Ion acoustic waves associated with interplanetary shocks

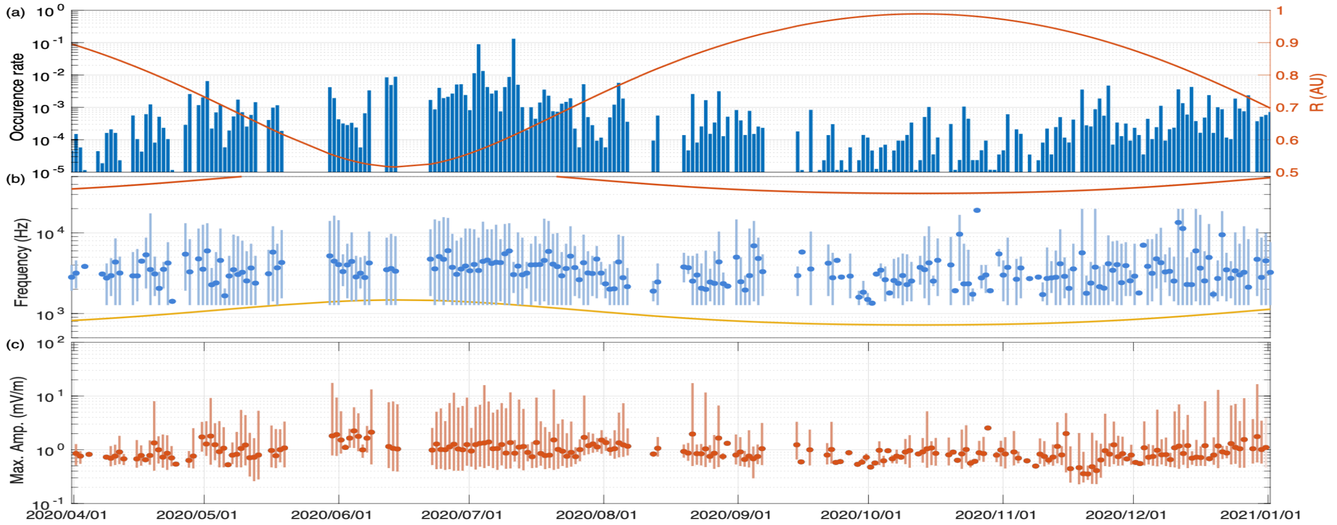
Jordi Boldu, Daniel Graham, Michiko Morooka, Mats André, Yuri Khotyaintsev, Andrew Dimmock, Jan Soucek, David Pisa, Milan Maksimovic

Motivation

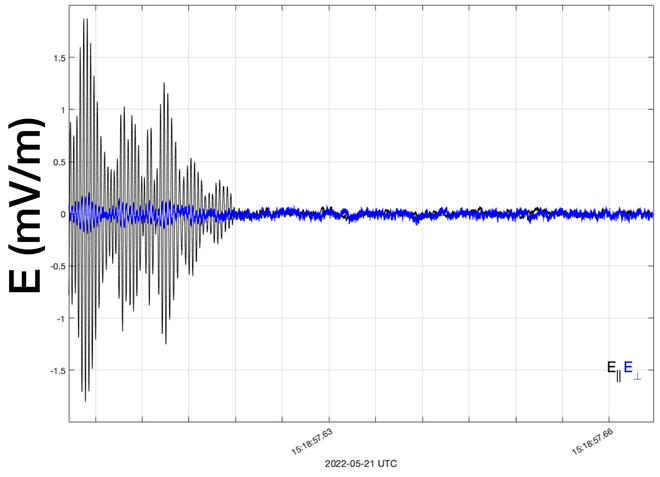
- Through wave-particle interactions, IAWs can play an important role in the energy dissipation required in interplanetary shocks.
- There is an enhancement of ion-acoustic waves (IAW) occurrence rate in the vicinity of interplanetary (IP) shocks. (Hess1998,Wilson2007).
- The enhancement in IAW activity can often be observed very far from the IP shock ramp, however, it is not clear how far an IP shock can influence the excitation of IAW.
- Even if the shock is responsible for the waves, it is not clear how the shock parameters (Mach no., shock normal angle, etc.) affect the IAW occurrence rate.

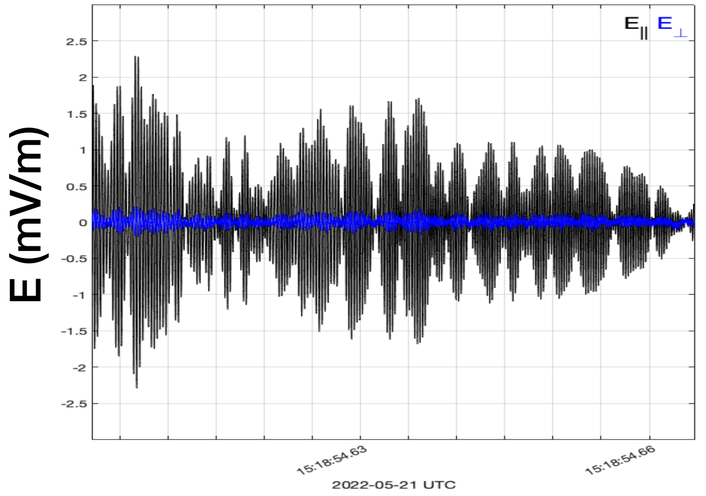
Ion acoustic waves

- Ion acoustic wave:
  - Electrostatic wave close to ω_{pi} in plasma frame.
  - Highly Doppler-shifted in s/c frame, up to ~20 kHz.
- Identification of IAW:
  - Triggered snapshot waveforms (TSWF): Peak PSD at a frequency below 20 kHz and two orders of magnitude above background value.
  - STAT data: median frequency below 20 kHz.



