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Plasma processes at comet Churyumov–Gerasimenko: Expectations for Rosetta

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Abstract. The Rosetta–Philae mission to comet 67P/Churyumov–Gerasimenkoin 2014 will provide a unique opportunity to observe the variable nature of the interaction of a comet with the solar radiation and the solar wind, as the comet approaches the Sun. In this short paper we will focus on the varying global structure of the cometary plasma environment. Specifically we make predictions on the varying locations of the two basic transitions in the global, contaminated solar wind flow toward the comet: the outer bow shock and the ionopause.

1. Introduction

As of this time there have been almost a dozen spacecraft missions to comets, all of which have been fast 'flybys'. While these missions have led to a major enhancement of our knowledge of comets and their interaction with the solar radiation and the solar wind (Mendis 2007), they provide only 'snapshots' of individual comets and their particles and fields environments at fixed distances from the sun. However what makes comets so interesting are their multiple modes of interaction with the solar radiation and the solar wind, ranging from that of a bare nucleus to that of a well-developed, outgassed atmosphere. Consequently, there is great anticipation for the forthcoming Rosetta–Philae Rendezvous and Lander mission to comet 67P/Churyumov–Gerasimenko. In this mission the spacecraft will rendezvous with the target comet in May 2014, at a heliocentric distance of 4 AU, deploy the lander in November 2014 at 3.6 AU, and escort the comet through perihelion passage at 1.29 AU and beyond. It will thus provide a unique opportunity to revisit the entire range of phenomena, observed at previous comets in a single comet (Mendis and Horányi 2013). Here we focus on the plasma environment of the comet, particularly on its varying spatial structure, and predict the positions of the basic transitions in the global flow, namely the bow shock and the ionopause. This paper is dedicated to the memory of our esteemed colleague Professor Padma Shukla.

2. Production rate of cometary neutrals

Central to the study of comets is the heliocentric variation of the production rate of sublimated neutrals from the solar heated nucleus. For a nucleus of known composition, radius R_N, and biometric albedo, A_B, of the active icy surface, from which sublimation takes place, we can calculate the temperature, T_N, of this active surface and the flux of sublimated molecules, Z, as a function of the heliocentric distance d of the comet. This is done by simultaneously solving the Clausius–Clapeyron equation (which relates the surface pressure and hence the surface number density to T_N) and making an assumption about the expansion speed, V_N, of the sublimating molecules to be the sonic speed corresponding to T_N, i.e. the drag of the entrained dust on the gas is negligible (Mendis et al. 1985). We have done this for comet 67P/Churyumov–Gerasimenko, assuming that the volatile (active) patches on the surface are entirely composed of H_2O ice (known to be the dominant volatile component of all observed comets). We have further assumed that all these active regions on the surface would have the same temperature, $T_N(d)$, at a given heliocentric distance. The total production rate is given by

$$Q_N(d) = 4\pi R_N^2 f Z(d). \tag{2.1}$$

Here we have taken $R_N = 1.7$ km and adjusted the fraction of the active surface area $f \simeq 8\%$ to match $Q_N(d) = 2 \times 10^{27}$ moles s^{-1} at $d = 1.27$ AU, which was the observed production rate at the last perihelion passage (de Almeida et al. 2009). The value for A_B on the active icy regions is taken to be 0.1 corresponding to 'dirty' ice (Mendis et al. 1985), its value on the non-active regions could be in the range of 0.02 – 0.04, which corresponds to the values inferred from the five cometary nuclei observed so far by spacecraft (Mendis 2007). Since

f is only 8% of the surface, comet 67P/Churyumov–Gerasimenkoalso appears to be effectively very dark.

3. The bow shock

Next, we discuss the conditions for the formation of the comet's outer bow shock and calculate its nucleocentric distance, $R_S(d)$, along the sun-comet axis, as a function of d, for the comet 67P/Churyumov–Gerasimenko. The mass-loading of the inflowing solar wind by newly produced cometary pick-up ions causes the solar wind to decelerate and heat up. As first shown by Biermann et al. (1967), this mass-loading of the solar wind can proceed only as long as the normalized mass loaded flux $\hat{x} = (\rho u)/(\rho_\infty u_\infty)$ is less than some critical value, where ρ and u are respectively the mass density and flow speed of the contaminated solar wind, and ∞ denotes the values far upstream of the comet, when the solar wind is uncontaminated. Before this critical value is reached, a shock is expected to form upstream at such a position to divert enough of the solar wind around the comet to ensure that this critical value is not reached. Subsequent numerical calculations by several authors have shown that a weak collisionless shock will form in the solar wind by the time the solar wind (magnetosonic) Mach number, M_m, has decreased from its undisturbed value of about 10 to about 2. By integrating the momentum and energy equations of Biermann et al. (1967) along the sun–comet axis, it can be shown that when the flow is assumed to be both hypersonic and hyper-Alfvénic at infinity (Flammer 1991)

$$\hat{x} = \frac{\gamma^2}{\gamma - 1}\,\frac{M_m^2[(\gamma-1)M_m^2+2]}{(\gamma M_m^2+1)^2}. \tag{3.1}$$

