A possible mechanism for the formation of magnetic field dropouts in the coma of 67P/Churyumov-Gerasimenko

Z. Huang,1* G. Tóth,1 T. I. Gombosi,1 A. Bieler,1 M. R. Combi,1 K. C. Hansen,1 X. Jia,1 N. Fougere,1 Y. Shou,1 T. E. Cravens,2 V. Tenishev,1 K. Altwegg,3 and M. Rubin3

1Climate and Space Sciences and Engineering, University of Michigan, Ann Arbor, MI 48109, USA
2Physics and Astronomy Department, University of Kansas, Lawrence, Kansas, USA
3Physikalisches Institut, University of Bern, Bern, Switzerland

Abstract
The Rosetta Plasma Consortium MAGnetometer (RPC-MAG) has detected signatures of diamagnetic regions associated with comet 67P/Churyumov-Gerasimenko at distances from 30 km to 400 km at different heliocentric distances, which is larger than what has been predicted by numerical simulations of the cometary plasma environment. The physical mechanism behind these diamagnetic regions is still unknown. In the present work, we use our newly developed multi-fluid plasma–neutral model (Huang et al. 2016) to explore a possible physical mechanism that might create such regions. The model solves the governing multi-fluid MHD equations for cometary and solar wind ions and electrons, and the Euler equations for the neutral gas fluid. We find that a local increase of electron thermal pressure is capable to generate many of the observed features of the diamagnetic regions observed by RPC-MAG. The simulation results show that a magnetic field free region is formed and the recovery phase of the magnetic field magnitude is faster than the declining phase.

Key words: MHD, comets: individual: Comet 67P/Churyumov-Gerasimenko, planets and satellites: magnetic fields

1 INTRODUCTION
The diamagnetic cavity is an important plasma boundary in the inner coma region near an active comet. It was first observed by the Giotto spacecraft at comet 1P/Halley in 1986. Based on the Giotto magnetometer data Neubauer et al. (1986) reported a magnetic field-free region inside around 4500 km from the nucleus. Cravens (1986) and Ip & Axford (1987) suggested that a diamagnetic cavity is formed inside the region where the $\mathbf{j} \times \mathbf{B}$ force is balanced by the ion-neutral drag force. Cravens (1989) later applied a 1-D magnetohydrodynamical model to study the inner coma of comet 1P/Halley and predicted that the diamagnetic cavity should be between 3300 and 4000 km, which is somewhat less than the value of 4500 km observed by Neubauer et al. (1986); but he pointed out that the difference may come from the uncertainties in the input parameters. Also, Puhl-Quinn & Cravens (1995) applied a 1-D hybrid (particle ions and fluid electrons) code to investigate the diamagnetic cavity of comet Halley and their simulation results agreed well with the fluid simulations provided by Cravens (1989). Gombosi et al. (1996) developed a 3-D single fluid MHD model to simulate the plasma environment of comet Halley and showed that the diamagnetic cavity obtained from the MHD model agreed well with Giotto observations. A more recent global multi-ion MHD simulation of comet Halley by Rubin et al. (2014b) showed that the simulated diamagnetic cavity matched the Giotto observations very well as it captured the non-symmetric nature of the interaction between the solar wind and the cometary atmosphere.

The Rosetta mission (cf. Glassmeier et al. 2007a) investigates the physical and chemical properties of comet 67P/Churyumov-Gerasimenko (CG). Study of the plasma environment, which is carried out by the Rosetta Plasma Consortium (RPC, Carr et al. 2007), is critical for understanding the interaction between the solar wind and comet CG.

