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# Revisiting cometary bow shock positions

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ABSTRACT

The Rosetta spacecraft will arrive at comet 67P/Churyumov–Gerasimenko in 2014 and will escort the comet along its journey around the Sun. The predicted outgassing rate of the comet and the solar wind properties close to its perihelion at 1.24 AU lead to the expectation that a cometary bow shock will form during the escort phase. Since the forecasts of the subsolar stand off distances differ, this study revisits selected models and presents hybrid simulations of the comet–solar wind interaction region performed with the A.I.K.E.F. code. It is shown that small variations of the solar wind parameters will shift the bow shock position considerably. In addition, a model is presented that reproduces the bow shock distances observed in the hybrid simulations.



## 1. Introduction

In May 2014 the Rosetta spacecraft of the European Space Agency (ESA) will arrive at comet 67P/Churyumov–Gerasimenko and deliver its lander Philea six months later (Glassmeier et al., 2007a). Thereafter, the Rosetta orbiter will escort the comet during its journey around the Sun.

The spacecraft is equipped with the plasma instruments of the Rosetta Plasma Consortium (RPC), which are able to study the evolution of the interaction of the comet with the solar wind (Carr et al., 2007; Glassmeier et al., 2007b). This interaction arises from the neutral gas which is evaporating from the nucleus due to surface heating by insolation. The neutral gas has a radial velocity of about 1 km/s and it forms an exosphere, in which the solar UV radiation causes the ionisation of the neutral gas. These new cometary ions will then be accelerated by the solar wind. The acceleration process depends on the Parker angle the angle between the solar wind velocity and the interplanetary magnetic field (IMF).

On one hand, in case of perpendicular orientation of the IMF to the solar wind velocity vector, the ions are accelerated by the Lorentz force. Assuming ideal frozen-in conditions and a situation far away from the nucleus, the force is determined by the IMF and the solar wind speed. In case of the single-particle-motion model, in which the fields are constant, the ions will perform a cycloidal motion in the cometary rest frame which leads to a ring distribution in the phase space (cf. Coates and Jones, 2009; Wu and Davidson, 1972). On the other hand, if the fields are in a parallel orientation, the Lorentz force vanishes and different instabilities occur (cf. Lee, 1989). But this case is less important for the study of comet 67P/Churyumov–Gerasimenko since the Parker angle is much larger than $45^{\circ}$ most of the time. Thus, the pick-up process, based on the Lorentz force, is supposed to dominate the acceleration. In contrast to the acceleration of the cometary ions, the solar wind has to be decelerated in order to fulfil momentum and energy conservation requirements.

However, the strength of the deceleration will vary during the escort phase of the Rosetta mission because the critical parameters of the interaction change, too. This implies that not every structure or boundary within the comet–solar wind interaction region does exist during the whole period of the escort phase of the mission and the positions of the boundaries or the size of the structures change as well. This variability of the interaction region requires careful planning of the measurement campaigns as much as energy and telemetry considerations do. Consequently, precise measurements of the boundaries require extensive preparation. This is even more true since the trajectory of the spacecraft and its pointing has to be chosen in order to fulfil the science objectives of the different on-board instruments. In addition, the limited fuel available, the time which is consumed by the measurements and

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**Table 1**
Characteristic parameters of the plasma interaction between comet 67P/Churyumov–Gerasimenko and the solar wind at 1.3 AU (Hansen et al., 2007). For a better comparability, the Parker angle is set to $\theta = 90^\circ$.

| Quantity | Value |
|---|---|
| Gas production rate ($Q$) | $5\times10^{27}$ s$^{-1}$ |
| Cometary ion mass ($m_i$) | 17 amu |
| Ionisation rate ($\nu$) | 5.88 s$^{-1}$ |
| Neutral gas velocity ($u_{ng}$) | 1 km/s |
| Solar wind number density ($n_{sw}$) | 6 cm$^{-3}$ |
| Solar wind velocity ($u_{sw}$) | 400 km/s |
| Strength of interplanetary magnetic field ($B_{IMF}$) | 4.9 nT |
| Parker angle ($\theta$) | 90° |

the spacecraft safety also need to be taken into account. The latter point is important since the non-gravitational forces in the cometary environment lead to strongly perturbed spacecraft trajectories whereas the first two points play a major role in case the feature of interest, for example the cometary bow shock, is far away from the comet.

The cometary bow shock has already been observed at different comets by other spacecraft missions (cf. Neubauer et al., 1986, 1993; Richter et al., 2011 or Smith et al., 1986), but predictions of the location differ depending on the model used. For example, the model by Biermann et al. (1967), hereafter also named the Biermann model, predicts a subsolar stand off distance at comet 67P/Churyumov–Gerasimenko of about 5000 km at 1.3 AU (see Table 1). In contrast, the model by Gortsas et al. (2010) only calculated a distance of 1610 km for the same comet while Hansen et al. (2007) reported a distance of about 3500 km in their 3D MHD simulations.

