Two-stream plasma instability as a potential mechanism for particle escape from the Venusian ionosphere

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Abstract. In this work, we investigate the possibility of two-stream instability in the Venusian atmosphere leading to momentum transfer, then to the subsequent escape of hydrogen and oxygen ions from the ionosphere. We employ the hydrodynamic model and obtain the linear dispersion relation from which the two-stream instability is studied. Further, the interaction of solar wind with the ions of Venus ionosphere from which the instability sets in, has been studied using the data from ASPERA-4 of Venus express. The data support the fact that the two-stream instability can provide sufficient energy to accelerate ions to escape velocity of the planet and thus leave the Venusian ionosphere.

Keywords. Two-stream instability; linear dispersion; solar wind; hydrodynamic model; Venus express; ASPERA-4.

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1. Introduction

Planets that have strong magnetic fields in their interior region, like Earth, Jupiter, Saturn and Mercury, are enclosed by invisible magnetosphere \cite{1}. The charged particles of the solar wind radiation (electrons and protons) are deflected by their magnetic fields as they stream far away from the Sun. This deflection by the magnetic field creates a magnetic sphere that acts as a protective ‘bubble’ covering the planet \cite{2}. Venus has no intrinsic magnetic field to act as protection against the incoming stream of charged particles. However, the solar wind and UV radiation from the Sun pull out electrons from the atoms and molecules in the higher atmosphere, making a section of electrically charged gas referred to as the ionosphere. The planet is protected partially by the induced magnetic force field due to this ionosphere. But this induced magnetic field is very small in magnitude and not sufficient to deflect the solar wind unlike other planets. Thus, the electrons in the solar wind end up directly interacting with the higher atmosphere. We have suggested a likely ion escape route resulting from the instability under some physical conditions. We have used analytical and simulation tools and their outcomes, which depend on the occurrences of the ionisation processes, as well as solar wind conditions. Newborn ions are at rest relative to the Venus frame. From previous studies \cite{3,4} we can observe that ion acceleration on Venus can occur through three mechanisms: \(a\) ion uptake (through acceleration in a convective electric field), \(b\) through induced instabilities in the ionosphere and lastly \(c\) through polarisation electrical fields at low altitude on the night side of the Venusian ionosphere. We are going to explore the second mechanism of ion acceleration in this paper.

This paper explores the possibility of two-stream instability to cause ions to escape from the atmosphere of Venus. It has been observed that the critical condition under which the instability can occur for the classical regime plays a major role in particle energisation. The following is the outline of the paper. We discuss the fluid model of Venusian plasma in \S 2, the dispersion relation has been obtained in \S 3, \S 4 finally describes the possible ion escape mechanisms via two-stream instability by analysing the Venus express data.
2. Fluid model of the Venusian ionosphere

In 1937, Jeffreys [5] was the first to build the model of Venus from Bullens’ model [6] of the Earth. In 1983, Zharkov [7] provided a complete model of Venus. Venus has an extremely low magnetic field. So planetary magnetosphere is less important in this case. A magnetospheric plasma shell which exists around some planets have been investigated by many [8–14] but not with respect to Venus. We have considered a homogeneous plasma [15,16] comprised of electrons and ions. The basic governing equations for the fluid model [17–27] are as follows [28–32]:

\[ \frac{\partial n_j}{\partial t} + \nabla \cdot (n_j v_j) = 0 \]  
\[ \frac{\partial v_j}{\partial t} + v_j \cdot \nabla v_j = -\frac{Q_j}{m_j} (\nabla \phi - v_j \times B) - \frac{1}{m_j n_j} \nabla P_j \]  
\[ \nabla \times E = -\frac{\partial B}{\partial t}. \] (1-3)

The terms on the right side of eq. (2) denote Lorentz force and stress term [33]. Let us assume that the equation of state [28] is given by

\[ P_{j0} = n_{j0} k_B T, \]  
where \( n_j \) signifies the number density, \( v_j \) represents the fluid velocity, \( p_j \) indicates the pressure, \( m_j \) represents the mass, \( E \) and \( B \) represent the electric and magnetic fields, respectively and \( k_B \) is the Boltzmann constant.