In the present work, we focus on the magnetic field observations by the Rosetta Plasma Consortium MAGnetometer (RPC-MAG, Glassmeier et al. 2007b). Before the Rosetta spacecraft arrived at comet CG in August 2014, simulations were performed to predict the plasma environment (cf. Hansen et al. 2007). After Rosetta’s arrival even more sophisticated simulations were carried out (cf. Rubin et al. 2015a; Koenders et al. 2015; Huang et al. 2016). Specifically,
using their multi-fluid simulations of comet CG, Rubin et al. (2015a) predicted that at 1.3 AU (near perihelion, with a total neutral gas production rate of $5.0 \times 10^{27}$/s) the subsolar distance of the diamagnetic cavity boundary would be around 30 km from the nucleus. Using hybrid simulations for the same heliocentric distance and the same total neutral gas production rate, Koenders et al. (2015) found this boundary even closer to the nucleus at around 25 km. Both Rubin et al. (2015a) and Koenders et al. (2015) applied spherically symmetric neutral gas production from the nucleus in their simulations and did not consider the more realistic situation when on the dayside the neutral gas outflow is much higher than on the nightside. This phenomenon was taken into account by Huang et al. (2016) who assumed that the neutral gas outflow is solar illumination driven, thus obtained a subsolar diamagnetic cavity boundary distance at around 100 km from their multifluid simulations for the same heliocentric distance and slightly higher total neutral gas production rate ($8.0 \times 10^{27}$/s). The production rates applied in Rubin et al. (2015a), Koenders et al. (2015) and Huang et al. (2016) are close to the gas production rate reported by Hansen et al. (2016), who showed that the total water gas production rate is about $6.72 \times 10^{27}$/s and the total neutral gas production rate is about $8.4 \times 10^{27}$/s at 1.3 AU, based on the neutral gas observations by various instruments onboard Rosetta for the inbound Rosetta orbit.

After monitoring the evolution of the cometary plasma environment for an extended period of time the Rosetta magnetometer observed several short-duration (tens of seconds to tens of minutes) diamagnetic regions (Goetz et al. 2016a). Quite surprisingly, these diamagnetic regions were found around twice as far from the nucleus (~170 km) than predicted by simulations (Rubin et al. 2015a; Koenders et al. 2015; Huang et al. 2016). A detailed study by Goetz et al. (2016b) showed that the RPC-MAG has observed diamagnetic regions at distances from 30 km to 400 km at different heliocentric distances. All these diamagnetic regions were observed much further from the nucleus than the predicted distances of the diamagnetic cavity boundary. The physical mechanism responsible for these diamagnetic regions is still unclear.

In this paper we suggest that the observed diamagnetic regions (Goetz et al. 2016a,b) may not be associated with the “classical” diamagnetic cavity observed at comet 1P/Halley (Neubauer et al. 1986) and explained by Cravens (1986) and Ip & Axford (1987). We raise the possibility that the observed diamagnetic regions are small-scale phenomena caused by short-lived increases of the local electron pressure.
2 OBSERVATIONS

RPC-MAG can measure the magnetic field in the range of ±16.384 nT with a resolution of 39 pT (Glassmeier et al. 2007b). A complete detailed description of the MAG instrument can be found in Glassmeier et al. (2007b). It is important to point out that there are two major uncertainties for MAG: 1. the influence of the reaction wheels, which can be filtered out in burst mode (Glassmeier et al. 2007b); 2. the offset of the magnetic field with an error of ~5 nT.

Figure 1 is a reproduction of Figure 1 in Goetz et al. (2016a), which plots the three magnetic field components and the field magnitude on July 26, 2015. It is important to point out that they corrected the observed values with the spacecraft bias field of 6.5 nT by subtracting the mean value of the remaining field in the diamagnetic region from each component. We focus on the time interval from 15:16 to 15:41 during which the data show no magnetic fluctuations for about 25 minutes. Another important feature of this structure is the asymmetry between the outbound and inbound traversals: outbound crossing is a factor of 2.2 shorter than the inbound one. Goetz et al. (2016a) put forward the argument that because RPC-MAG did not observe any waves, this region is associated with the diamagnetic cavity.

