.99	12	0.99	22
20020527 02:15/0527 17:15	0.79	-3	0.99	-3	0.98	0	0.98	0
20020530 05:00/0530 10:30	0.29	3	1.00	-38	0.99	3	0.99	3
20020601 19:30/0602 01:00	0.68	-2	1.00	18	0.99	-6	0.99	-7
20020602 21:45/0603 17:45	0.62	-5	0.99	-1	0.98	2	0.99	2
20020605 10:30/0606 06:00	0.18	0	1.00	-7	0.97	10	0.98	9
20020607 18:00/0607 22:00	0.92	-35	1.00	-36	0.99	16	0.99	16
20020608 01:15/0608 18:15	0.53	-4	0.99	-39	0.96	-6	0.97	-6
20020610 01:30/0610 09:30	0.76	5	0.99	8	0.99	-5	0.99	-7
20020610 11:00/0611 01:00	0.87	-4	0.99	-33	0.98	23	0.99	6
20020612 18:30/0613 06:15	0.44	-2	0.99	-7	0.97	4	0.97	-32
20020615 07:00/0615 23:30			1.00	47	0.98	-3	0.98	-3
20020617 05:00/0618 03:45	0.76	4	1.00	28	0.98	10	0.98	8
20020620 04:00/0620 11:00	0.61	-8	0.99	-6	0.97	12	0.98	4
20020622 14:30/0622 18:00	0.98	55	1.00	35	0.99	16	1.00	16
20021201 04:15/1202 07:45	0.38	1	1.00	2	0.99	6	0.99	6
20021203 15:30/1204 19:30	0.67	1	0.99	60	0.98	59	0.98	59
20021207 00:30/1207 07:45	0.49	37	0.98	-56	0.99	-19	0.99	-4
20021208 09:30/1209 08:00	0.69	2	0.98	-35	0.97	6	0.98	4
20021212 23:30/1213 14:30	0.51	5	1.00	36	0.99	-3	0.81	-56
20021213 21:15/1214 09:30	0.93	5	0.99	-35	0.99	-13	0.99	-47
20021215 12:45/1216 18:00	0.76	2	0.99	-60	0.94	-60	0.98	31
20021217 16:30/1218 01:45	0.99	2	1.00	-54	0.99	3	0.99	3
20021220 01:30/1220 06:15	0.92	0	1.00	60	0.99	2	0.99	3
20021223 02:15/1223 13:00	0.91	1	0.97	49	0.93	49	0.99	-14
20021223 14:00/1223 22:30	0.84	1	0.99	-2	0.99	-1	1.00	-3
20021224 19:00/1225 01:45	0.94	0	1.00	-44	0.99	26	0.99	27

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Table 2 – *Continued from previous page*

