Electrostatic Waves in the Venusian Ionosphere

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Tanta University.

Outline

- **Background**

  - **(1) Effect of Solar wind and Venus streaming velocity on the phase velocity and instability of two-dimensional IAWs in the lower Venusian ionosphere**

- **(2) Agreement Between Observations and Theoretical for IAWS in the Lower Venusian Ionosphere**

- **Conclusion**

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Background (Plasma)

- **Plasma** is a state of matter where gases become ionized. Under certain conditions, such as **quasi-neutrality**, **collective behavior of charged particles**, and a **high plasma frequency** compared to the collision frequency, the ionized gas is called **plasma**, resulting in a mixture of free electrons, ions, and sometimes dust particles that depend on experiment or observation.
- **Plasma Environment**: It consists of multiple frames, each representing a specific location within a certain time, with its own components and behaviors.

Background (Plasma)

- **Plasma Frame** $\longrightarrow$ (Response of Modes to Perturbation):
  - **Linear Response**
  - **Non-linear Response**
- **Linear Response (Modes Response)** can be:
  - **stable modes**
  - **non-stable modes (instability)**
- **Wave Classification in Plasma:**
  - **Electrostatic Waves**: $\overline{B} = 0$
    - Langmuir waves (electron plasma waves)
    - Ion acoustic waves (IAWs)
  - **Electromagnetic Waves**: $\overline{B} \neq 0$
    - Alfvén waves
    - Whistler waves
    - Electromagnetic ion-cyclotron waves

Background (Venus)

Venus is the second planet in the solar system, seen from the Sun.

Venus to the sun 0.723 Astronomical Unit (AU) (Yadav [2021]).

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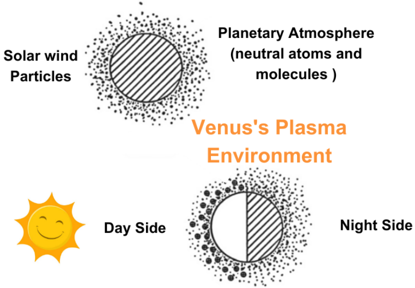

Figure: Schematic of Venus's plasma environment showing solar wind interaction with the planetary atmosphere and the day and night sides of Venus's plasma environment.

Background (Venus)

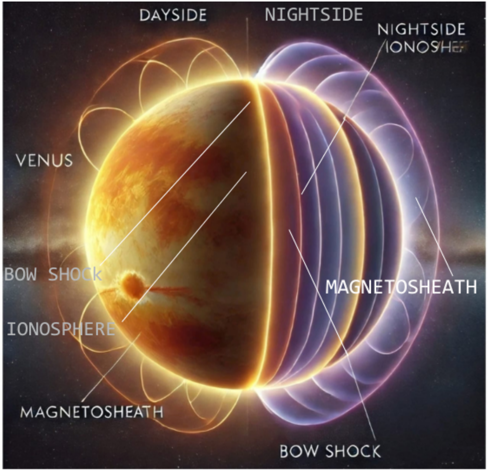

Figure: Schematic of Venus's plasma environment, highlighting the bow shock, magnetosheath, ionosphere in the planet's dayside and nightside regions.

Background (Venus)

Space missions to Venus (Yadav [2021]).

- Short-term missions to Venus.
- Long-term missions to Venus:
  - Pioneer Venus Orbiter (**PVO**, 1978–1992):
    - Temperature Ratio of ion to electron= 0.1 to 0.2.
    - Among its observations: ion acoustic waves at frequencies of approximately 730 Hz and 5.4 kHz.
  - Venus Express (**VEX**, 2006 - 2014):
    collect Venusian Ionosphere Data (Density and Velocity Profiles).

Background (Venus)

Density and velocity profiles are adopted from Ref. (Lundin et al. [2011]).