Pisa et al., 2021

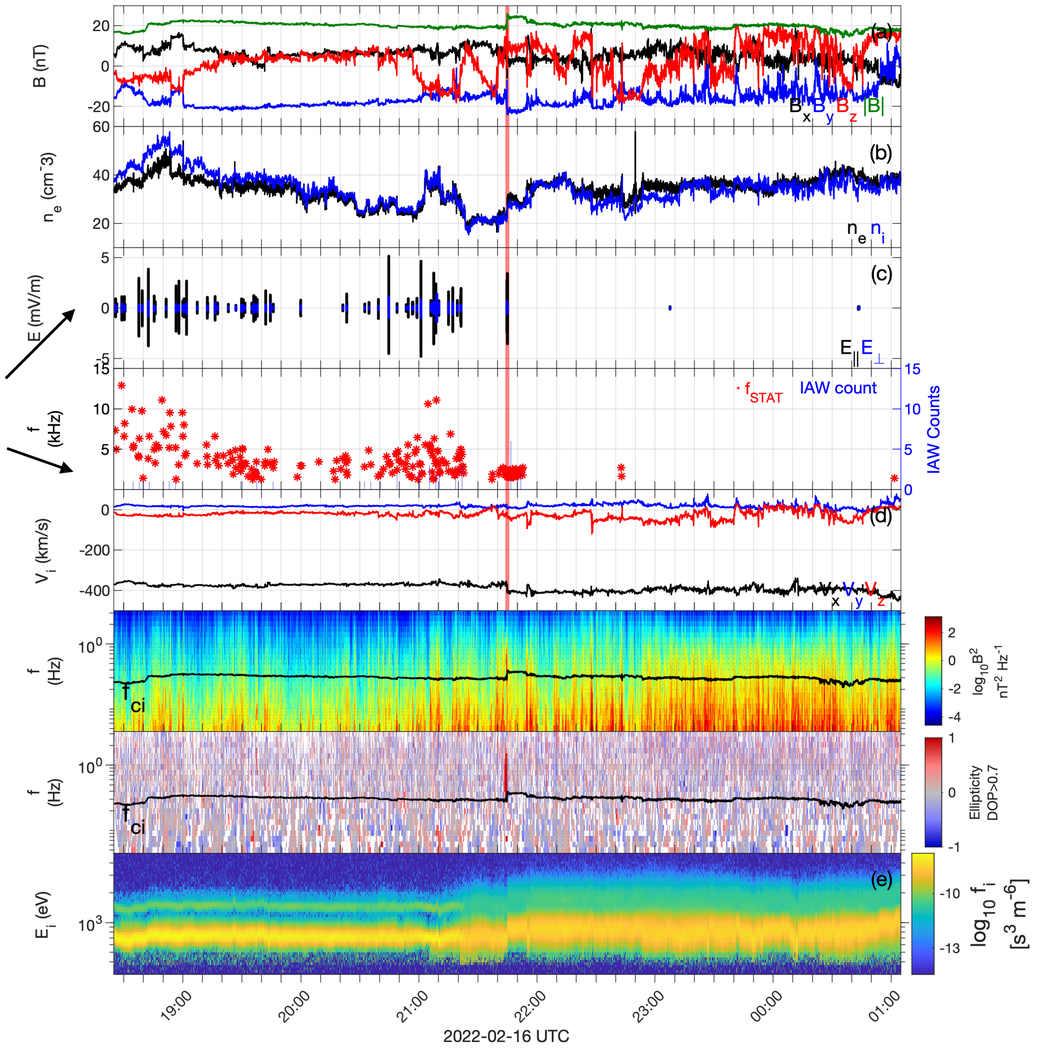


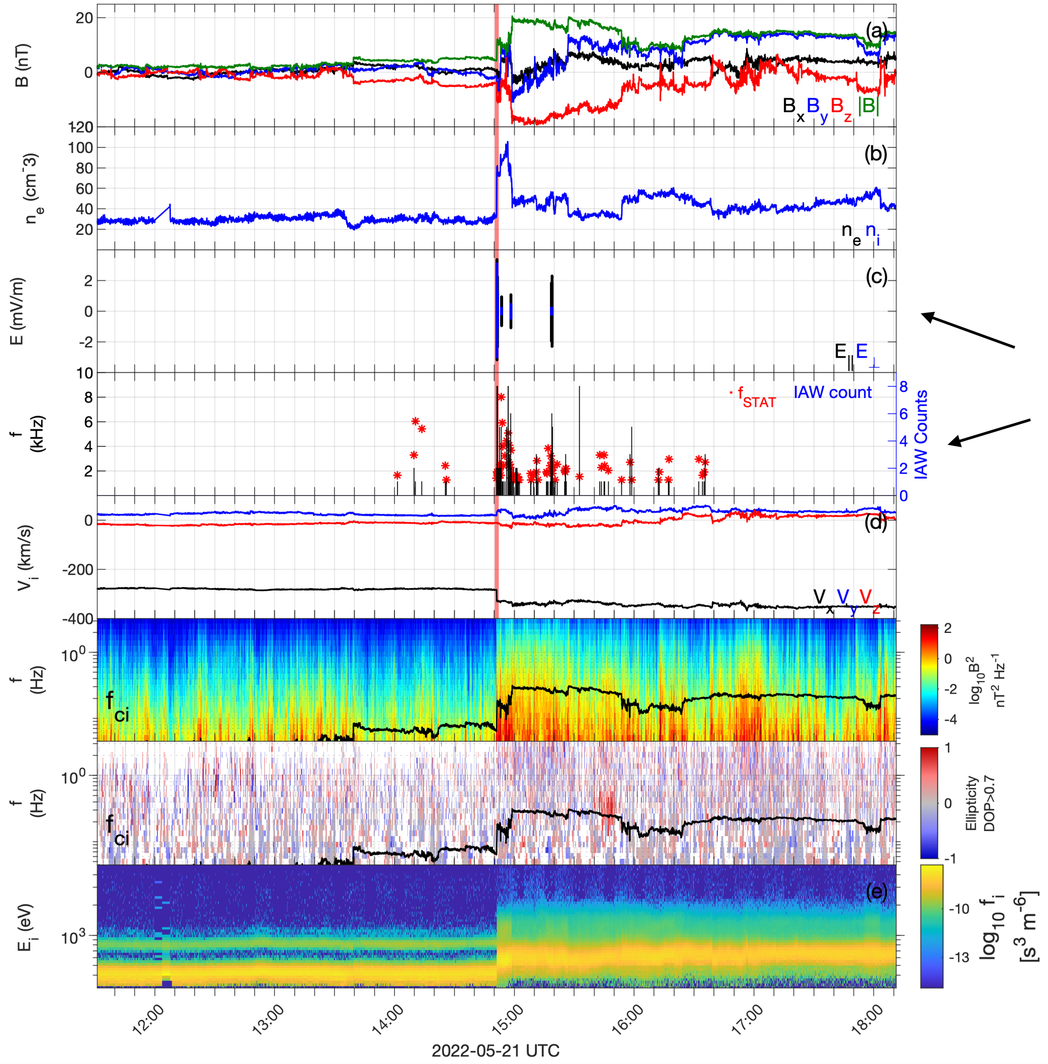


Interplanetary shocks

Solar Orbiter shock list (Dimmock et al. 2023)