Start/End	C_{B_z}	δt_{B_z}	C_{V_x}	δt_{V_x}	$C_{n_{CIS}}$	$\delta t_{n_{CIS}}$	$C_{n_{EFW}}$	$\delta t_{n_{EFW}}$
		[min]		[min]		[min]		[min]
20021225 23:45/1226 07:15	0.96	7	1.00	-17	0.99	56	0.99	55
20021226 23:00/1227 09:45	0.79	2	1.00	2	0.98	4	0.99	3
20021229 11:45/1229 17:00	0.60	2	1.00	-60	0.98	-19	0.98	50
20021230 17:45/1231 01:00	0.69	1	0.98	52	0.98	60	0.98	22
20021231 23:00/0101 05:15	0.89	2	0.99	15	0.99	-54	1.00	-58
20030105 14:00/0105 21:00	0.69	0	0.99	1	0.98	-60	0.99	-60
20030106 23:15/0107 03:00	0.52	9	0.98	60	0.99	56	1.00	-60
20030109 08:45/0109 16:15			0.91	-56	0.98	-13	0.98	-26
20030110 07:15/0110 15:15	0.94	1	0.99	-7	0.99	1	0.98	5
20030111 08:15/0111 22:30	0.84	0	0.99	-59	0.94	-15	0.94	8
20030112 17:30/0113 00:15	0.98	0	1.00	-52	0.99	39	0.99	51
20030114 00:30/0114 08:30	0.84	-1	0.99	-60	0.98	23	0.98	8
20030116 10:15/0116 17:45	0.62	60	0.93	52	0.99	60	0.99	30
20030117 09:30/0117 13:30	0.68	-3	1.00	8	1.00	-31	0.99	-33
20030118 23:30/0119 03:45	0.93	3	1.00	-12	1.00	7	0.99	7
20030119 21:00/0120 01:00	0.94	3	1.00	5	1.00	38	1.00	19
20030121 06:30/0121 11:30	0.82	-15	0.96	47	0.98	7	0.99	-39
20030122 04:45/0122 09:30	0.69	-2	1.00	10	0.99	-9	0.99	-5
20030126 01:45/0126 06:30	0.85	3	0.99	-15	0.99	-50	0.99	23
20030127 08:15/0127 13:00	1.00	9	1.00	-60	0.98	0	0.99	1
20030128 12:30/0128 17:15	0.77	60	0.99	-24	0.99	-6	0.988	20
20030130 19:45/0131 00:15	0.98	2	0.99	51	0.99	25	0.99	9

Table 3: The studied magnetosphere intervals (UT).

Start/End
20020213 23:00/0214 01:30
20020217 18:30/0218 02:00
20020220 00:45/0220 12:00
20020222 11:15/0222 20:15
20020225 02:15/0225 08:30
20020227 06:00/0227 12:00
20020302 00:00/0302 03:15
20020306 10:00/0306 18:30
20020308 17:30/0309 06:00
20020311 02:15/0311 12:00
20020313 11:15/0314 00:15
20020316 04:45/0316 08:00
20020318 09:00/0318 14:45
20020320 20:30/0320 23:55
20020323 04:00/0323 09:45
20020327 23:45/0328 06:15
20020330 07:15/0330 12:45
20020401 19:30/0401 22:00
20020406 09:30/0406 18:00
20020408 15:00/0409 00:00
20020410 23:30/0411 09:45
20020413 08:30/0413 19:00
20020416 18:00/0417 04:30
20020418 06:00/0418 12:00
20020420 15:00/0420 23:00
20020422 20:00/0423 07:00
20020425 08:30/0425 18:00
20020430 04:40/0430 12:00
20020504 14:30/0504 16:45

Continued on next page

Table 3 – *Continued from previous page*

Start/End
20020505 02:30/0505 07:00
20020507 01:30/0507 15:45
20020508 11:00/0510 04:15
20020512 02:45/0512 09:30
20020514 10:30/0514 12:45
20020519 00:30/0519 19:30
20020521 01:30/0521 22:00
20020523 23:30/0524 02:00
20020524 19:00/0525 08:15
20020526 07:30/0526 10:30
20020528 20:00/0529 05:00
20020531 02:15/0531 13:30
20020602 04:30/0602 07:30
20020602 12:00/0602 21:30
20020604 08:30/0605 07:00
20020606 14:30/0607 16:30
20020609 06:00/0609 20:00
20020611 11:00/0612 13:00
20020614 01:00/0614 16:00
20020616 08:00/0616 18:00
20020620 13:30/0622 01:00
20020623 13:00/0623 17:00
20020624 04:00/0624 10:15
20020630 17:45/0701 15:00
20020701 21:00/0703 10:30
20020703 23:00/0706 03:15
20020707 01:00/0708 23:00
20020710 11:30/0714 03:30
20020714 15:45/0715 15:30
20020716 23:30/0717 16:00

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Table 3 – *Continued from previous page*