3. Dispersion relation

As the solar wind flows freely into the Venusian atmosphere, it excites the neutral particles to form ions. This constitutes the plasma of the ionosphere. The resulting magnetic field has a very low value unlike the intrinsic magnetic fields of planets like, Earth, Jupiter, etc. The electrons in the solar wind stream into the stationary ions of the ionosphere. This relative motion between the ions and fast moving electrons causes the so-called two-stream instability. Two-stream instability can be discussed based on the consideration of electron–ion streams having densities \( n_e, n_i \) and temperatures \( T_e, T_i \) with the velocities \( v_e, v_i \). The electron and ion thermal velocities are \( v_{T,e}, v_{T,i} \), respectively. We further investigate whether the aforesaid situation is relevant for Venussian ionosphere or not. Here, \( \omega_{pi} \) and \( \omega_{pe} \) represent the plasma frequency with which ions and electrons oscillate, respectively. We get the dispersion as follows:

\[ 1 - \frac{\omega_{pe}^2/4}{(\omega - kv_e)^2 - k^2 v_{T,e}^2/2} - \frac{\omega_{pi}^2/4}{(\omega - kv_i)^2 - k^2 v_{T,i}^2/2} = 0, \]  
where \( v_{T,e} = \sqrt{2T_e/m_e} \) and \( v_{T,i} = \sqrt{2T_i/m_i} \) are the thermal speed of electrons and ions, respectively [28].

The condition for instability, \( \mathcal{F}(\omega) > 0 \) is given by

\[ \mathcal{F}(\omega) = \frac{\omega_{pe}^2/4}{(\omega - kv_e)^2 - k^2 v_{T,e}^2/2} + \frac{\omega_{pi}^2/4}{(\omega - kv_i)^2 - k^2 v_{T,i}^2/2}. \]  

For the extremum point we have,

\[ \xi = [q + \{(q^2 + (r - p^2)^3/2)^{1/2}\}]^{1/3} + [q - \{(q^2 + (r - p^2)^3/2)^{1/2}\}]^{1/3} + p, \]

where

\[ \alpha = \frac{\omega_{pi}^2}{\omega_{pe}^2}, \xi = \frac{\omega}{kv}, p = \frac{2\alpha^2}{3(1 + \alpha^2)}, \]

\[ q = \frac{[(-2\alpha^2)(\alpha^2 - 1 - (1 + \alpha^2)\frac{v_0^2}{2v_e^2}) - 3(1 + \alpha^2)\frac{v_0^2}{2v_e^2}]}{6(1 + \alpha^2)^2}, \]

\[ r = \frac{\alpha^2 - 1 - (1 + \alpha^2)\frac{v_0^2}{2v_e^2}}{3(1 + \alpha^2)} \]

and \( v_0 \) is the speed at thermal equilibrium. Now at that point,

\[ \omega = \omega_s = kv_e [q + \{(q^2 + (r - p^2)^3/2)^{1/2}\}]^{1/3} + kv_e [q - \{(q^2 + (r - p^2)^3/2)^{1/2}\}]^{1/3} + pkv_e. \]

The condition for instability, \( \mathcal{F}(\omega_s) > 1 \).

If the above obtained value for \( \omega_s \) is substituted in the expression for \( \mathcal{F}(\omega) \) and is equated to 1, then by a small algebraic manipulation, \( v_e \) will be determined.
We define this electron velocity satisfying the instability condition to be the threshold velocity ($v_{th}$).

$$v_{th} \equiv v = \frac{\omega_{pe}}{k} \left[ 1 + \left( \frac{m_e^{1/3}}{m_p} \right)^{3/2} \right]. \quad (9)$$

Any relative electron velocity greater than this threshold velocity will make the system unstable and the resultant instability might accelerate the ions to escape velocity. A detailed discussion on this is done in the subsequent sections.