Many IAW upstream





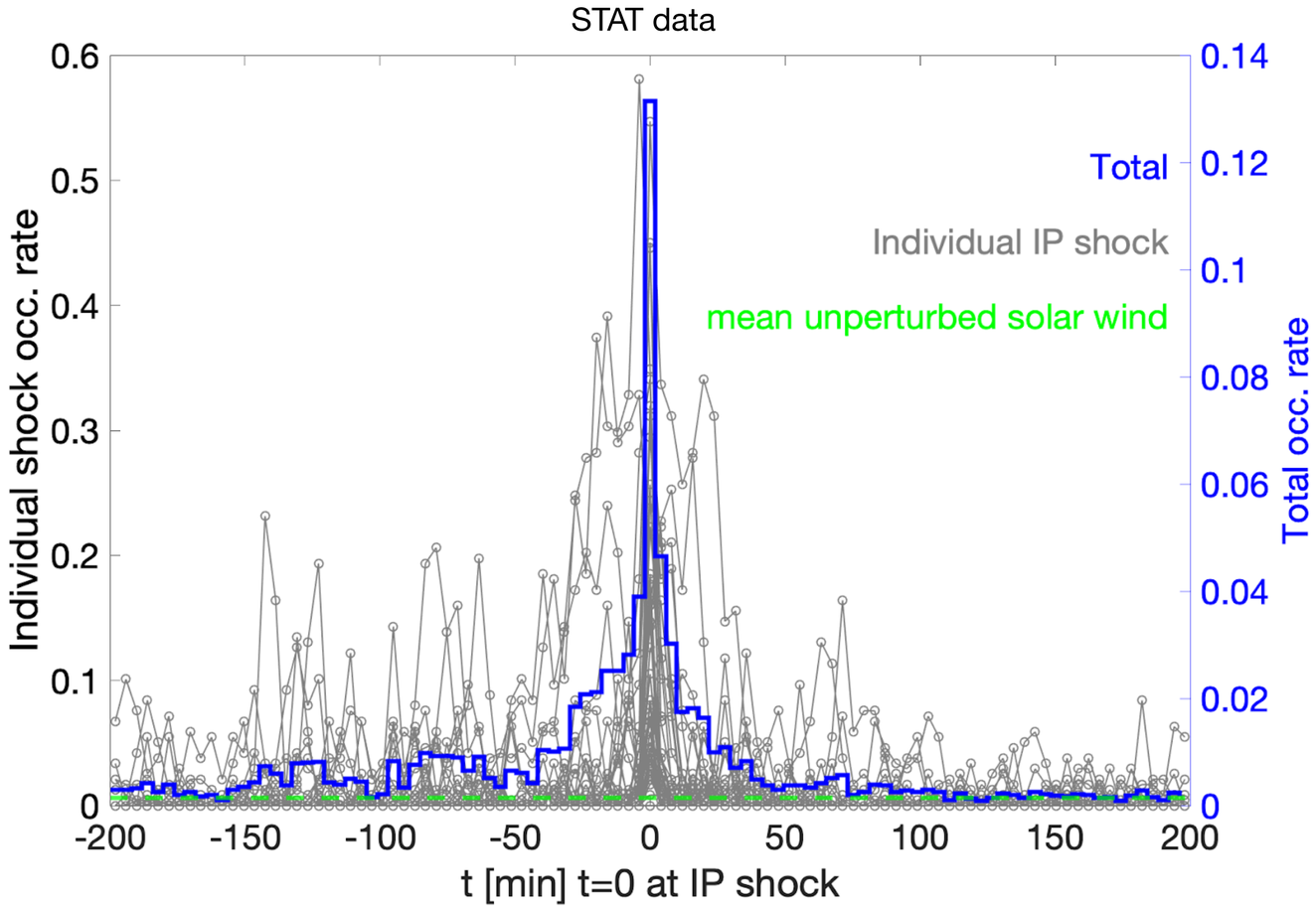
Many IAW downstream

Ion acoustic waves near IP shocks

- Occurrence rate:

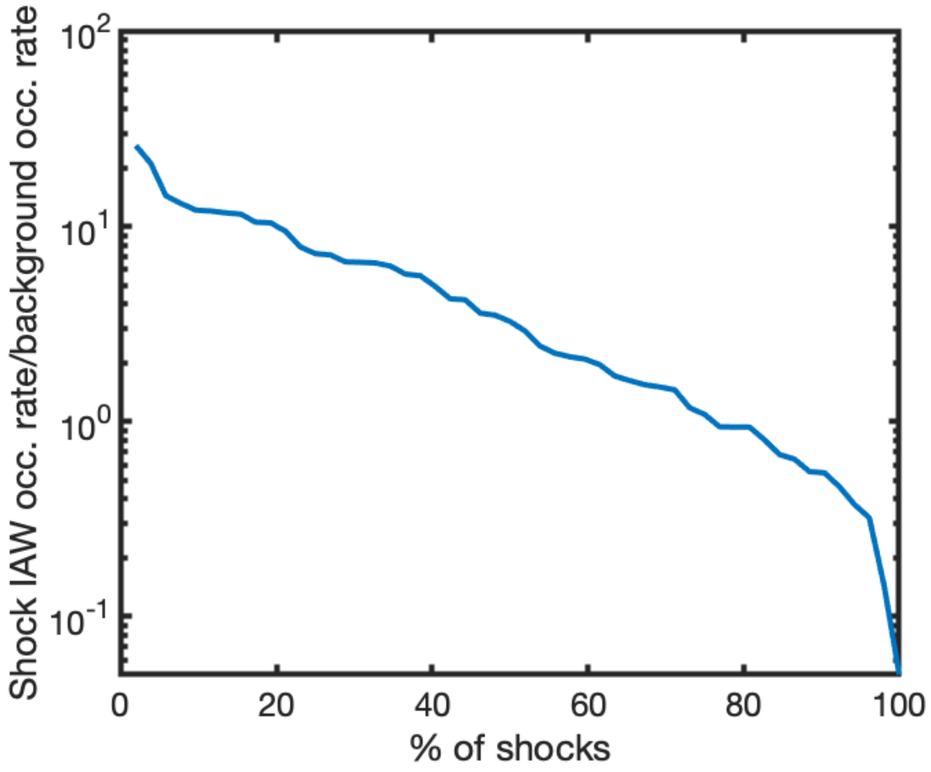
$$O.R. = \frac{\#\ IAW\ \ in\ \ interval}{total\ \ \#\ \ snapshots\ \ in\ \ interval}$$