Start/End
20020718 05:45/0722 11:00
20020722 23:45/0728 01:00
20020728 02:00/0804 03:45
20020804 04:45/0811 06:15
20020811 07:30/0816 01:00
20020816 15:30/0818 09:00
20020818 10:00/0825 11:30
20020825 13:00/0901 14:15
20020901 17:15/0903 23:30
20020905 02:15/0906 16:30
20020907 10:30/0908 17:00
20020908 18:00/0915 19:30
20020915 21:00/0922 22:30
20020923 00:00/0923 23:30
20020924 03:30/0928 22:45
20020928 23:30/0930 01:00
20020930 02:15/1006 17:00
20021006 17:45/1007 03:30
20021007 05:00/1007 17:30
20021008 07:30/1010 22:00
20021010 22:30/1012 22:30
20021012 23:00/1014 06:30
20021014 09:00/1016 04:00
20021016 14:00/1019 00:15
20021019 01:30/1019 22:00
20021021 04:00/1022 19:30
20021022 22:30/1026 02:30
20021026 04:00/1029 20:15
20021030 01:30/1102 08:00
20021102 22:00/1104 22:00

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Table 3 – *Continued from previous page*

Start/End
20021106 00:00/1107 18:00
20021108 02:00/1109 18:45
20021111 00:00/1112 01:30
20021113 03:45/1114 14:15
20021115 20:30/1116 23:00
20021118 01:00/1118 23:30
20021120 17:00/1121 06:00
20021122 21:30/1124 01:00
20021125 04:00/1126 08:30
20021127 20:00/1128 18:30
20021130 04:00/1201 01:30
20021202 14:30/1203 09:00
20021204 22:00/1205 19:30
20021207 09:00/1207 16:30
20021207 18:00/1207 22:00
20021209 16:30/1210 14:30
20021212 13:45/1212 21:30
20021214 13:30/1214 20:00
20021214 21:00/1215 07:30
20021216 21:00/1217 15:00
20021219 08:00/1219 19:30
20021221 15:45/1221 23:15
20021222 00:30/1222 08:45
20021224 02:30/1224 14:00
20021226 10:00/1226 19:00
20021228 19:30/1229 02:30
20021229 04:00/1229 10:00
20021231 05:00/1231 18:45
20030102 12:30/0102 20:45
20030104 20:45/0105 06:00

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Table 3 – *Continued from previous page*

Start/End
20030105 07:00/0105 13:30
20030107 05:45/0107 21:00
20030109 17:00/0110 00:45
20030112 00:00/0112 09:15
20030112 10:30/0112 16:00
20030114 11:00/0114 20:00
20030116 20:30/0116 22:45
20030119 04:30/0119 09:30
20030119 14:00/0119 17:00
20030121 13:30/0121 21:30
20030126 07:30/0126 15:45
20030128 17:45/0129 08:15
20030131 01:30/0131 11:45

Start/End	OMNI			Cluster SC3			
	B_z [nT]	V_x [km/s]	P [cm $^{-3}$]	B_z	V_x	n_{CIS}	n_{EFW}
20020201 20:00/0203 04:00	-1.25	-373.52	4.08	y	y	n	y
20020211 13:00/0212 12:00	0.03	-533.11	2.18	y	y	y	y
20020218 09:00/0219 02:00	2.56	-362.41	3.46	y	n	n	y
20020219 06:30/0219 15:00	3.55	-401.63	1.25	y	y	n	n
20020220 18:30/0222 00:00	1.95	-440.18	1.96	y	y	n	y
20020318 17:30/0319 02:30	3.79	-429.30	15.34	y	n	n	n
20020412 20:30/0413 02:00	-1.81	-420.35	3.24	y	n	n	y
20021227 12:00/1228 03:00	0.09	-714.40	2.72	y	n	n	y
20021229 20:00/1230 16:00	-0.37	-526.40	2.26	y	y	n	n
20030106 06:00/0106 19:00	2.25	-399.91	1.50	y	n	n	n
20030108 07:00/0109 03:30	-0.58	-280.80	2.97	n	n	y	n
20030113 08:30/0113 18:00	0.68	-397.83	1.72	y	y	y	n
20030120 07:30/0120 13:00	2.16	-630.69	2.43	y	y	y	y
20030122 12:00/0123 14:00	0.13	-608.96	3.41	y	y	y	n
20030124 18:00/0126 00:00	-0.71	-739.68	2.87	y	y	n	n
20030127 16:00/0128 06:00	-0.92	-451.84	3.12	y	y	n	n
20030129 12:00/0130 18:00	-3.09	-450.00	3.96	y	y	n	y

