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Magnetic tension in the tails of Titan, Venus and comet Halley

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ABSTRACT

Magnetic tension in the tail of the classical induced magnetosphere produced by field line draping is directed downstream along the external plasma flow. This is confirmed by the calculation of tension in magnetospheres of Venus and comet Halley which are firmly established as celestial bodies with negligible magnetic field.

On the contrary, magnetic field structure observed in numerous *Cassini* flybys in the region of Titan interaction with the corotating flow of Kronian magnetosheric plasma contradicts the classical picture of the ideal induced magnetosphere produced by magnetic field line draping about the obstacle. Clear draping is observed only upstream of the Titan, but not in the Titan magnetic wake.

We consider the magnetic field tension downstream the Titan magnetic tail and show that the magnetic field direction is not consistent with the induced magnetosphere produced by magnetic field lines draping. We arrive at the conclusion that the mechanisms alternative to the induced magnetosphere formation should be considered for the Titan magnetic environment.

1. Introduction

Induced magnetosphere arises when a magnetized plasma flow interacts with a non-magnetic body possessing ionosphere. Electric currents are induced under the action of Lorentz electric field $\mathbf{E} = -\mathbf{v} \times \mathbf{B}$. Superposition of the external magnetic field and field produced by induced currents results in a configuration proposed by Alfvén (1957) for cometary tail and can be described be magnetic field lines draping about an obstacle. Magnetic field configuration of the magnetic tail in the classical induced magnetosphere is shown in Fig. 1. It consists of two lobes of oppositely directed magnetic field lines separated by the current sheet. The upper lobe of the tail is shown in the figure.

Orientation of such an induced magnetosphere depends on the direction of the magnetic field in the plasma flow. If we consider the coordinate system $X_M Y_M Z_M$ with the unit vectors defined as

$$\mathbf{e}_x = \mathbf{v}_0 / v_0$$

$$\mathbf{e}_y = -(\mathbf{v}_0 \times \mathbf{B}_0)/|\mathbf{v}_0 \times \mathbf{B}_0|$$

$$\mathbf{e}_z = \mathbf{e}_x \times \mathbf{e}_y \quad (1)$$

where $\mathbf{v}_0$ and $\mathbf{B}_0$ are flow velocity and magnetic field in the free flow upstream of the obstacle, respectively. Simple criterion for ideal induced magnetosphere (field line draping) can be formulated as

$$B_x > 0 \text{ for } z > 0$$
$$B_x < 0 \text{ for } z < 0 \quad (2)$$

and $B_z > 0$ inside the magnetosphere.

Moreover, the direction of projection of the magnetic field onto the *YZ*-plane is close to the *Z*-axis. Fig. 2 shows the magnetic field vector projections onto induced magnetic tail cross section as obtained in single fluid MHD simulations (Kabin et al., 2000). The clock angle of the magnetic field inside the induced magnetosphere does not exceed $\sim 15^{\circ}$ Such a configuration was observed in a typical induced magnetosphere of Venus (Dolginov et al., 1981; McComas et al., 1986) and comet Halley (Israelevich et al., 1994).

Titan orbit is located mostly inside the Kronian magnetosphere. Therefore Titan interacts with subsonic flow of corotating plasma (with rather rare exceptions when Titan leaves the planetary magnetosphere and appears in the shocked solar wind flow). It is commonly believed that the induced magnetosphere results from interaction of the Titan atmosphere with the Kronian plasma stream. The magnetic field perturbation in the Titan wake was first observed by Voyager-1 (Ness et al., 1982) (Fig. 3).

However, Voyager observations do not satisfy the above criteria of an ideal induced magnetosphere. Strong rotation of the magnetic field around the flow direction (*Z*-axis) occurred in the Titan magnetic tail, and the direction of flow aligned component of the magnetic field does not correspond to the field line draping (Kabin et al., 2000). Depending on the Titan orbital position, directions of the incoming magnetospheric plasma and the solar EUV flux may be different resulting in the asymmetry of the plasma obstacle for

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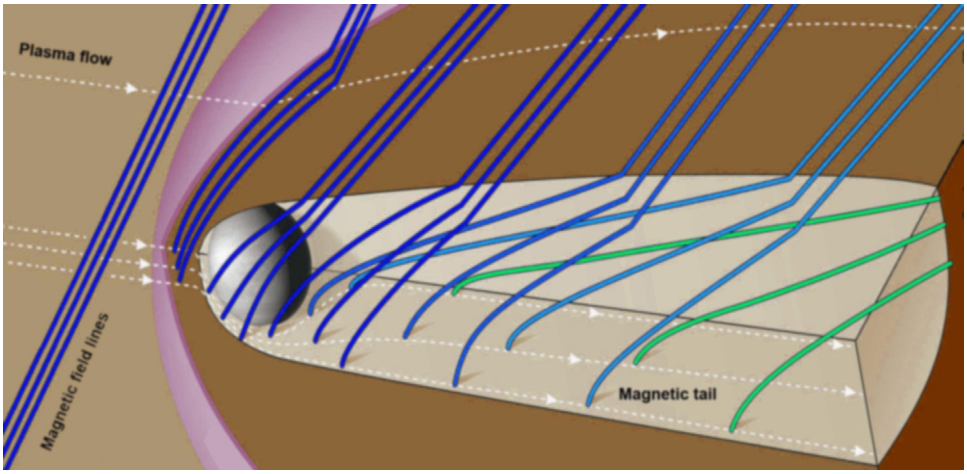

Fig. 1. Configuration of an ideal induced magnetosphere resulting from the magnetic field line draping about the conducting obstacle. The magnetic tail consists of two lobes with oppositely directed magnetic field. The field lines are shown only above the current sheet.