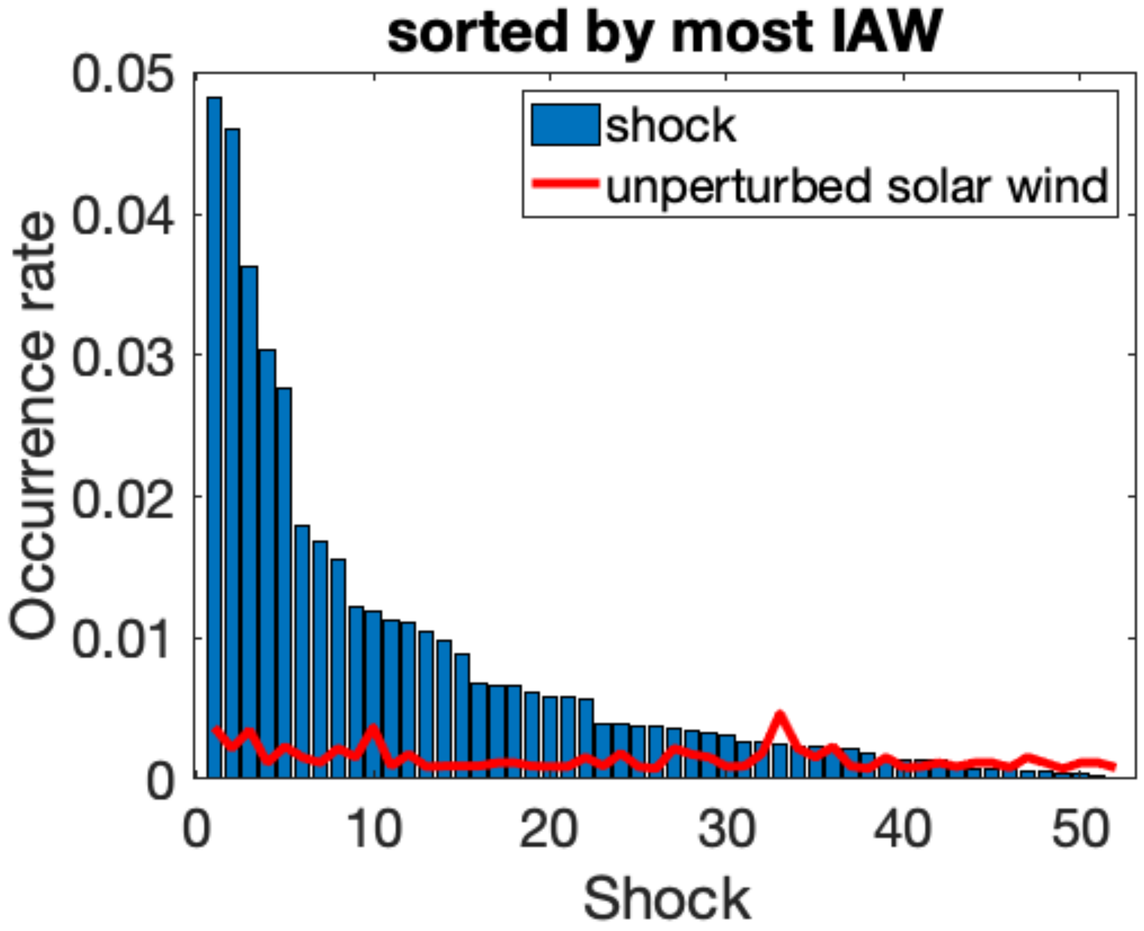
  - Upstream, individual events with higher O.R.
  - Downstream, more constant O.R. among shocks, reaching background level faster than in the upstream region.
  - In some cases the O.R. can get higher than background as far as 200 min from the shock ramp, especially in the upstream region.
  - Close to the ramp the downstream O.R. is higher than the upstream O.R. in most of the IP shocks analyzed.



Occurrence rate compared with background solar wind

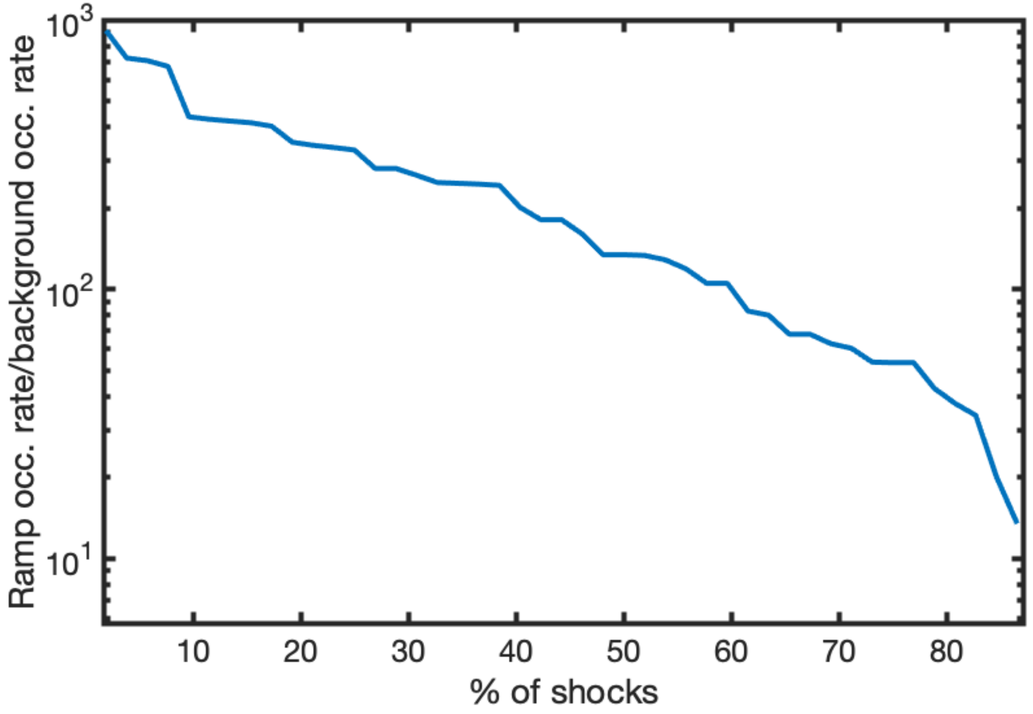
- 75% of the shocks analyzed showed an enhancement in O.R.