In our opinion it is possible that the observed diamagnetic region in Goetz et al. (2016a) is not a “classical” diamagnetic cavity, but it might be a local phenomenon caused by some different process. There are (at least) two reasons why the diamagnetic region might not be associated with a global diamagnetic cavity surrounding the nucleus: (i) the total gas production rate is not sufficient to create such a large diamagnetic cavity, and (ii) the large number and short duration of these magnetic field free regions. As Goetz et al. (2016a) discussed, the total gas production rate must be larger than $3 \times 10^{28} \text{s}^{-1}$ at 1.3 AU to create an extended cavity expanding to around 170 km. Hansen et al. (2016) obtained a total gas production rate of $\sim 10^{28} \text{s}^{-1}$ at 1.3 AU from a multi-instrumental analysis of Rosetta observations, which is a factor of 3 smaller than the gas production rate necessary to push the diamagnetic cavity boundary out to the Rosetta’s location.

An additional point is that between April 2015 and February 2016 RPC-MAG observed over 650 diamagnetic regions at cometocentric distances around 2 to 3 times further than the expected diamagnetic cavity boundary. The duration of these events is between $\sim 10$ s and $\sim 40$ minutes. During this time Rosetta moves only $\sim 10$ m to $\sim 2$ km, implying that these diamagnetic regions must be very fast moving. In their first paper, Goetz et al. (2016a) associated these diamagnetic regions with instabilities propagating along the cavity boundary. Recently, Goetz et al. (2016b) further investigated these events and further argued that instabilities are indeed a possible explanation for the observed diamagnetic regions.

In this paper we consider an alternative scenario. Our main argument against the diamagnetic cavity “fingers” advocated by Goetz et al. (2016a,b) is that the neutral gas production rate is not sufficient to create such a large diamagnetic cavity. The instability mechanism proposed by Goetz et al. (2016a,b) may explain the the large number and short duration of the observed diamagnetic regions. However, the neutral gas production rate is still at least a factor of 3 smaller than the necessary gas production rate as discussed in the previous paragraph. We suggest that these events are associated with some short-lived process in the inner coma region. Instead of calling these structures diamagnetic cavities, we refer to them as magnetic field dropouts. We also argue that the minimum magnetic field magnitude is not necessary zero as assumed by Goetz et al. (2016a). It can be some small field, like a few nT.

We must point out that at this point we were unable to positively identify a specific process producing such a short-lived diamagnetic region. In this paper we consider a generic process that temporarily increases the local electron pressure in a magnetic flux tube. Such process could involve interaction with an energetic electron beam with the coma (Gan & Cravens 1990) or some other process. However, Rosetta observations do not show increased energetic electron fluxes in the vicinity of diamagnetic droput (Madanian et al. 2016b,a; Nemeth et al. 2016). On the other hand the spacecraft potential stays very negative during the magnetic dropouts (Eriksson 2016). Assuming the spacecraft surfaces (including solar array cover glasses) are still as conductive as they were at launch, and as properly grounded, this must be driven by electrons of sufficiently high energy. Such are plentifully available: photoelectrons at 10 eV are sufficient for driving spacecraft potential to the observed negative potentials of the same order. Such low energy electrons cannot be observed by the Ion and Electron Sensor (IES) instrument (Buruch et al. 2007) because IES can only observe electrons that overcome the spacecraft potential if negative or not even at all. Further investigation is necessary, but at this point we argue that a localized increase of thermal electron pressure is not inconsistent with the Rosetta observations and we will use this process as a placeholder for the source of observed magnetic dropouts.

3 SIMULATIONS

Multi-fluid simulations with the Space Weather Modeling Framework (SWMF) (Tóth et al. 2005; Tóth et al. 2012) have been widely applied in planetary studies (cf. Najib et al. 2011; Rubin et al. 2014b,a; Dong et al. 2014; Rubin et al. 2015b). In an effort to understand the possible mechanism for the magnetic field dropouts, we use the SWMF-based multi-fluid plasma-neutral model developed by Huang et al. (2016). The dropouts are simulated by introducing a narrow magnetic flux-tube aligned thermal electron heating source in the model. This approach is similar to the idea explored by Gan & Cravens (1990) for comet 1P/Halley. In this section, we briefly describe the multi-fluid model as well as the modifications that we have made to model the magnetic field dropouts.