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Ion flow and momentum transfer in the Venus plasma environ

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Background (Venus)

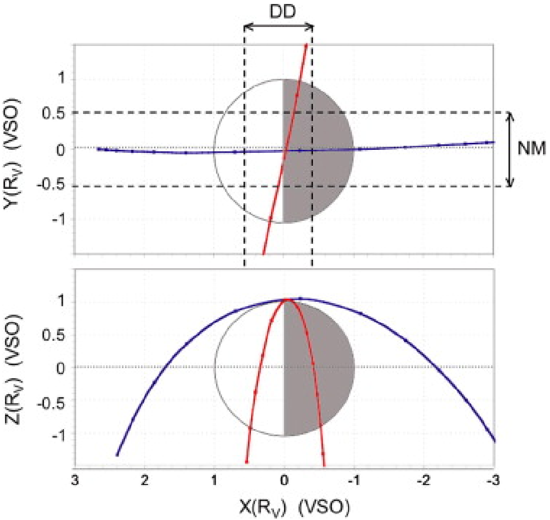


Figure: Two mederians of VEX were adopted from Ref. (Lundin et al. [2011]).

Background (Venus)

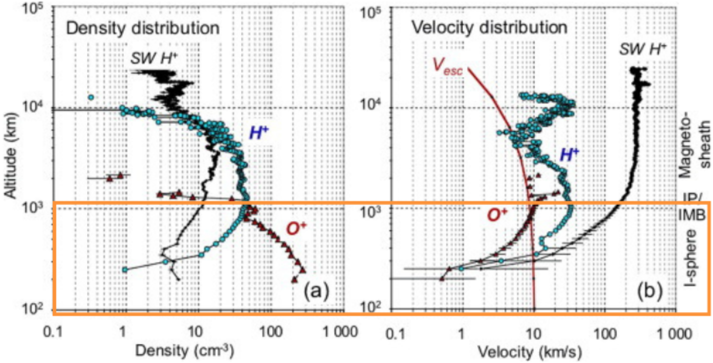
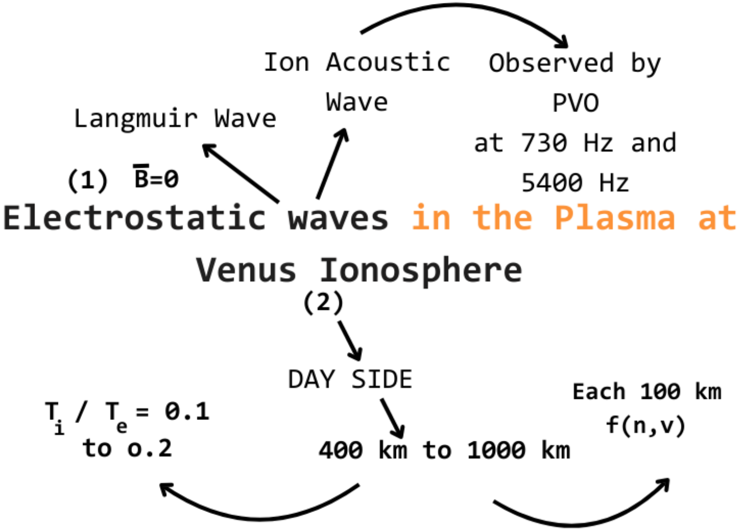


Figure: Dawn-Dusk Medirian Density and Velocity Profile Data adapted from Ref. (Lundin et al. [2011]).

Title Structure



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(1) Effect of Solar wind and Venus streaming velocity...

Ionosphere Characteristics

Component:

- ew^- solar wind electron
- Hw^+ solar wind hydrogen
- e^- Venusian electrons
- H^+ Venusian hydrogen ion
- O^+ Venusian oxygen ion

Behaviour(Conditions):

- Equilibrium, Homogeneous, Collision-less, Isothermal, and Streaming Fluid Component.
- unperturbed streaming fluid component in (x) direction and perturbed streaming fluid component in (x and y plane).

Normalized basic equation

Suppose: solar wind electrons create perturbation and observed linear modes from the frame scale of O^+.