4. Discussion

The particles have a speed nearly equal to the phase speed with which plasma waves can supply the energy necessary for escape. A probable process for coupling of collisionless momentum between the plasmas which are interpenetrating with each other at the blocking layer might result in a stream of electrons causing streaming instability.

4.1 Analysis with particle in a cell (PIC) simulation

In this system, electrons got accelerated by the electric field in the vicinity of the particle following the Poisson equation,

$$\frac{d^2 \phi(x_j)}{dx^2} \approx \frac{\phi_{j+1} + \phi_{j-1} - 2\phi_j}{(\Delta x)^2}.$$

Using the above equation, we looked for the potential at each point in the mesh. We assumed a periodic sinusoidal boundary condition and interpolated from adjacent grid points $j$ and $j+1$. Using the leap-frog integration method, we calculated the velocity and position at each time step.

4.1.1 Simulation parameters. The parameter values for our configurations are as follows: the PIC algorithm was simulated with 40,000 particles ($N$) and 400 mesh cells. The growth of instability was measured with a time step $(dt)$ of 1 s from $t = 1$ to 50. To construct the matrix for the gradient operator for computing the first derivative, we used the minimum separation $\Delta x = 0.125$. We have used these values to calculate the initial gravitational accelerations of electrons. Next we constructed two oppositely moving streams adding periodic perturbation with the amplitude of sinusoidal function around 0.1. The initial relative velocity is taken as 4.5 km/s.

4.1.2 Initial conditions. In our code, we implemented two uniform counter-propagating streams travelling initially ($t = 0$). The orientations of the particles are chosen randomly with a uniform distribution. The velocities are measured using a Gaussian centred distribution about the rate of streams. A tiny perturbation in periodic form (sinusoidal function) is applied to the velocity distribution. We simulated with a large number of particles (around 40,000 particles) in phase space.

4.1.3 Emergent phase space. Let us now discuss how the ions get energised by interpenetrating the flow of particles. A prevalent electric field, which is not stable, links the two streams. The energy from the strongly interacting streams is transferred to the driven electric field. The streams mix as the destabilising electric field increases, ultimately destroying the streams or dispersing the particles in phase space. As the acceleration of the streams grows, the instability tends to increase, potentially causing the streams to become more turbulent. Several electrons have been ascertained moving at a faster rate than their initial velocity due to a boost in energy from the wave, continuing to increase their velocity at the outlay of the wave energy, leading to a reduction in wave velocity. The energy due to the electric field increases as the stream velocity increases. The energy of the particles increases as the density of the streaming particles increases, however, at different rates, indicating that the streaming particles become thermalised across the simulation, causing the plasma to become much more intense.

To analyse the distribution of variables like density, temperature, velocity, etc., the data should be organised according to the occurrence of different results in each category. We have carried out a PIC simulation which is depicted in figures 1 and 2 and the procedure has been discussed in the Appendix. Plasma waves are formed by the free energy imparted to the system by the inward streaming solar wind electrons, and due to this, particles start disappearing from the simulation box. Thereafter, a particle-starved region in phase space emerges. The relatively moving particles pile over each other. Both components exist side by side to the right, form a distribution of particles that is unstable for the aforesaid instability under the condition that threshold velocity is much lower than relative velocity. The instability due to relative propagating particles in the inhomogeneous plasma becomes saturated, generating phase-space-starved pockets as particles are trapped by an increasingly unstable mode [37]. In the phase-space simulation, the process takes place spatially and temporally as well. We investigated the efficiency of the emerging two-stream instability of interacting solar wind ions with Venusian ionospheric plasma. The conservation of streaming energy for this case using the Poisson equation is obeyed. For the time-scale $t = 0$ to 50 s, the growth of two-stream
instability has been checked for different initial conditions such as relative velocities and densities to study the regions where the energy conservation is obeyed. We have checked the energy conservation with relative velocity, 4.5 km/s and density around 4 cm$^{-3}$. We have checked the ratio of energy of electrons to the initial energy with time scale ($t$). Initially, the energy is zero. Then, instability sets in and the energy increases. Eventually, the system comes to a dynamic equilibrium at a time-scale, $t \approx 30$ s, and the energy becomes constant at around 2.14 eV. When the accelerated stream of particles interacts with the stationary component of the electrons which were reflected further, a phase-space trench forms towards the left of the box. It has been found that an electron-depleted region drifts away from the centre of the phase space with increasing time.