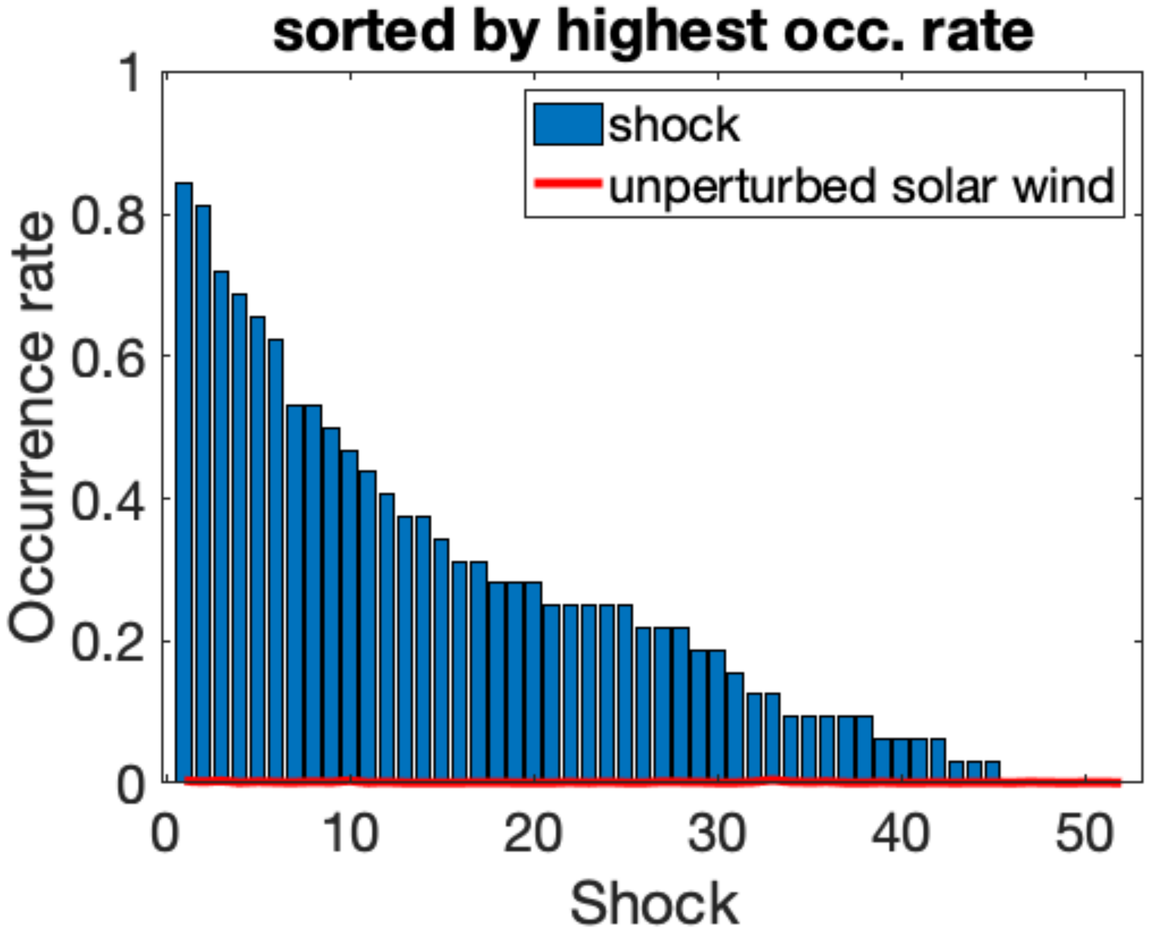




Occurrence rate near the ramp

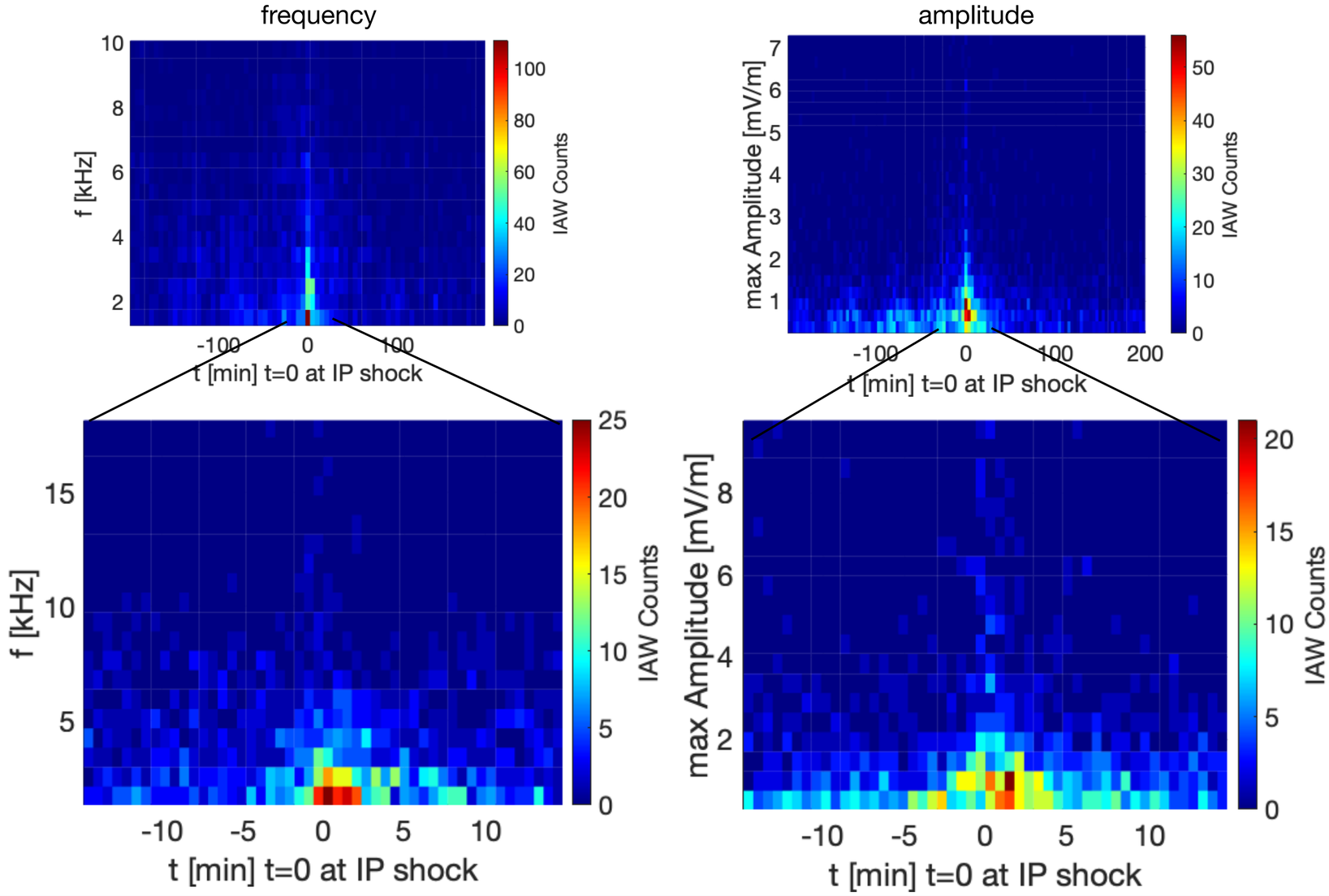
- IAW occurrence rate is highest close to the ramp.