1062 **Table 4.** The average OMNI input parameters in the solar wind and the good/bad agreement
 1063 of the GUMICS–4 simulations to the Cluster B_z magnetic field component, the V_x solar wind
 1064 speed component, the n_{CIS} solar wind density measured by the Cluster CIS HIA instrument and
 1065 the n_{EFW} solar wind density calculated from the spacecraft potential measured by the Cluster
 1066 EFW instrument in the solar wind.

Table 5: The average OMNI input parameters in the solar wind and the good/bad agreement of the GUMICS–4 simulations to the Cluster B_z magnetic field component, the V_x solar wind speed component, the n_{CIS} solar wind density measured by the Cluster CIS HIA instrument and the n_{EFW} solar wind density calculated from the spacecraft potential measured by the Cluster EFW instrument in the magnetosheath.

Start/End	OMNI			Cluster SC3			
	B_z	V_x	P	B_z	V_x	n_{CIS}	n_{EFW}
	[nT]	[km/s]	[cm $^{-3}$]				
20020201 13:30/0201 18:30	0.19	-342.87	4.62	y	n	n	n
20020208 18:15/0209 00:00	-0.48	-508.16	1.61	y	n	n	n
20020211 02:30/0211 09:00	-1.85	-425.67	1.78	y	y	y	y
20020212 16:30/0212 21:00	2.98	-509.22	2.34	y	n	n	n
20020219 17:30/0219 23:00	1.46	-431.50	1.46	y	y	y	y
20020222 23:00/0223 06:30	0.86	-391.22	1.14	y	n	n	n
20020227 16:30/0227 23:15	1.89	-343.13	1.52	n	n	n	n
20020310 18:30/0311 00:30	-2.81	-379.46	1.78	y	y	y	y
20020311 14:00/0311 19:00	1.63	-371.43	2.68	n	n	n	n
20020406 19:00/0407 01:15	-2.71	-333.13	0.93	y	n	n	n
20020410 17:30/0410 23:00	0.31	-312.43	4.42	n	n	y	y
20020411 11:30/0411 16:30	-1.50	-494.02	4.25	y	y	n	n
20020418 18:30/0418 22:45	-0.92	-450.82	0.30	n	n	n	n
20020421 04:30/0421 07:45	0.40	-455.69	1.37	n	n	n	n
20020422 11:45/0422 15:45	0.25	-419.98	1.14	n	n	y	y
20020423 08:30/0423 12:30	2.77	-507.99	6.82	n	n	n	n
20020430 12:30/0430 17:00	2.15	-479.51	3.02	n	n	n	n
20020505 07:00/0505 11:15	0.20	-336.81	1.74	n	n	n	n
20020506 19:15/0507 00:15	0.78	-390.00	2.46	y	n	n	n
20020507 17:30/0507 23:00	2.87	-392.40	3.49	y	n	n	n
20020514 22:45/0515 03:00	-2.42	-414.01	1.82	n	n	n	n

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Table 5 – *Continued from previous page*