We have considered two situations here: one is when the velocity of the threshold is lower than the relative velocity, and the other is when the velocity of the threshold is higher than the relative velocity. At first, all particles are able to flow smoothly. Figure 1 shows the growth of vortex-like instabilities in phase space at two different times. When the threshold velocity is much lower than relative velocity, all electrons become kinetic. Electrons subject to strong acceleration become kinetic. On the other hand, figure 2 shows that the threshold velocity is larger than the relative velocity. Then, instability does not arise. Now, we have already discussed that the threshold for instability, $\mathcal{F}(\omega_k) > 1$. We have used the data of the ionosphere of Venus. As we have seen, two-stream instability is not seen everywhere in the ionosphere. There are some specific regions where the particles are able to get energy from such instability. In the next part of our study we have focussed on that regions where ion-loss occurs. Our study concentrates in that velocity regime where two-stream instability leads to a strong acceleration of planetary ions which are very energetic in the range of suprathermal energies [38]. Some newer simulation studies based on homotopy [39–43] can provide some additional information.

4.2 Morphology of ion escape process

In different regions of the ionosphere, the average energies of the ions are different corresponding to different fluxes of particle escape.
Table 1. Parameters for the instability and the ion energisation.

| Parameter                           | Notation | Value |
|-------------------------------------|----------|-------|
| Density of SW                       | $n_{\text{SW}}$ | 5 cm$^{-3}$ |
| Velocity of SW                      | $v_{\text{SW}}$ | 350 km/s |
| Temperature of SW electrons         | $T_e$    | 27 eV  |
| Thermal velocity of electrons       | $v_{\text{th},e}$ | 2500 km/s |
| Planetary ion temperature           | $T_{\text{ion}}$ | 0.3–0.4 eV |
| Electron plasma frequency           | $f_e$    | 9 kHz  |
| Surface gravity of Venus            | $g_v$    | 8.88 m/s$^2$ |

4.3 A possible way of the particle escape process

A simple estimation of the flux escaping from Venus caused by the solar wind stands on momentum conservation. It has been found that ions like $\text{O}^+$ which are comparatively heavier than $\text{H}^+$ ions remain uninfluenced by the magnetic field. This causes an electric field to appear that extracts and also accelerates planetary ions like $\text{H}^+$, $\text{O}^+$ to reach quasineutrality condition [49]. A cross-sectional view of flux measurement of ions like oxygen and hydrogen in the Venusian magnetotail region in ‘Venus-Solar-Electric coordinate system’ [50] is shown in figure 4. The vertical red arrow defines the electric field.

Density over magnetic field distribution is shown in figure 5. Higher density is experienced slightly by the induced magnetic field. The thermal leakage of lighter ions, mostly $\text{H}^+$ ions, is quite dominant in Venus [51]. On other hand, heavier atoms like oxygen ($\text{O}^+$) follow the mechanism

$$ \text{O}_2^+ + e^- \rightarrow \text{O}^*(\text{normal}) + \text{O}^*(\text{energetic}) $$

and energy is supplied by two-stream instability for escape. Our investigation therefore can only explain ion-loss within the energy range 10 to 100 eV.

