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Corkscrew Flow Motion of Planetary Ions in the Venus Plasma Wake

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Measurements conducted with the Venus Express spacecraft (VEX) have led to the detection of a vortex structure in the Venus plasma wake. The scale size of that feature together with the local speed of ions in the vortex and values of the kinematic viscosity coefficient of the solar wind provide an estimate of the swirl period of the vortex. Comparative values of the speed of the particles produced by the period of the vortex and also their speed along the wake axis lead to a corkscrew shape for their motion as they move downstream from Venus. The flow streamlines are warped up within the wake and are oriented at a rate that varies with the solar wind conditions. Calculations show that the orientation of the flow streamlines along the corkscrew is dictated by the local value of the Reynolds number R given by the speed of the solar wind and the scale size of the vortex. At values of the Reynolds number smaller than those inferred from the VEX measurements the flow streamlines will be more warped up along the corkscrew. The opposite will occur at larger values of the Reynolds number.

VEX DATA

An overall description of a vortex structure measured in the Venus wake is reproduced in **Figure 1.** The orientation of the velocity vectors of H+ ions on the YZ plane transverse to the sun-Venus direction is shown in the upper panel). Their orientation along the X-axis in cylindrical coordinates is indicated in lower panel. The distribution of the velocity vectors is consistent with the presence of a vortex structure that extends across most of the Venus wake and that leads to a return flow in its central region directed back to Venus [1, 2]. The magnitude of the velocity vectors directed towards positive Y values at the top of the lower panel is larger than those of the velocity vectors closer to the wake axis. This difference implies the presence of a velocity boundary layer across the wake with velocity vectors directed back to Venus in the central part.

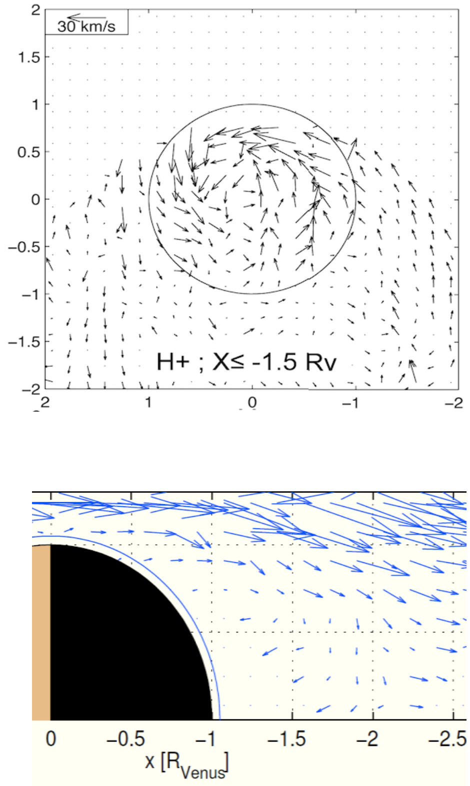

Figure 1 (upper panel) Velocity vectors of 1 - 300 eV H+ ions measured with the VEX spacecraft in the Venus near wake projected on the YZ plane transverse to the solar wind direction (Y and Z are the horizontal and the vertical axis). Data are averaged in 1000 x 1000 km columns at X < -1.5 R_V (1). (lower panel) Average direction of solar wind ion velocity vectors across the Venus near wake collected from many VEX orbits and projected in cylindrical coordinates (2).

The vorticity equation

The vorticity (Helmholtz) equation of a rotational flow (3) is:

$$\partial\boldsymbol{\omega}/\partial t = \nabla \times (\mathbf{V} \times \boldsymbol{\omega}) + \nu \nabla^2 \omega \qquad (1)$$

where the first term in the right side states changes of the vorticity vector $\boldsymbol{\omega} = \nabla \times \mathbf{V}$ produced by its own convection, and the second term is related to diffusion processes. $\mathbf{V}$ is the velocity vector of the flow, and ν is its kinematic viscosity coefficient. In dimensional form for incompressible fluids equation (1) can be reduced to:

$$\omega/T = U\,\omega/L + \boldsymbol{\nu}\,\omega/L^2 \qquad (2)$$

where U is the dominant speed of the flow and L the scale length of the vortex within the flow.

In terms of the Reynolds number $R = UL/\boldsymbol{\nu}$ this equation is in turn:

$$T = RT^*/(1 + R) \qquad (3)$$

where $T = L/U$ is the travel time of a flow parcel around the vortex structure and T* is that for very small values of the kinematic viscosity coefficient.

Using L = 6000 km as the scale size of the average vortex reproduced in Figure 1 and by taking U = 30 km/s as the speed limit of the H+ ions in the Venus wake shown in Figure 1we can first derive T* = 200 s as an approximate value for the travel time of a fluid parcel on a distance πL around the vortex for the limiting case of very small kinematic viscosity coefficient values ($R \rightarrow \infty$) More representative calculations can be conducted by employing values of the order of $\nu \sim (10^3 - 10^5)$ km^2/s for the lower and upper order of magnitude of the kinematic viscosity coefficient [4]. With these numbers we are led to R ~ 180 – 1.8 for the Reynolds number leading to the values for the swirl period of the vortex presented in **Table 1.**

υ	Reynolds Number	Rotation Period
	∞	200 s
10^3 km^2/s	180	198 s
10^4 km^2/s	18	189 s
10^5 km^2/s	1.8	128 s
∞	0	0 s

Table 1 (left column) Nominal values of the kinematic viscosity coefficient υ of the solar wind. (middle-right columns) Values of the Reynolds number and the rotation period for the vortex in the upper panel of Figure 1.

The corkscrew flow in the O+ ion streamlines

The effect of adding the ion motion along the vortex to their velocity component along the wake axis will produce a torque in the manner that they are displaced thus leading to a corkscrew shape in their displacement as it is illustrated in **Figure 2**. Even though the shape of the flow motion in **Figure 1** corresponds to average conditions the warping of the flow streamlines will vary depending on the solar wind speed and the scale size of the vortex. Smaller values of the Reynolds number R in equation (3) will lead to smaller values of the rotation period thus increasing the particles rotation speed around the vortex in order to complete each turn. Under such conditions the flow streamlines in the corkscrew diagram will be more warped up than that predicted from the measured values. With larger R values the opposite will occur.

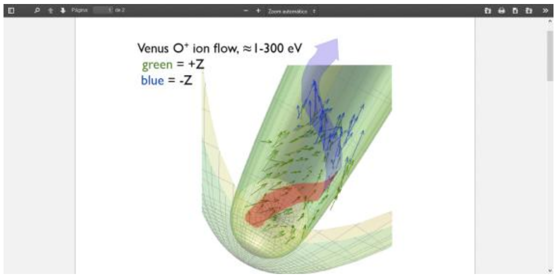

Figure 2. Schematic view of the corkscrew shape in the distribution of velocity vectors of O+ ions inferred from VEX measurements as they move downstream from Venus.

References:

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[3] Drummond, J. E., Plasma Physics, p. 197, McGrawHill,1961.
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