Two limiting cases can be considered to set the value for γ. In the first scenario, one assumes that the interplanetary magnetic field is strictly normal to the solar wind flow and the picked up cometary ions retain their magnetic moment at the point of pickup, forming a gyrotropic ring distribution in velocity space. Under this assumption $\gamma = 2$. In the second case the flow is oblique to the magnetic field, in which case hydromagnetic waves are excited, which in turn elastically scatter the newly formed ions in the initial gyrotropic ring into an isotropic shell distribution in velocity space. This leads to $\gamma = 5/3$. Using (3.1) we find that in the first case ($\gamma = 2$) $\hat{x} = 1.185$ when $M_m = 2$, while in the second case ($\gamma = 5/3$) $\hat{x} = 1.323$ when $M_m = 2$.

Integrating the equation of mass continuity, of the mass-loaded solar wind flow (along the sun–comet axis) together with the mass continuity equation for the outflowing cometary neutrals, allowing for their loss by photoionization (and charge exchange) with a characteristic timescale $\tau_i(d)$ another expression for $\hat{x}$, now as a function of the nucleocentric distance r can be obtained (Galeev et al. 1985; Flammer 1991). Using this expression and noting that the cometocentric shock distance, $R_S \lll V_n\tau_i$ ($\tau_i \simeq 2 \times 10^6$ s and $V_N \simeq 0.4$ km s^{-1} at $d = 1$ AU), one obtains the following result:

$$R_S(d) = \frac{Q_N(d)m_i}{4\pi V_N(d)\tau_i(d)\rho_\infty u_\infty(\hat{x}-1)}. \tag{3.2}$$

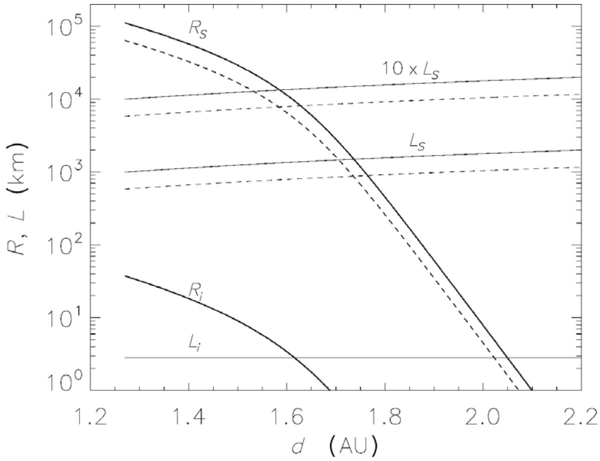

Figure 1. The heliocentric variation of the nucleocentric distance of the bow shock, R_S, ahead of the comet and the Larmor radii, L_S (as well as $10 \times L_S$) of the picked up cometary O^+ ions just inside the shock. Both the isotropic $\gamma = 5/3$ (*dashed lines*) and the gyroscopic $\gamma = 2$ (*continuous lines*) cases are plotted. R_i is the predicted position of the ionopause, and L_i is the Larmor radius of an O^+ ion just outside R_i.

Figure 1 shows a plot of $R_S(d)$ for both $\gamma = 2$ ($\hat{x} = 1.185$) and $\gamma = 5/3$ ($\hat{x} = 1.323$). While ρ_∞ and u_∞ vary greatly over time, here we use the single case of a slow solar wind $u_\infty = 360$ km s^{-1} and $n_\infty = 8.6$ cm^{-3} (corresponding to a measurement at Halley in 1986). Also, m_i is taken to be 16 AMU (corresponding to O^+).

It has been shown that the thickness of the cometary bow shock is of the order of the cometary ion Larmor radius L_{iS} (just inside the shock) in the case of a quasi-perpendicular shock and of the order of $10 \times L_{iS}$ in the case of a quasi-parallel shock (Galeev et al. 1985). It is also shown that

$$L_{iS} = \frac{m_i c u_\infty \hat{u}_2^2}{eB_\infty}, \tag{3.3}$$

where $\hat{u} = u_2/u_\infty = 0.375$ when $\gamma = 2$, and $\hat{u} = 0.287$ when $\gamma = 5/3$ (the subscript 2 indicates conditions just inside the shock), and we used (Flammer 1991)

$$B_\infty = 6\left(\frac{1}{2}\left(\frac{1}{d^2} + \frac{1}{d^4}\right)\right)^{1/2} \text{nT}. \tag{3.4}$$