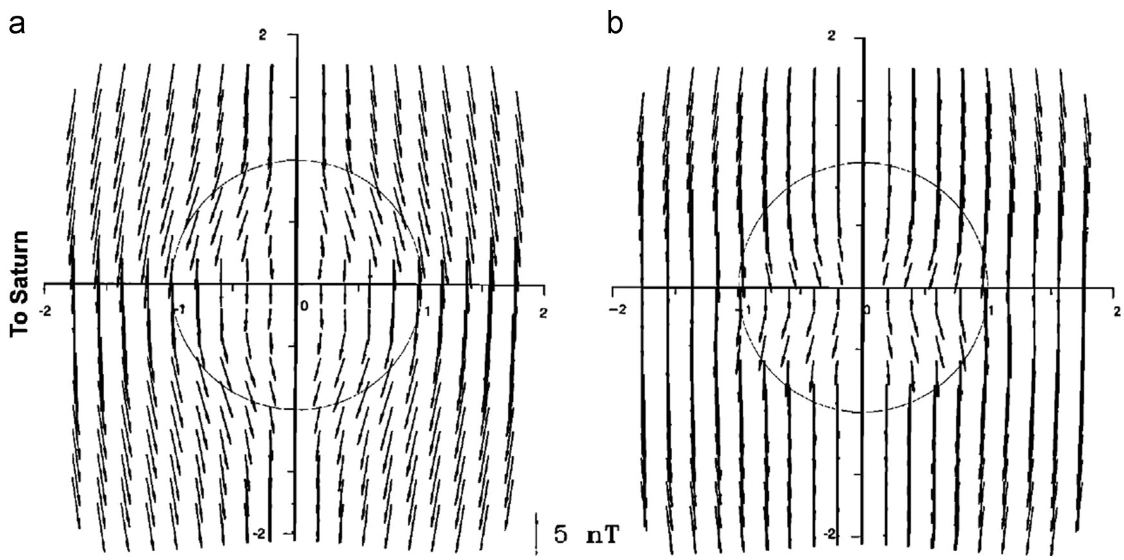

Fig. 2. Projections of magnetic field vectors in the wake of the induced magnetosphere onto the plane perpendicular to the stream velocity: (a) at the distance of 1R and (b) 1.85R behind the obstacle of radius R.

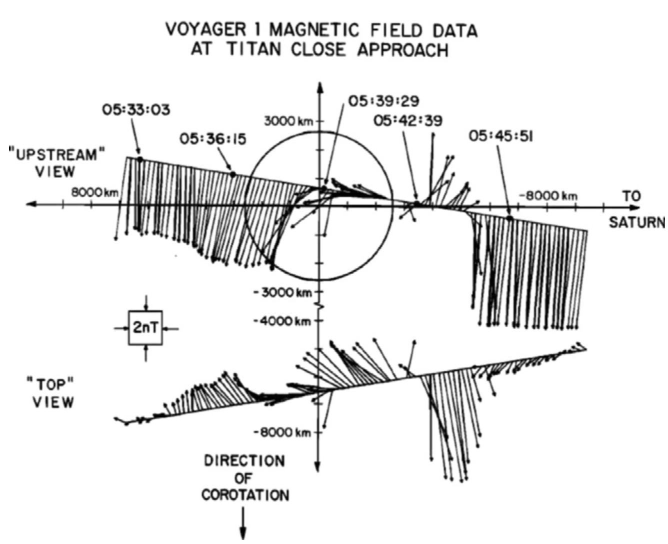

Fig. 3. Plots of magnetic field vector components along the trajectory of Voyager-1 (Ness et al., 1982).

corotating flow. However, the effect of this difference between 'dawn' and 'dusk' sides of the ionosphere may account only for asymmetry of the magnetic strength in the tails, and cannot explain the magnetic field vector rotation shown in Fig. 3. Kabin et al. (2000) ascribed this violation of draping criterion to possible influence of Titan's own magnetic field.

Only a few of numerous flybys of Cassini spacecraft correspond to field line draping typical for classical induced magnetosphere (Simon et al., 2013). On the contrary, magnetic field structure observed during most of the flybys deviates significantly from the draping picture and often reveals the rotation of the magnetic field around the tail axis first observed by Voyager 1 (Fig. 3) (e.g. Bertucci et al., 2007, 2008, 2009; Neubauer et al., 2006).

Numerical simulations – MHD (e.g. Backes, 2004; Ma et al., 2006), hybrid (e.g. Simon et al., 2006, 2007a,b, 2008, Simon, 2009; Modolo et al., 2007), kinetic (Kallio et al., 2004) – succeeded to reproduce day side magnetic field line draping similar to that shown in Fig. 2, asymmetry of the magnetic field strength and deflection of the tail from the corotation flow direction toward Saturn (Kallio et al., 2004; Ma et al., 2006) and away from Saturn (Simon et al., 2007a,b; Modolo et al., 2007). No model reproduces the magnetic field rotation around the tail axis. Nevertheless, the