3.1 Multi-fluid Model

The multi-fluid plasma-neutral model of Huang et al. (2016) self-consistently treats the cometary neutral gas as well as the solar wind and cometary plasma.

The neutral component is assumed to be water group atoms/molecules (O, OH, H₂O) and it is treated as a single
fluid described by the Euler equations:

\[
\frac{\partial \rho_s}{\partial t} + \nabla \cdot (\rho_s \mathbf{u}_s) = \frac{\delta \rho_s}{\delta t}
\]

\[
\frac{\partial \rho_e}{\partial t} + \nabla \cdot (\rho_e \mathbf{u}_e) = \frac{\delta \rho_e}{\delta t}
\]

\[
\frac{\partial \rho_\mathbf{u}_s}{\partial t} + \nabla \cdot (\rho_s \mathbf{u}_s \mathbf{u}_s + p_s \mathbf{I}) = \frac{\delta \rho_\mathbf{u}_s}{\delta t}
\]

\[
- Z_s \frac{\rho_s}{m_s} (\mathbf{E} + \mathbf{u}_s \times \mathbf{B}) = \frac{\delta \rho_\mathbf{u}_s}{\delta t}
\]

\[
\frac{\partial \rho_e}{\partial t} + \nabla \cdot (\rho_e \mathbf{u}_e) = \frac{\delta \rho_e}{\delta t}
\]

\[
\frac{\partial \rho_\mathbf{u}_e}{\partial t} + \nabla \cdot (\rho_e \mathbf{u}_e \mathbf{u}_e + p_e \mathbf{I}) = \frac{\delta \rho_\mathbf{u}_e}{\delta t}
\]

while the multi-fluid MHD equations are applied to the plasma fluids:

\[
\frac{\partial \rho_s}{\partial t} + \nabla \cdot (\rho_s \mathbf{u}_s) = \frac{\delta \rho_s}{\delta t}
\]

\[
\frac{\partial \rho_e}{\partial t} + \nabla \cdot (\rho_e \mathbf{u}_e) = \frac{\delta \rho_e}{\delta t}
\]

\[
\frac{\partial \rho_\mathbf{u}_e}{\partial t} + \nabla \cdot (\rho_e \mathbf{u}_e \mathbf{u}_e + p_e \mathbf{I}) = \frac{\delta \rho_\mathbf{u}_e}{\delta t}
\]

Here, \( \rho_s, \mathbf{u}_s \) and \( s \) represent the mass density, velocity vector, and pressure, of each fluid. The subscript \( n \) indicates the neutral fluid, \( e \) indicates the plasma electron fluid, and \( s \) indicates one of the two species of the ion fluids (either the solar wind protons or the cometary heavy ions). \( I \) is the identity matrix and \( \gamma \) is the specific heat ratio. The ion charge state and the unit charge are given by \( Z \) and \( e \). Because we assume charge neutrality, the electron number density is given by \( n_e = \sum_{i=ions} Z_i n_i. \) To solve Equations (2a – 2d) we must know the electric field \( \mathbf{E} \) and the electron velocity \( \mathbf{u}_e. \)

We use the simplified Ohm’s law obtained by neglecting the inertial terms in the electron momentum equation. In this approximation the electric field is the sum of the motional and ambipolar electric fields: \( \mathbf{E} = -\mathbf{u}_e \times \mathbf{B} - \nabla p_e/e n_e. \)