In the present work, a state of the art hybrid simulation is presented, which predicts a bow shock stand off distance of about 2000 km. All the models used comparable solar wind conditions and cometary outgassing rates. However these values vary significantly and therefore it is necessary that the used models are revisited to provide a best-effort approach for the mission planning. This is the purpose of the present study. Furthermore, this study will present a model based on the latest hybrid simulations which is able to describe the differences in the bow shock positions between the fluid approaches and the hybrid simulations. This is very useful for operational purposes.

In the first part of this paper an overview of some models which allow the calculations of the bow shock position will be given. Initially, a summary of the pioneering work of Biermann et al. (1967) will be presented in Section 2. The following section briefly describes a simple MHD model, which is based on the model by Biermann et al. (1967) and which has later been extended by Flammer and Mendis (1991). Finally, this paper presents an overview of state of the art hybrid simulations of comets. In Section 6 a comparison of the different model results is drawn and their behaviour in case of the variation of important parameters will be shown. Additionally, the hybrid based model which gives us a physical explanation of the behaviour of the bow shock position in the hybrid simulations, is also described in that section. Finally, an outlook of the bow shock position during the Rosetta mission will be presented.

## 2. Revisiting the Biermann model

The first model of the interaction between the solar wind and comets was proposed by Biermann et al. (1967). It describes the interaction with a one-dimensional inviscid gas dynamic flow, which implies that no magnetic field effects are taken into account. The authors also assume a stationary situation in front of the bow shock and an ideal gas as a medium. Furthermore, the model treats newly ionised cometary ions in such a way that instantly after their ionisation the ions have the same bulk velocity as the ambient solar wind. These assumptions lead to the following set of equations.

$$\partial_x(\varrho u_x) = M_s \tag{1}$$

$$\partial_x(\varrho u_x^2 + p_t) = I_s \tag{2}$$

$$\partial_x\left(\frac{1}{2}\varrho u_x^3 + \frac{\gamma}{\gamma-1}p_t u_x\right) = E_s \tag{3}$$

In these equations $\varrho$ is the mass density. The velocity of the massloaded solar wind is $u$ and $p_t$ is the thermal pressure, which Biermann et al. (1967) assume to be negligible in the undisturbed solar wind. The $x$-component of the massloaded solar wind velocity is $u_x$ being parallel to the $x$-axis, i.e. anti-sunward. In the present study the nucleus is located at the origin of the coordinate system. Furthermore, $\gamma = (f+2)/f$ is the ratio of specific heats and $f$ the number of degrees of freedom of the ideal gas. Initially, Biermann et al. (1967) chose a value of $\gamma = 2$ assuming only the motional degrees of freedom of a particle gyrating around the magnetic field.

The quantities $M_s$, $I_s$ and $E_s$ represent the local sources for the mass density, the momentum and the energy density. As discussed by Biermann et al. (1967), the source of the mass density dominates the other sources as long as the distance to the nucleus is much larger than the stand off distance of the cometary ionopause. Hence, the authors only considered the mass source, whereas all the others were assumed to be negligible. Due to these assumptions, the model by Biermann et al. (1967) describes the comet only as a source which adds mass to the solar wind flow and thus increases the mass density $\varrho$ of the flow whilst approaching the comet.

A simple integration of Eqs. (2) and (3) leads to the following expression for the normalised velocity (Biermann et al., 1967)

$$u_x^* = \frac{u_x}{u_\infty} = \frac{1}{(\gamma+1)(\varrho u_x)^*}\left(\gamma \pm \sqrt{\gamma^2 - (\gamma^2-1)(\varrho u_x)^*}\right), \tag{4}$$

where $u_\infty$ is the velocity in the undisturbed solar wind. Since this work is focussing on the supersonic case, it discusses only the branch with the plus sign in front of the root. The normalised value of the mass flux density $(\varrho u_x)^* = (\varrho u_x)/(\varrho_\infty u_\infty)$ increases due to newly injected cometary ions once the flow approaches the comet. One can easily see that the velocity becomes complex if the mass flux density is greater than the critical mass flux density

$$(\varrho u_x)^*_{\rm crit} = \frac{\gamma^2}{\gamma^2-1}. \tag{5}$$

Reaching this point, a stationary solution of the set of Eqs. (1)–(3) does not exist anymore and the velocity of the flow becomes equal to the sonic speed. Biermann et al. (1967) reported that a shock will develop in a real flow in front of this point, which will generate a divergence of the flow and thus allows further mass loading. These effects cannot be described by the Biermann model, nevertheless, the model allows to calculate the position of the shock. This can be done for comet 67P/Churyumov–Gerasimenko using Eq. (1), however the mass source $M_s$ needs to be known in more detail. Since 67P/Churyumov–Gerasimenko is a weak outgassing comet, the current work uses expression

$$M_s = \frac{\nu Q m_i}{4\pi u_{ng}}\frac{1}{r^2}, \tag{6}$$

for the mass source, where $\nu$ is the ionisation rate, $Q$ the gas production rate, $u_{ng}$ the velocity of the cometary neutral gas