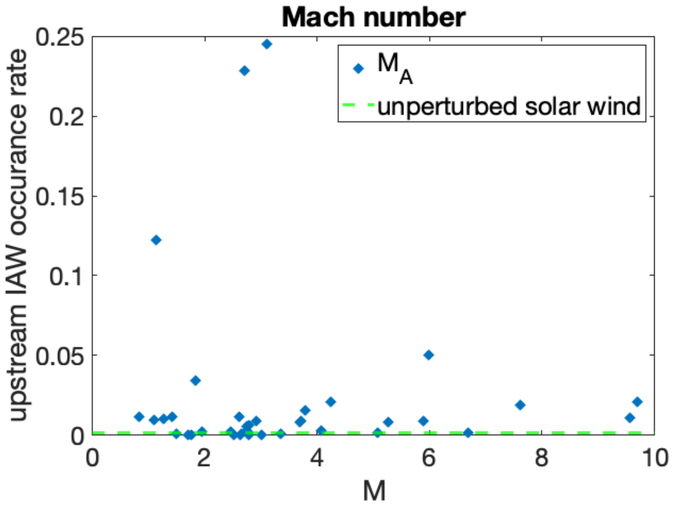


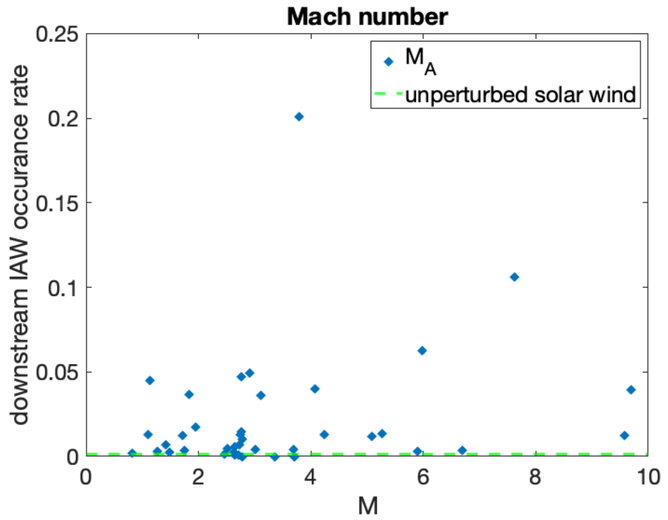
Wave properties near interplanetary shocks