The electron velocity, \( \mathbf{u}_e = \mathbf{u}_i + \mathbf{u}_{HI} \), is derived from the charge averaged ion velocity, \( \mathbf{u}_i = \sum_{i=ions} Z_i n_i \mathbf{u}_i/n_i, \) and the Hall velocity \( \mathbf{u}_{HI} = -j_e/e n_e = (\nabla \times \mathbf{B})/\mu_0 e n_e. \) Here the Hall velocity and the ambipolar electric field are neglected in the induction equation, therefore Faraday’s law becomes \( \partial \mathbf{B}/\partial t = \nabla \times (\mathbf{u}_e \times \mathbf{B}) = \nabla \times (\mathbf{u}_i \times \mathbf{B}). \) This is the well-known result that the magnetic field is convected with the electron fluid.

Equations (1a – 1c) and (2a – 2d) describe the individual behavior and the interactions of the neutral, the cometary heavy ion, the solar wind proton, and the electron fluids. The source terms on the right hand side are used to model physical process not treated by the fluid conservation equations, including ionization, charge exchange, recombinations, elastic and inelastic collisions. Other than the additional source term described below to simulate the magnetic dropouts, all other source terms are the same as described in Huang et al. (2016).

Equations (1a – 1c) and (2a – 2d) are solved using our global multiphysics, multifluid simulation code, BATS-R-US (Block-Adaptive Tree Solarwind Roe-type Upwind Scheme) code (Powell et al. 1999; Tóth et al. 2012). It discretizes the equations on a 3D block adaptive grid which is ideal for resolving the drastically different length scales common to comets. In the simulations presented here we use the same computational domain as Huang et al. (2016). Cells range in size from 0.12 km, near the spherical nucleus, to 31.250 km far from the comet at the outer boundaries. The boundaries of the domain extend from \(-10^6 \) to \(+10^6 \) km in the \( x \) direction (+\( x \) points to the Sun), and from \(-0.5 \times 10^6 \) to \(0.5 \times 10^6 \) km in both \( y \) and \( z \) directions. For this study, the solar wind moves along the \( -x \) direction while the interplanetary magnetic field points in the \(+y \) direction. We apply the same boundary conditions as described in Huang et al. (2016).

The BATS-R-US code (Powell et al. 1999; Tóth et al. 2012) can be run in either steady-state mode or time-accurate mode. Huang et al. (2016) used the steady-state mode because it runs significantly faster than the time-accurate mode and their main goal was to determine the typical location and structure of basic discontinuities such as the bow shock and the diamagnetic cavity boundary. In the present study, we wish to simulate the time evolution of the magnetic field in the inner coma region and therefore we must run the model in time-accurate mode. This represents a computational challenge, because the plasma source terms can result in very large changes during a stable time step determined by the neutral sound wave speed and the fast magnetosonic wave speed. Under such conditions explicit time-stepping can (and will) result in unstable solutions. To avoid this instability we used a point-implicit algorithm (Tóth et al. 2012) to evaluate the source terms.

### 3.2 Simulating Magnetic Dropouts

In this section, we describe how we simulate magnetic field dropouts in our model. The simulation is based on an idealized comet with a spherical body, and the neutral gas outflow is driven by solar illumination, which is Case 2 in Huang et al. (2016). In this case, the cometary neutral gas is water molecules, and the cometary ions are \( H_2O^+ \). The specific heat ratio is 4/3 for \( \text{H}_2O \) and \( \text{H}_2O^+ \), while it is 5/3 for the solar wind protons and electrons. The parameters for the simulation are listed in Table 1.

Gan & Cravens (1990) simulated the electron energetics in the inner coma of comet Halley and found a sharp jump of electron temperature at a subsolar cometocentric distance of about 15,000 km, while the magnetic cavity is located at a distance of 4500 km. Here we consider a similar scenario: a short-lived local electron heating process takes place along a magnetic flux tube. Under these conditions the extra heating results in a strong electron pressure gradient perpendicular to the flux tube (see Figure 2). The electron pressure gradient creates a strong ambipolar electric field that will be...
eventually responsible for the development of a short-lived magnetic dropout.