Hartle and Grabowsky [52,53] have shown that the lighter ion streams in the Venus ionospheric zone are caused by the magnetic and the electrical pressure gradients given by

$$ qn_e E = -\nabla P_e - \nabla B_z^2 / 2\mu_0, $$

We see that planetary protons or lighter ions ($\text{H}^+$) move quite faster than the comparably heavier ions ($\text{O}^+$) which are still much slower than ions in the solar wind flow. Bulk speeds of oxygen and hydrogen ions are grouped around, $V_{\text{O}^+} = V_{\text{H}^+} \times \sqrt{m_{\text{H}^+} / m_{\text{O}^+}}$ implying the relation between the possible velocities of escape for particles with approximately the same energy. It may be concluded that though subject to different electric fields, the ion’s energy gain of similar order is obtained through the exchange of momentum [55]. The relative velocity regime associated with our simulation strictly relates to the flux map in figure 4. This shows a correspondence between simulation and particle escape scenarios.
Figure 4. Measured flux map of (a) O$^+$, (b) H$^+$ fluxes within the magnetotail area of Venus (obtained by Barabash et al) [54] in 'Venus-solar-electrical coordinate' [50]. Colour map indicates the energy (eV) and dots are flux (cm$^{-2}$s$^{-1}$).

Figure 5. Density of oxygen-like heavy ions over the z-component of the magnetic field plot and heat map for Venus plasma ionosphere.

The flux map showing the sky blue bubbles in figure 4 (10$^1$–10$^2$ eV), are the regions where the instability is dominating. In these regions, our PIC code forms the instability. The particles can be out of the ionosphere of the planet if the ion velocity is greater than the escape velocity. Using the condition $\mathcal{F}(\omega_i) > 1$ we obtained the threshold velocity as

\[ v_{th} \equiv v = \frac{\omega_{pe}}{k} \left[ 1 + \left( \frac{m_e}{m_p} \right)^{1/3} \right]^{3/2}. \]  

From this, the threshold energy ($E_{th}$) comes out to be about 5.0661 eV and the extra energy due to instability which is about 2.138 eV. The escape energy of oxygen ions is nearly 8.7 eV. From the cross-sectional view, the energy of oxygen ions ranges from 10 to 100 eV, and the excess energy can be estimated using the threshold. We got extra energy of about 2 to 4 eV, which is enough for the ions to escape from the ionosphere.

So, the fundamental problem of depletion of the hydrogen and oxygen ions from the atmosphere can be directly related to the energisation of ions through two-stream instability induced by the solar wind. The streaming instability energises the ions, pushing them to velocities higher than the escape velocity, causing the loss of planetary ions.

Interestingly, the rate of escape of the ions in the Venustian ionosphere, estimated by the various researchers [56–58] based on the observations by ASPERA-4 and in distinct energy spectra are quite similar in their form and is in tune with the present investigation. It may be also possible that some shock like nonlinear resonant mechanisms can accelerate the process [30,59–62]. In this respect, some recent works can provide some insights [63,64].

Appendix

We have designed a particle-in-cell (PIC) simulation figure (figure 1) to demonstrate the phase-space mechanism and two-stream instability. We have framed a python code to simulate the instability. At the beginning, we calculated the acceleration on each particle due to the field, then computed the electron number density on the mesh by placing the particles into the two nearest bins ($j$ and $j + 1$, with proper weights) and then
normalised them. Next, we applied a periodic boundary condition on them following which we solved the Poisson equation and applied derivative to get the electric field and interpolated the grid value onto the locations of the particle. Afterwards, we run our defined functions in the main PIC simulation function with appropriate parameter values. They are constructed by two matrices to computer gradient and Laplacian for the field quantities. Finally, simulating in the main loop with drift (and applying some periodic boundary conditions), we obtained the two-stream instability in phase space. Such instabilities can be explained elaborately in the light of studies carried out by some researchers [65–69] using dynamical systems [70–74]. In figure 4, flux map has been shown in ‘Venus solar electrical coordinate’ using python and this has been motivated by Barabash et al [54]. Density map (figure 5) of hydrogen and oxygen is plotted first and then smoothen using the sigmas in python numerically.

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