(1) Continuity eq

$$\frac{\partial \overline{n}_j}{\partial \overline{t}} + \frac{\partial(\overline{n}_j \overline{V}_{jx})}{\partial \overline{x}} + \frac{\partial(\overline{n}_j \overline{V}_{jy})}{\partial \overline{y}} = 0. \tag{2.1}$$

(2) Momentum eq in x-direction

$$\left(\frac{\partial}{\partial \overline{t}} + \overline{V}_{jx}\frac{\partial}{\partial \overline{x}} + \overline{V}_{jy}\frac{\partial}{\partial \overline{y}}\right)\overline{V}_{jx} + q_j Q_j \left(\frac{\partial \overline{\phi}}{\partial \overline{x}}\right) + \frac{\sigma_j Q_j}{\overline{n_j}}\left(\frac{\partial \overline{n}_j}{\partial \overline{x}}\right) = 0. \tag{2.2}$$

Normalized basic equations

(3) Momentum eq in y-direction

$$\left(\frac{\partial}{\partial \overline{t}} + \overline{V}_{jx}\frac{\partial}{\partial \overline{x}} + \overline{V}_{jy}\frac{\partial}{\partial \overline{y}}\right)\overline{V}_{jy} + q_j Q_j \left(\frac{\partial \overline{\phi}}{\partial \overline{y}}\right) + \frac{\sigma_j Q_j}{\overline{n_j}}\left(\frac{\partial \overline{n}_j}{\partial \overline{y}}\right) = 0. \quad (2.3)$$

(4) Poisson equation that closed the system of Eqs.(2.1) - (2.3) is

$$\left(\frac{\partial^2}{\partial \overline{x}^2} + \frac{\partial^2}{\partial \overline{y}^2}\right)\overline{\phi} = \alpha n_e + \beta n_{ew} - \gamma n_H - n_O - \delta n_{Hw}. \quad (2.4)$$

(1) Effect of Solar wind and Venus streaming velocity...

Normalized basic equations terms

- $j = H^+, O^+, e^-, Hw^+$ and ew^-
- $q_j = +$ for H^+, O^+, Hw^+ and $q_j = -$ for e^-, ew^-
- $\overline{n}_j = n_j / n_j^{(0)}$
- $\overline{V}_{jx}, \overline{V}_{jy} = V_{jx}/C_s, V_{jy}/C_s,$
  $C_s = (k_B T_{ew}/m_o)^{1/2}$
- $Q_j = m_O / m_j$
- $\sigma_j = T_j / T_{ew}$
- $\overline{t} = t\omega_{PO}$, $\omega_{PO} = (e^2 n_O^{(0)}/\epsilon_0 m_O)^{1/2}$.

Normalized basic equations terms

- $\bar{x}, \bar{y} = x/\lambda_{DO}, y/\lambda_{DO}$,
  $\lambda_{DO} = (\epsilon_0 k_B T_{ew}/e^2 n_O^{(0)})^{1/2}$.
- $\alpha = n_e^{(0)}/n_O^{(0)}$
- $\beta = n_{ew}^{(0)}/n_O^{(0)}$
- $\gamma = n_H^{(0)}/n_O^{(0)}$
- $\delta = n_{Hw}^{(0)}/n_O^{(0)}$
- $\bar{\phi}$ is normalised by the thermal potential $k_B T_{ew}/e$

Linear analysis

A small perturbation during streaming species j in the same moving direction:

$$
\begin{aligned}
\overline{n}_j &= 1 + n'_j \exp i(k_x x + k_y y - \omega t), \\
\overline{V}_{jx} &= V_{jx}^{(0)} + V'_{jx} \exp i(k_x x + k_y y - \omega t), \\
\overline{V}_{jy} &= V'_{jy} \exp i(k_x x + k_y y - \omega t), \\
\overline{\phi} &= \phi^{(0)} + \phi' \exp i(k_x x + k_y y - \omega t).
\end{aligned} \tag{2.5}
$$