Let us consider the electric field due to the motion of the electron fluid and the ambipolar electric field \( \mathbf{E} = -\mathbf{u}_e \times \mathbf{B} - \nabla p_e/en_e \) and substitute it into the cometary ion momentum equation:

\[
\frac{\partial p_i u_i}{\partial t} + \nabla \cdot (p_i u_i u_i + p_i I) - Z_n n_e (u_i - u_e) \times B
- \frac{Z_e n_e}{n_e} (j \times B - \nabla p_e) + Z_s n_s = \frac{\delta p_s u_s}{\delta t} \tag{3}
\]

In Equation (3), we notice that a strong ambipolar electric field (or the electron pressure gradient) may push the cometary ions out of the region where a short-lived electron heating process takes place and create a region with strongly reduced or almost zero magnetic field since the field is frozen into the plasma. Based on this idea, we add an artificial electron heating source in a localized region for a short period of time (several minutes) to mimic the presence of some local electron heating process. We run the code in time-accurate mode to see how the plasma environment responds to this heating process.

The source terms for the electron pressure can be written as (Rubin et al. 2014a,b)

\[
\delta p_e = -p_e n_e \sum_{s=\text{ions}} \alpha_{e,s} n_s + \frac{1}{3} m_e \sum_{n=\text{neutrals}} n^i_{n\rightarrow s} n_s (u_n - u_e)^2
+ \frac{2}{3} \left( \sum_{s'=\text{ions}} \nu^i_{e,s'} m_{e,s'} n_{e,s'} \left[ \frac{k_B}{m_{e,s'}} (T_{e,s'} - T_e) + \frac{1}{3} (u_{e,s'} - u_e)^2 \right] \right)
+ \frac{2}{3} \sum_{n'=\text{neutrals}} \nu^i_{e,n'} m_{e,n'} \left[ \frac{k_B}{m_{e,n'}} (T_{e,n'} - T_e) + \frac{1}{3} (u_{e,n'} - u_e)^2 \right] - \frac{2}{3} \nu_{nH_2O Q_{nH_2O}} \tag{4}
\]

where the total ionization frequency of cometary neutrals is \( \nu^i_{n\rightarrow s} \), while \( \nu_{i,ph}^{e,s} \) and \( \nu_{i,e}^{e,s} \) are the photoionization frequency and the electron impact ionization rate, respectively. The recombination rate is \( \alpha_s \) and \( \nu_{e,s'} \) and \( \nu_{e,n'} \) are the momentum transfer collision frequencies between electrons and ions and electrons and neutrals. In Equation (4) the first term on the right is the loss due to ion-electron recombination, the second term considers the newly born electrons implanted at the neutral gas speed, the third term is the energy gained from the excess energies of the photo electrons and the energies lost due to electron impact ionization. The next two terms are associated with elastic collisions with ions (either cometary ions or solar wind protons) and with the neutral gas. The last term comes from the inelastic collisions with water molecules. In the current runs we do not include photoelectrons in the inner coma region. If there is a large electron pressure source from photoelectrons, such as that suggested in Gan & Cravens (1990), then there will be additional contributions to the electron pressure source equation. In order to mimic this heating process, we can introduce an additional term \( S_{\text{additional}} \) in Equation (4).

Figure 2 shows how we implement this idea into the model. We apply an artificial heating rate of \( S_{\text{additional}} = 1, 2, 5, 10 \text{nPa/s} \) along a thin tube in the \( z = 0 \) plane during \( t = 180 \text{ s} \) to 300 \text{ s} (where \( t = 0 \) corresponds to the steady state solution obtained from Case 2 in Huang et al. (2016)) to see how the enhanced electron pressure (temperature) affects the magnetic field in the inner coma region. The tube has a constant cross sectional radius of 1.5 km, as the cross section is not an important parameter in this study. We increase the grid resolution in the region where the tube is embedded to 0.5 km to make sure that the tube is well resolved. Figure 2 plots one of the four cases with \( S_{\text{additional}} = 5 \text{nPa/s} \) in the \( z = 0 \) plane.