Start/End	OMNI			Cluster SC3			
	B_z [nT]	V_x [km/s]	P $[cm^{-3}]$	B_z	V_x	n_{CIS}	n_{EFW}
20020517 07:00/0517 12:15	-0.39	-379.32	1.52	y	y	y	y
20020518 13:30/0518 19:30	0.63	-345.87	1.59	n	n	y	y
20020519 20:00/0520 03:30	4.75	-408.56	1.12	y	y	y	y
20020520 10:45/0520 20:15	0.74	-448.89	1.93	y	y	y	y
20020522 02:00/0522 08:45	-1.07	-398.12	1.63	n	y	y	y
20020527 02:15/0527 17:15	-3.11	-542.53	2.07	y	y	y	y
20020530 05:00/0530 10:30	0.03	-493.86	2.08	y	n	y	y
20020601 19:30/0602 01:00	-3.38	-342.27	4.16	y	y	y	y
20020602 21:45/0603 17:45	0.38	-435.47	1.89	y	y	y	y
20020605 10:30/0606 06:00	-0.42	-394.49	1.08	y	y	n	n
20020607 18:00/0607 22:00	-1.60	-291.85	1.80	y	y	y	y
20020608 01:15/0608 18:15	0.06	-335.39	2.74	y	n	y	y
20020610 01:30/0610 09:30	1.60	-465.52	3.00	y	y	y	y
20020610 11:00/0611 01:00	-2.27	-419.86	2.16	y	n	y	y
20020612 18:30/0613 06:15	-1.13	-351.03	1.16	y	y	y	y
20020615 07:00/0615 23:30	-1.16	-334.27	2.84	n	n	y	y
20020617 05:00/0618 03:45	0.78	-351.47	1.87	y	n	y	y
20020620 04:00/0620 11:00	0.46	-485.48	1.73	y	y	y	y
20020622 14:30/0622 18:00	-0.72	-429.02	1.93	n	n	y	y
20021201 04:15/1202 07:45	-1.09	-499.23	2.62	y	y	y	y
20021203 15:30/1204 19:30	0.34	-449.09	2.06	y	n	n	n
20021207 00:30/1207 07:45	0.80	-451.80	7.33	n	n	y	y
20021208 09:30/1209 08:00	0.60	-600.27	1.49	y	n	y	y
20021212 23:30/1213 14:30	0.10	-337.77	1.32	y	n	n	n
20021213 21:15/1214 09:30	-0.74	-361.19	2.99	y	n	y	y
20021215 12:45/1216 18:00	1.32	-479.48	1.53	y	n	n	n
20021217 16:30/1218 01:45	4.56	-393.99	2.49	y	n	y	y
20021220 01:30/1220 06:15	-1.21	-530.62	3.01	y	n	y	y

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Table 5 – *Continued from previous page*

Start/End	OMNI			Cluster SC3			
	B_z [nT]	V_x [km/s]	P $[cm^{-3}]$	B_z	V_x	n_{CIS}	n_{EFW}
20021223 02:15/1223 13:00	-2.32	-516.12	2.22	y	n	n	n
20021223 14:00/1223 22:30	0.89	-519.77	2.55	y	y	y	y
20021224 19:00/1225 01:45	0.88	-523.86	3.41	y	n	y	y
20021225 23:45/1226 07:15	-0.61	-414.38	2.21	y	y	n	n
20021226 23:00/1227 09:45	-1.79	-618.14	6.20	y	y	y	y
20021229 11:45/1229 17:00	-0.41	-580.12	2.39	y	n	n	n
20021230 17:45/1231 01:00	-1.01	-483.60	1.93	y	n	n	y
20021231 23:00/0101 05:15	0.60	-418.95	1.94	y	n	n	n
20030105 14:00/0105 21:00	-0.03	-414.46	1.69	y	n	n	n
20030106 23:15/0107 03:00	-1.62	-392.29	1.56	n	n	n	n
20030109 08:45/0109 16:15	1.45	-272.82	2.31	n	n	n	n
20030110 07:15/0110 15:15	-2.11	-401.03	2.72	y	n	y	y
20030111 08:15/0111 22:30	-0.20	-433.33	1.24	y	n	n	y
20030112 17:30/0113 00:15	1.53	-389.62	1.45	y	n	n	n
20030114 00:30/0114 08:30	-1.67	-388.53	2.27	y	n	n	y
20030116 10:15/0116 17:45	-1.20	-328.91	1.22	n	n	n	n
20030117 09:30/0117 13:30	-1.36	-327.09	2.55	y	y	y	y
20030118 23:30/0119 03:45	6.41	-459.46	4.82	y	y	y	y
20030119 21:00/0120 01:00	1.52	-597.95	2.38	y	n	y	y
20030121 06:30/0121 11:30	-1.77	-670.25	1.50	y	n	n	n
20030122 04:45/0122 09:30	0.11	-588.87	2.30	y	n	y	y
20030126 01:45/0126 06:30	-0.24	-713.82	2.75	y	y	y	y
20030127 08:15/0127 13:00	7.94	-509.30	0.47	y	n	y	y
20030128 12:30/0128 17:15	4.95	-443.83	4.15	y	y	y	y
20030130 19:45/0131 00:15	4.21	-510.33	2.63	y	n	y	y