- ω is normalized wave frequency.
- k_x and k_y are normalised wavenumber in (x and y) plane.
- $k_x = k\cos\theta$ and $k_y = k\sin\theta$ satisfy $k_x^2 + k_y^2 = 1$, k is a wave number.
- $\phi^{(0)}$ is normalized unperturbed potential of the system, homogeneity of the system leads to $\frac{\partial\phi^{(0)}}{\partial x} = 0$ and $\frac{\partial^2\phi^{(0)}}{\partial x^2} = 0$.
- $V_{jx}^{(0)}$ is normalised unperturbed velocity in x direction by oxygen ion acoustic speed C_s, $C_s = (k_B T_{ew}/m_o)^{1/2}$.
- The quantities n_j', V_{jx}', V_{jy}', and ϕ' are a small perturbation in the dependent plasma parameters.

(1) Effect of Solar wind and Venus streaming velocity...

Dispersion Relation:

$$
\begin{aligned}
1 &- \frac{\alpha Q_e}{(\omega - k\cos\theta V_{ex}^{(0)})^2 - \sigma_e Q_e} \\
&- \frac{\gamma Q_H}{(\omega - k\cos\theta V_{Hx}^{(0)})^2 - \sigma_H Q_H} \\
&- \frac{1}{(\omega - k\cos\theta V_{Ox}^{(0)})^2 - \sigma_O} \\
&- \frac{\beta Q_{ew}}{(\omega - k\cos\theta V_{ewx}^{(0)})^2 - Q_{ew}} \\
&- \frac{\delta Q_{Hw}}{(\omega - k\cos\theta V_{Hwx}^{(0)})^2 - \sigma_{Hw} Q_{Hw}} = 0.
\end{aligned}
\tag{2.6}
$$

Results and Discussion

By solving Eq. (2.6), we obtain the normalized phase velocity:

$$\overline{V_{ph}} = \frac{\omega}{k}, k = 1.$$

To compare this with observational velocity and escape velocity, we determine the specific angle at which these velocities match (Lundin et al. [2011]). The normalized phase velocity $\overline{V_{ph}}$ is de-normalized using the oxygen acoustic speed c_s, following:

$$V_{ph} = \overline{V_{ph}} c_s.$$

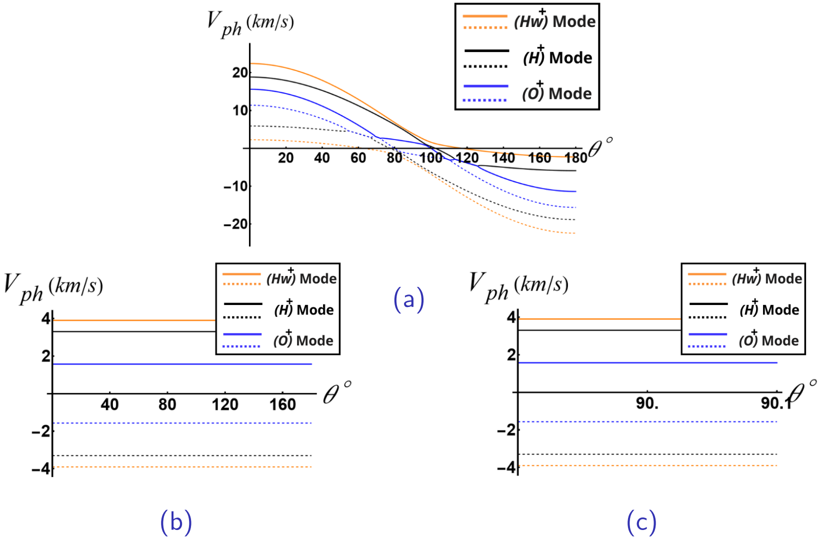
where V_{ph} represents the phase speed velocity in units of km/s.

(1) Effect of Solar wind and Venus streaming velocity...