The necessary condition for the existence of a well-defined cometary bow shock is that $R_S(d) > L_{iS}(d)$. In order to see the range of d where this is the case, $L_{iS,\gamma=2}$ and $10L_{iS,\gamma=5/3}$ are also shown in Fig. 1. For conditions when the interplanetary magnetic field is close to normal, the solar wind flow, R_{gS} (corresponding to the gyrotropic case $\gamma = 2$) intersects the $L_{iS,\gamma=2}$ curve at the heliocentric distance of $d = 1.43$ AU and has a value of $R_{gS} = 1150$ km. For this case at perihelion, $R_{gS} = 3400$ km is predicted. For the periods when the magnetic field will be close to parallel to the solar wind flow, the R_{iS} curve does not exceed the needed value of $10L_{iS,\gamma=5/3}$, hence the formation of a well-defined shock is not expected. Since the solar wind conditions can be highly variable, we expect that Rosetta will intermittently observe sharp shocks alternating with more diffuse solar wind flow changes in front of the comet as function of the orientation of the upstream magnetic fields.

4. Ionopause

The cometary 'ionopause', as briefly discussed earlier, is the transition that separates the inflowing, contaminated, solar wind plasma, downstream of the bow shock, from the outflowing, purely cometary plasma. The current view of the formation of this ionopause is the one proposed by Ip and Axford (1982), which was strongly supported by the *Giotto* observations of Halley's Comet in 1986. As the contaminated solar wind continued to slow down, the magnetic field would continue to increase and eventually the flow will be brought to stagnation along the sun–comet line when the $\mathbf{j} \times \mathbf{B}$ force on a fluid element just outside the boundary (the ionopause) will be balanced by the drag of the freely outflowing neutrals to which the cometary ions are collisionally coupled. Of the two terms into which the $\mathbf{j} \times \mathbf{B}$ force decomposes, the magnetic tension due to the curvature of the magnetic field lines, wrapped around the ionopause, is dominant.

Assuming photochemical equilibrium, and using a simple model for the ionospheric plasma flow, we obtained the cometocentric distance of the ionopause along the sun–comet axis as follows:

$$R_i^2 = \frac{k_D m_i Q_n^2(d)}{4\pi\tau_i u_n^2(d)} \frac{1}{B_i^2}, \qquad (4.1)$$

where the ion-neutral collision rate coefficient $k_D = 1.1 \times 10^{-9}$ cm^3 s^{-1}. B_i is the magnetic field in the magnetic pile-up region and it can be estimated by assuming that the entire ram pressure of the super magnetosonic solar wind is converted to magnetic pressure just ahead of the ionopause ($\rho_\infty u_\infty^2 = B_i^2/8\pi$), giving an estimate for $B_i \simeq 60$ nT , since we assume that ρ_∞ and u_∞ are independent of d. $R_i(d)$ is shown in Fig. 1.

Once again, for the existence of a well-defined ionopause, the size of the ionopause R_i must be significantly larger than the Larmor radius L_{ii} of an ion just ahead of the ionopause (Flammer 1991):

$$L_{ii} = \frac{c}{eB_i}(k_B T_2 m_i)^{1/2}. \qquad (4.2)$$

We set $B_i \simeq 60$ nT independent of d for the assumed, undistributed solar wind parameters corresponding to a slow solar wind. T_2 is the ion temperature just ahead of the ionopause boundary. The calculation of T_2 is beyond the scope of this brief analysis. Here we simply assume that T_2 does not vary substantially from those values observed by spacecrafts around 1 AU, which is about 2000^{o}K (Ip and Axford 1990; Flammer et al. 1991). In taking B_i and T_2 to be independent of d, $L_{ii} = 2.84$ km and remains independent of d (Fig. 1). R_i becomes $> L_{ii}$ at $d = 1.61$ AU, which is the heliocentric distance at which a well-defined ionopause is likely to be first observed. The size of the ionopause increases as d decreases, reaching a value of 34 km at perihelion ($d = 1.29$ AU). The existence of the ionopause is the necessary condition for the formation of 'a magnetic field-free cavity', which was observed by the Giotto spacecraft at comet Halley. So the appearance of such a cavity would be an excellent indication of the formation of the ionopause. The small size of the ionopause makes it unstable to the fluid 'flute' mode (Ip and Mendis 1978). Consequently there is the possibility that such a magnetic field-free cavity would not exist even when the criterion of $R_i > L_{ii}$ is satisfied. What one might observe instead is perhaps a region of depleted magnetic fields. Finally, we note that the time at which a thin central plasma tail is expected to appear is when a well-developed ionopause first forms (Flammer 1991). This is yet another prediction that could be easily verified by the Rosetta mission to comet 67P/Churyumov–Gerasimenko.

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