Table 6: Intervals around the studied bow shock crossings. The Cluster SC3 crossed the bow shock in all cases. The 2nd column shows whether the bow shock is visible in the GUMICS–4 simulations.

Start/End	GUMICS Bow Shock
20020201 12:00/0202 00:00	+
20020203 00:00/0203 12:00	+
20020206 06:00/0206 18:00	+
20020208 18:00/0209 06:00	+
20020211 06:00/0211 18:00	+
20020212 12:00/0212 18:00	+
20020213 12:00/0213 18:00	+
20020216 00:00/0216 12:00	+
20020217 06:00/0217 12:00	-
20020218 06:00/0218 18:00	+
20020219 00:00/0219 18:00	+
20020220 12:00/0221 00:00	+
20020221 18:00/0222 00:00	+
20020301 06:00/0301 12:00	+
20020304 12:00/0304 18:00	+
20020306 00:00/0306 06:00	+
20020307 00:00/0307 06:00	+
20020308 06:00/0308 12:00	+
20020309 06:00/0309 12:00	+
20020310 12:00/0311 00:00	+
20020311 18:00/0312 00:00	+
20020313 00:00/0313 06:00	-
20020314 00:00/0314 12:00	+
20020316 06:00/0316 18:00	+
20020318 12:00/0319 00:00	+
20020323 12:00/0323 18:00	+

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Table 6 – *Continued from previous page*

Start/End	GUMICS Bow Shock
20020325 18:00/0326 06:00	–
20020327 06:00/0327 12:00	+
20020329 18:00/0330 00:00	–
20020402 00:00/0402 06:00	+
20020405 18:00/0406 00:00	–
20020407 00:00/0407 06:00	–
20020409 06:00/0409 12:00	–
20020410 12:00/0410 18:00	–
20020411 12:00/0411 18:00	–
20020413 00:00/0413 06:00	+
20020413 18:00/0414 06:00	+
20020420 00:00/0420 06:00	+
20020423 12:00/0423 23:00	+
20020427 00:00/0427 06:00	+
20020428 06:00/0428 12:00	+
20020430 18:00/0501 00:00	+
20020505 06:00/0505 18:00	–
20020507 18:00/0509 06:00	+
20020510 06:00/0510 12:00	+
20020513 12:00/0513 18:00	+
20020515 00:00/0515 06:00	–
20020520 00:00/0520 06:00	+
20020522 06:00/0522 12:00	+
20020522 18:00/0523 06:00	+
20021206 06:00/1207 06:00	+
20021218 00:00/1219 00:00	+
20021220 18:00/1221 00:00	+
20021221 00:00/1221 12:00	+
20021222 12:00/1223 00:00	+
20021223 00:00/1223 06:00	+

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Table 6 – *Continued from previous page*

