Multi-fluid MHD studies of the magnetic flux ropes in un-magnetized ionospheres

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Magnetic flux ropes (MFRs) with twisted magnetic field lines are common in the solar system, most of which can be caused by magnetic reconnection[1] or velocity shear[2]. However, these two mechanisms have difficulties in explaining the formation of MFRs observed in the ionosphere of an unmagnetized body, such as Mars, Venus, and Titan[3-4]. Here we propose a new mechanism: an azimuthal component of $\nabla \times \boldsymbol{E}$ can be generated by the differential compression and diffusion at different parts of the flux tube when the tube is sinking into the partially ionized ionosphere, which generates azimuthal magnetic fields with twisted magnetic field lines and finally gives rise to an ionospheric MFR (Figure 1).

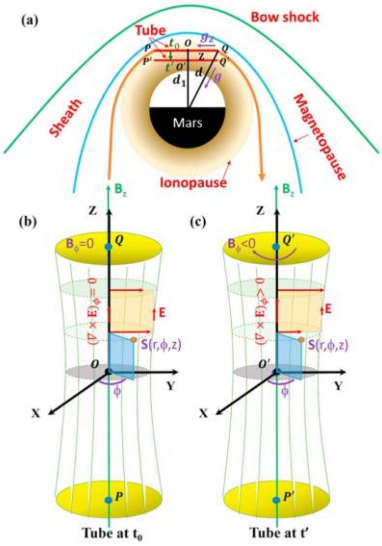

Figure 1. Schematic diagrams for the sinking and twisting of flux tube. (a) A global view of flux tube sinking, where the line segments of *AB* and *A'B'* representing the tubes at times t_0 and t', with midpoints of *O* and *O*', respectively. (b) The close view of the flux tube at t=0 with $(\nabla \times \boldsymbol{E})_\phi = 0$. (c) The $(\nabla \times \boldsymbol{E})_\phi$ can increase when the tube is sinking, which produces B_ϕ. The red arrows in (b) and (c) indicate the relative magnitudes (not scaled) of the electric fields.

We develop a multi-fluid MHD model to study the formation of MFR in the ionospheres of Mars and Venus. It is found that a straight flux tube can turn into a twisted MFR during its sinking into the lower ionosphere, caused by the differential compression at different parts of the tube (Figure 2). Further studies show that such a MFR is not force-free structure, in which there is always a pressure gradient force to balance the magnetic force. Moreover, we find that the ionospheric ions inside the MFR can be squeezed out from the two ends of the MFR, with an outflow flux of about 3.5×10^7 cm^{-2} s^{-1}, which can play an important role for the ion escape from the ionosphere. In addition, we find that both the sinking speed and the ratio of the ion gyroradius to the tube radius can affect characteristics of the MFR. A MFR can be more quickly formed for a larger sinking speed, but it can be also more quickly filled by the ambient ions. Oppositely, the MFR is more difficult to be filled when the ratio of the ion gyroradius to the tube radius is smaller. Once the MFR get filled, the compression is prevented by an outward pressure gradient force, and both the field strength and the rope helicity begin to decrease. Our results can explain the different altitude dependences of MFRs observed at Mars and Venus.

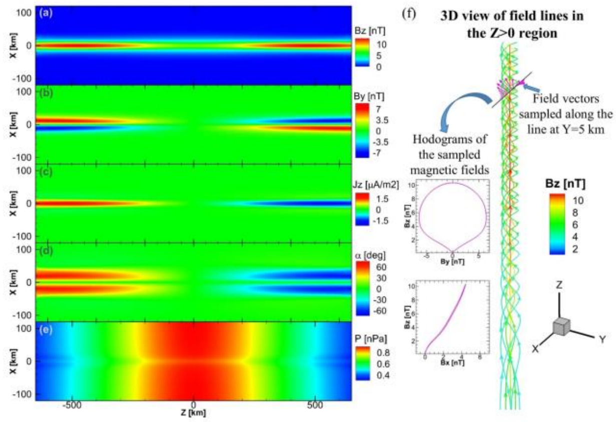

Figure 2. Simulation results of case 1 at t=1000 s. (a)-(e) show the results of *Bz, By,* α, *Jz*, and *P* in the y=0 plane, respectively, where is α the helical pitch angle defined as $\alpha = atan\frac{By}{Bz}$. (g) shows the three-dimensional view of magnetic field lines in z > 0 region, in which the different colors on the field lines represent the magnitude of *Bz*, the purple arrows indicate the field vectors sampled along the line in the z=600 km plane, with a distance of 5 km from tube axis, and the purple lines in the overlapped panels on the left indicate the hodograms of the sampled magnetic fields.

References

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Note: Abstract should be in (full) double-columned one page.