Figure 3 shows the magnetic field magnitude for four different additional electron heating rates in the \( z = 0 \) plane.
to vanish inside the tube where $S_{\text{additional}}$ is added. With increasing $S_{\text{additional}}$ values the magnetic field inside the tube becomes weaker and weaker. When $S_{\text{additional}}$ reaches 5 nPa/s, the magnetic field is completely expelled from the flux tube (as long as the extra heating lasts) and a magnetic field free region is formed. For $S_{\text{additional}} = 10$ nPa/s the magnetic field free region becomes much larger than the flux tube itself. From the simulations, the $S_{\text{additional}} = 5$ nPa/s case seems to approximate the observed properties of magnetic dropouts. In the following discussion we focus on this case.

We extract the magnetic field and various plasma parameters at 4 different locations along the Sun–comet line as indicated in Figure 4. Location 1 is upstream from the tube where $S_{\text{additional}}$ is added, Locations 2 and 3 are inside the tube but close to the leading and trailing edges, and Location 4 is chosen just downstream of the tube. These four locations give a good general idea of how the plasma evolves within and near the tube where $S_{\text{additional}}$ is applied.

Figure 5 shows the magnetic field evolution at the four selected locations for 500 seconds. When $S_{\text{additional}} = 5$ nPa/s is introduced at $t = 180$ s, the magnetic field magnitude starts to drop at all locations. After the magnetic field magnitude drops to a minimum value, it starts to increase a little for Locations 1 and 2; while for Locations 3 and 4, the magnetic field magnitude increases more significantly. Then the magnetic field magnitude remains more or less constant for the rest of the extra heating period. The magnetic field magnitude increases rapidly for all four locations when the additional heating source of $S_{\text{additional}} = 5$ nPa/s is removed. This figure also reveals that the recovery phase is faster than the decreasing phase for all four locations (it is most obvious for Location 1).

Figure 6 shows six snapshots of the magnetic field magnitude, the electron pressure, the cometary ion density, and the cometary ion velocity along the Sun–comet line from $x = 160$ km to 180 km during $t = 180$ s to $t = 200$ s period. Initially, the sudden addition of $S_{\text{additional}}$ increases the electron pressure, then the electron pressure gradient generates an ambipolar electric field. As a consequence, the cometary ion velocity points away from the tube and the cometary ion density and the magnetic field magnitude decrease inside. Finally, the outward pointing ambipolar electric field is balanced by the inward pointing magnetic pressure gradient. The figure reveals that the plasma motion is the critical factor in the decreasing phase that expells the magnetic field from the tube.

$S_{\text{additional}}$ switching off. Initially, the sudden removal of $S_{\text{additional}}$ decreases the electron pressure. The previous balance between the magnetic pressure and the ambipolar electric field pressure breaks down, so the cometary ions move towards the tube as can be seen in the $t = 300.5$ s snapshot. This results in a compression and slows down the decrease of the electron pressure in the 301 s and the 302 s snapshots. Later on, the region with enhanced electron pressure becomes narrower and moves in the +x direction because the cometary ions are moving in the +x direction. As a consequence, the magnetic field gradually recovers its original value.