Start/End	GUMICS Bow Shock
20021225 06:00/1226 00:00	+
20021227 06:00/1228 00:00	+
20021228 00:00/1228 12:00	+
20021229 12:00/1230 00:00	+
20030101 06:00/0102 00:00	+
20030103 06:00/0103 12:00	+
20030104 00:00/0104 18:00	+
20030106 00:00/0107 00:00	+
20030108 00:00/0108 12:00	+
20030113 00:00/0114 06:00	+
20030115 00:00/0115 12:00	+
20030118 18:00/0119 00:00	+
20030120 00:00/0121 12:00	+
20030122 06:00/0122 12:00	+
20030123 12:00/0124 00:00	+
20030124 12:00/0124 18:00	+
20030126 00:00/0126 06:00	+
20030127 00:00/0127 18:00	+
20030128 06:00/0128 18:00	+
20030129 06:00/0129 12:00	+
20030130 18:00/0131 00:00	+

Table 7: Intervals around the studied magnetopause crossings.
The Cluster SC3 crossed the magnetopause in all cases. The
2nd column shows whether the magnetopause is visible in the
GUMICS–4 simulations.

Start/End	GUMICS Magnetopause
20020203 06:00/0203 12:00	+
20020206 06:00/0206 12:00	-
20020211 00:00/0211 06:00	+
20020218 00:00/0218 06:00	+
20020225 06:00/0225 12:00	+
20020302 00:00/0302 06:00	+
20020306 18:00/0307 00:00	-
20020308 12:00/0308 18:00	-
20020311 12:00/0311 18:00	+
20020313 18:00/0314 00:00	-
20020314 00:00/0314 06:00	+
20020323 06:00/0323 12:00	+
20020330 12:00/0330 18:00	-
20020404 06:00/0404 12:00	-
20020409 00:00/0409 06:00	-
20020418 12:00/0418 18:00	+
20020422 12:00/0422 18:00	-
20020429 18:00/0430 00:00	-
20020507 12:00/0507 18:00	-
20020509 06:00/0509 12:00	-
20020510 00:00/0510 06:00	-
20020514 18:00/0515 00:00	-
20020519 12:00/0519 18:00	-
20020520 12:00/0521 00:00	-
20020522 00:00/0522 06:00	-
20020529 00:00/0529 12:00	-

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Table 7 – *Continued from previous page*

Start/End	GUMICS Magnetopause
20020530 06:00/0530 18:00	–
20020531 18:00/0601 00:00	–
20020602 18:00/0603 00:00	–
20020604 06:00/0604 12:00	–
20020605 06:00/0606 18:00	–
20020607 12:00/0608 06:00	+
20020609 00:00/0609 06:00	–
20020610 00:00/0610 06:00	–
20020611 00:00/0611 12:00	–
20020612 06:00/0614 00:00	–
20020614 18:00/0615 06:00	–
20020616 00:00/0616 12:00	+
20020620 00:00/0620 18:00	–
20020622 06:00/0622 18:00	–
20020704 12:00/0705 00:00	–
20020706 00:00/0706 12:00	+
20020709 00:00/0709 18:00	–
20020715 18:00/0716 12:00	–
20030105 06:00/0105 18:00	+
20030110 00:00/0110 12:00	+
20030112 12:00/0112 18:00	–
20030117 06:00/0117 12:00	+
20030121 06:00/0121 12:00	+
20030122 00:00/0122 06:00	–
20030126 18:00/0127 00:00	+
20030128 12:00/0128 18:00	+
20030129 00:00/0129 12:00	+
20030131 12:00/0201 00:00	+

Start/End	GUMICS Neutral Sheet
20020901 19:10/0901 23:54	–
20020906 14:07/0906 16:37	+
20020913 17:33/0913 20:06	+
20020918 12:47/0918 14:26	–
20020920 20:36/0921 02:13	+
20020928 02:58/0928 07:00	+
20021002 16:12/1002 23:52	–
20021014 12:34/1014 22:53	+
20021017 03:08/1017 04:11	–

1070 **Table 8.** Intervals around the studied neutral sheet crossings in the tail. The Cluster SC3
 1071 crossed the neutral sheet in all cases. The 2nd column shows whether the neutral sheet is visible
 1072 in the GUMICS–4 simulations.