Physical Plasma Parameters	
$\alpha = 1.072$	$\gamma = 0.072$
$\beta = \delta = 0.017$	$V_O^{(0)} = 1.7706$
$\sigma_{Hw} = \sigma_H = \sigma_O = 0.13$	$\sigma_e = 1$
$Q_e = Q_{ew} = 29194.5$	$Q_H = Q_{Hw} = 16$
$V_H^{(0)} = 6.58147$	$V_{Hw}^{(0)} = 8.26087$
$V_e^{(0)} = 9.8722$	$V_{ew}^{(0)} = 12.391305$

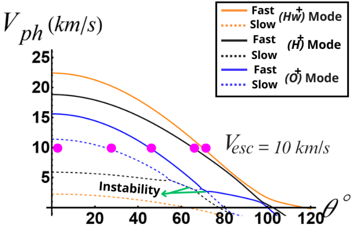
Table: physical plasma parameters to describe this model for lower ionosphere at altitude 300 km to 400 km, $C_s = 2.3$ km/s (Fayad et al. [2021]).

(1) Effect of Solar wind and Venus streaming velocity...



Figure

(1) Effect of Solar wind and Venus streaming velocity...



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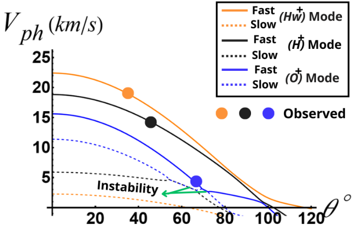

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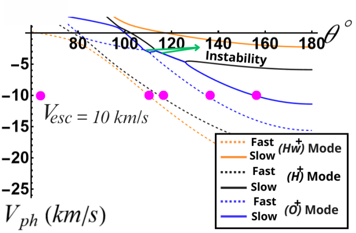

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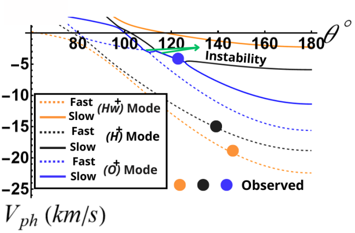

(d)

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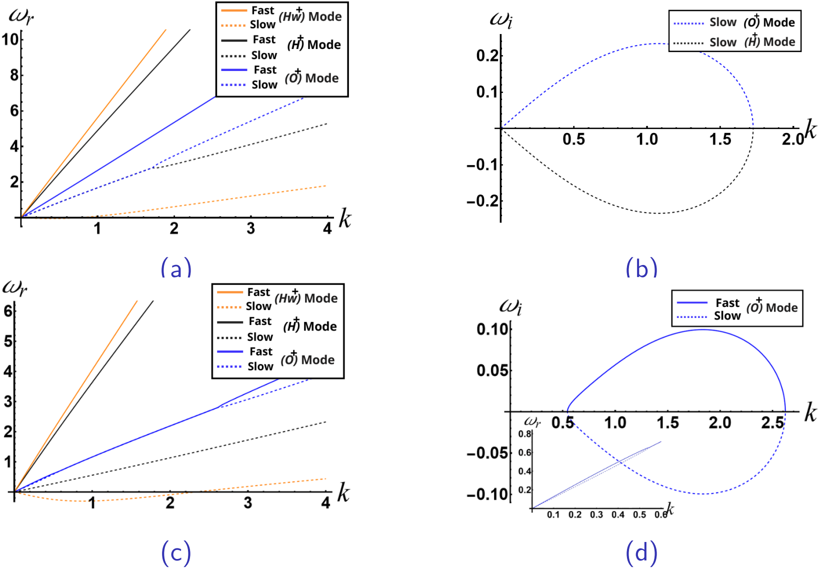