4 SUMMARY

We used our newly developed multifluid model (Huang et al. 2016), which separates the neutral gas, the cometary heavy ions, the solar wind protons, and the electrons, to investigate a possible mechanism for the formation of magnetic field dropouts observed at comet CG. We find that a local electron heating process is able to generate magnetic field free regions as observed in the RPC-MAG data (Goetz et al. 2016a,b). Our simulation results show that an increase of the electron pressure, introduced by a parametrized local electron heating process, leads to an ambipolar electric field that is strong enough to push out the cometary ions and create a magnetic field free region. The evolution of the magnetic field magnitude just upstream of the tube where the local electron heating process was applied (Location 1 in Figure 5) matches many of the observed features of the magnetic field dropout, including the fact that the recovery phase is much faster than the decreasing phase. We attribute this to the fast ion-electron recombination process. Note that in
Figure 6. The solid lines plot the magnetic field magnitude, the electron pressure, the cometary ion density, and the cometary ion velocity along the comet-Sun line from \( x = 160\) km to \( 180\) km during the onset of the event \((t = 180\) s to 200 s). The dashed lines show \( S_{\text{additional}}\) in the electron source term.

our simulated magnetic dropout regions is not necessarily zero, but can have a small, nearly constant value. This is consistent with the Rosetta RPC-MAG observations where the near constant magnetic field values in the “cavities” are assumed to represent a zero external field. We plan to do a more detailed comparison between our simulation results and the RPC-MAG observations with realistic solar wind parameters (including time varying solar wind drivers) in a follow-up study to further testify our proposed mechanism.

The physical picture we provide in this paper is simple: a local electron heating process can generate a magnetic field free region due to a strong ambipolar electric field. However, due to the limitations of fluid simulations, we are not able to simulate the local electron heating process self-consistently.
hand the spacecraft potential stays very negative during the magnetic dropouts (Eriksson 2016) implying the presence of large photoelectron fluxes $\lesssim 10$ eV that are sufficient for driving spacecraft potential to the observed negative potentials. Further investigation is necessary, but at this point we argue that a localized increase of thermal electron pressure is not inconsistent with the Rosetta observations and we used

Finally, as we mentioned earlier in this paper, at this time we are unable to identify a specific process producing such a short-lived electron heating in isolated magnetic flux tubes. Rosetta observations do not show increased energetic electron fluxes in the vicinity of diamagnetic dropouts (Madanian et al. 2016b,a; Nemeth et al. 2016). On the other hand the spacecraft potential stays very negative during the

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{fig7.png}
\caption{The solid lines plot the magnetic field magnitude, the electron pressure, the cometary ion density, and the cometary ion velocity along the comet-Sun line from $x = 160$ km to 180 km during the recovery phase ($t = 300$ s to 320 s). The dashed lines show $S_{\text{additional}}$ in the electron source term.}
\end{figure}
this process as a “placeholder” for the source of observed magnetic dropouts.

ACKNOWLEDGEMENTS

This work was supported by contracts JPL No. 1266313 and JPL No. 1266314 from the US Rosetta Project and NASA grant NNX14AG84G from the Planetary Atmospheres Program.

The authors thank the RPC-MAG and the ROSINA teams for supporting this research. The authors also thank the ESA Rosetta team for providing the opportunities to study this unique comet and their continuous support. Rosetta is an ESA mission with contributions from its member states and NASA. Rosetta’s Philae lander is provided by a consortium led by DLR, MPS, CNES and ASI.

The authors acknowledge the following high-performance computing resources: Yellowstone (ark:/85065/d7wd3xhc), provided by NCAR’s Computational and Information Systems Laboratory, sponsored by the National Science Foundation; Pleiades, provided by the NASA Supercomputer Division at Ames; and Extreme Science and Engineering Discovery Environment (XSEDE), supported by National Science Foundation grant number ACI-1053575

REFERENCES

Eriksson A., 2016, Private communication, email of September 6, 2016
Huang Z., et al., 2016, Journal of Geophysical Research (Space Physics), 121, 4247
Madanian H., Cravens T. E., others 2016a, J. Geophys. Res., 121, n/a
Madanian H., et al., 2016b, J. Geophys. Res., 121, 5815

Rubin M., et al., 2014a, icarus, 242, 38
Rubin M., et al., 2015b, Journal of Geophysical Research (Space Physics), 120, 3503
Tóth G., et al., 2005, Journal of Geophysical Research (Space Physics), 110, 12226