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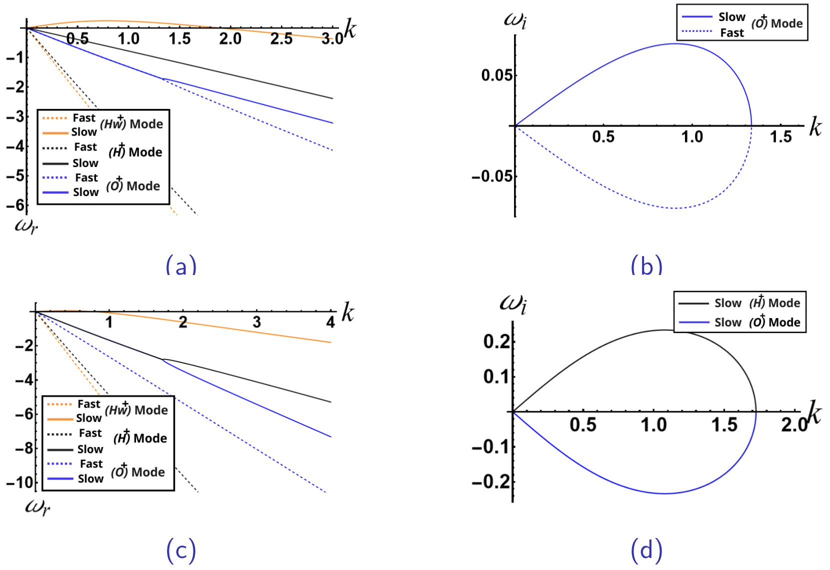

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Ionosphere Characteristics

Component	Behavior (Conditions)
H^{+} Venusian hydrogen ion	Equilibrium
O^{+} Venusian oxygen ion	Homogeneous
e^{-} Venusian electrons	Collision-less
	Isothermal fluid component
	Streaming fluid component

By the same way: Normalized Basic Equations

Suppose: electrons create perturbation and observed linear modes from the frame scale of O^+.

Dispersion Relation

$$1-\frac{\alpha Q_e}{(\omega-kV_e^{(0)})^2-k^2Q_e}-\frac{\gamma Q_H}{(\omega-kV_H^{(0)})^2-\sigma_H k^2 Q_H}-\frac{1}{(\omega-kV_O^{(0)})^2-\sigma_O k^2}=0. \tag{3.1}$$

- α and γ are the ratios between the unperturbed background e^- and H^+ densities -to- the unperturbed O^+ density.
- $V_j^{(0)}$ is unperturbed species j velocity normalized to oxygen ion acoustic speed $C_s = (k_B T_e/m_O)^{1/2}$.
- V_j is normalized velocities by oxygen ion acoustic speed $C_s = (k_B T_e/m_O)^{1/2}$.
- $Q_j = m_O/m_j$ is the mass ratio of oxygen ions -to- species j.
- $\sigma_j = T_j/T_e$ is the temperature ratio of species j -to- electrons.
- ω and K are normalized wave frequency and normalized wavenumber, respectively.

Results and discussion

By solving Eq. (3.1), we obtain:

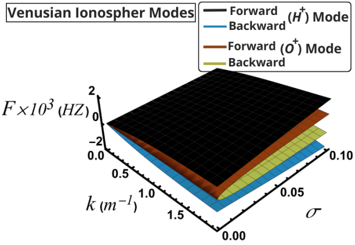
Frequency:

$$F = \frac{\omega \omega_{po}}{2\pi}, \omega_{po} = \sqrt{\frac{n_e^{(0)} e^2}{\epsilon_0 m_e}}.$$

- Phase Velocity:

$$V_{ph} = \frac{\omega}{K} C_s.$$

(2) Agreement Between Observations and Theoretical...



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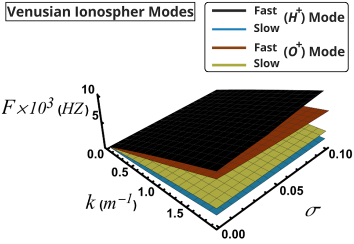

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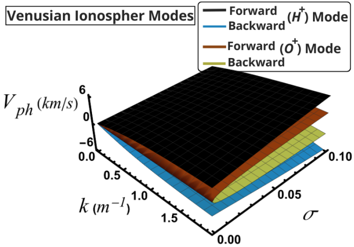

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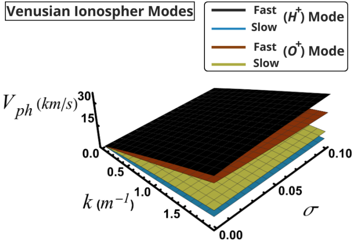

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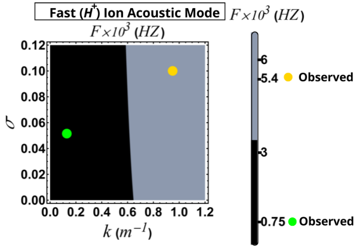

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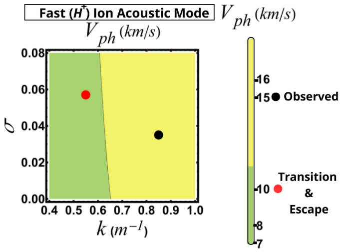

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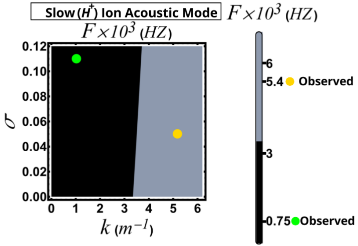

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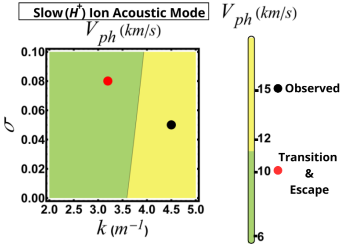

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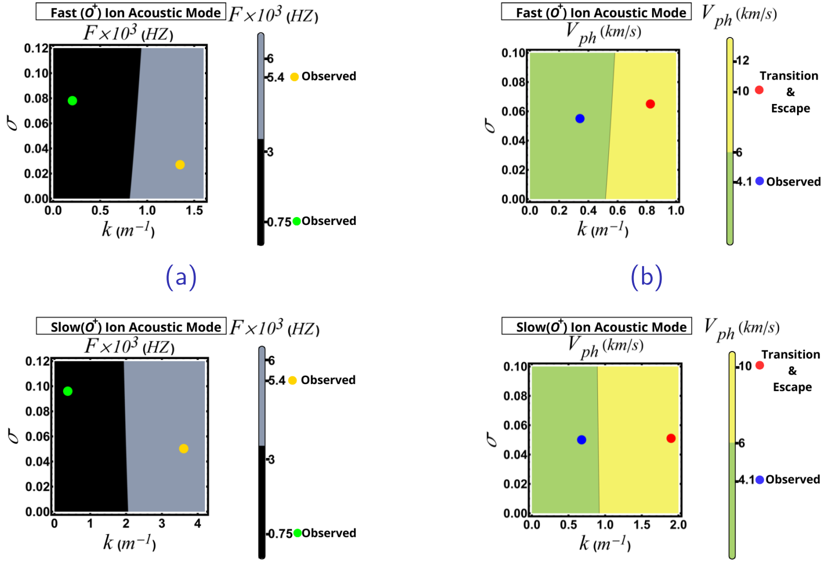

(a) (b) (c) (d)

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Conclusion

- (1) Analyze the dispersion and stability of ion-acoustic modes in the lower Venusian ionosphere, incorporating the effects of streaming velocity and solar wind interactions. Phase velocity strongly depends on wave propagation angles, with fast modes surpassing the critical escape velocity and slow modes mostly confined, except for the slow O^+ mode at specific angles. Additionally, instability regions arise due to mode coupling effects between two ion-acoustic modes, leading to distinct threshold angles for wave escape.

Conclusion

- (2) Analyze the dispersion and evaluate the agreement between the observed and theoretical frequencies and velocities for the Fast and Slow H^+ and O^+ Ion Acoustic Modes at specific values of k and σ. Additionally, determine the critical values of k and σ for each mode, corresponding to their escape and transition from the Venusian ionosphere.

Thank You
Open Questions!

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