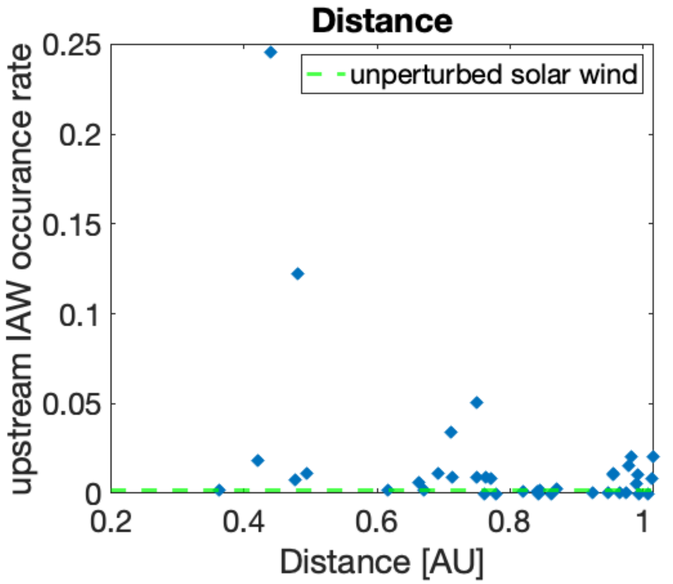
- Increasing frequency toward ramp.
- Higher frequencies close to the ramp in the downstream region than the upstream region
- Higher amplitude waves close to the ramp
- Similar wave amplitudes close to the ramp in the downstream region and the upstream region

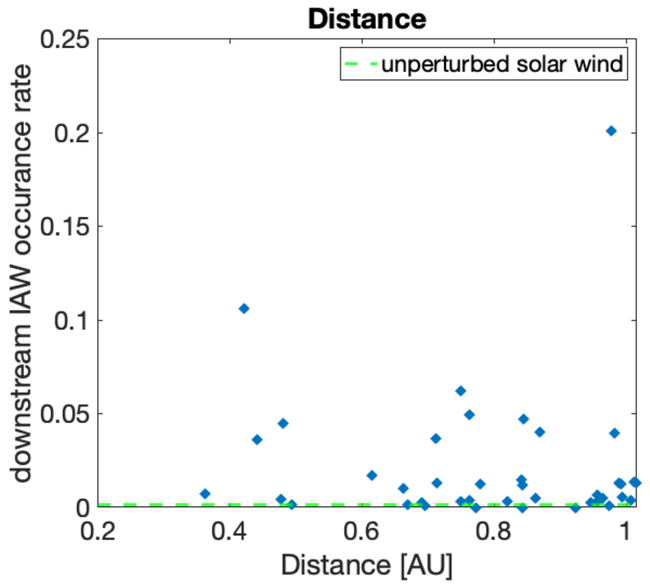


Shock properties vs occurrence rate

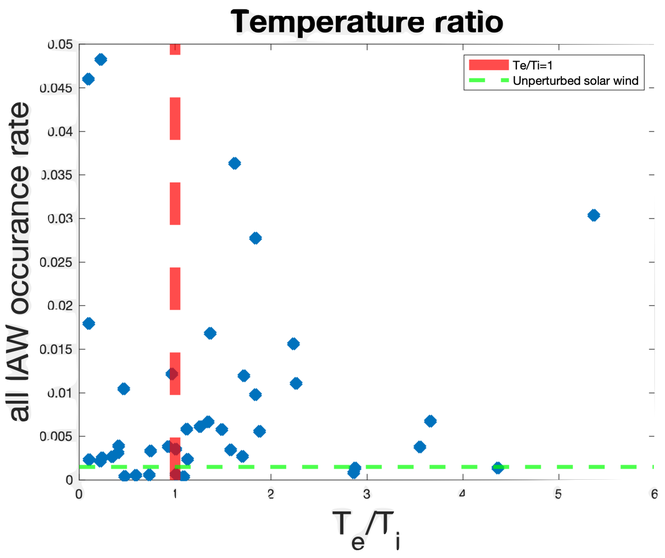


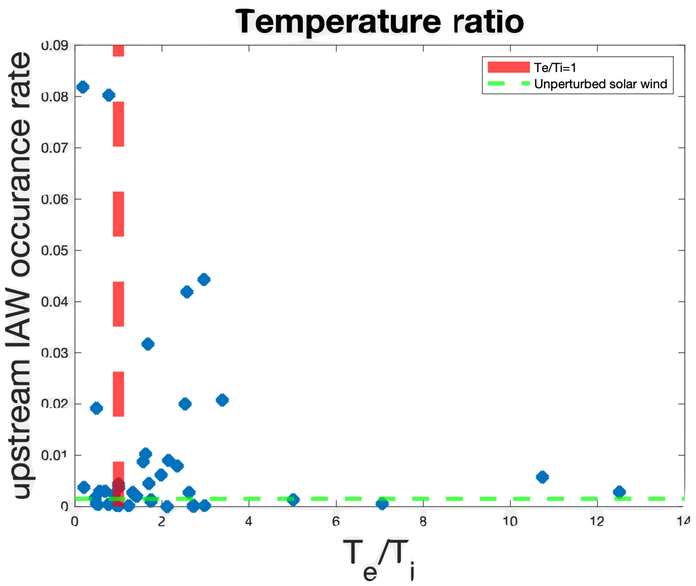


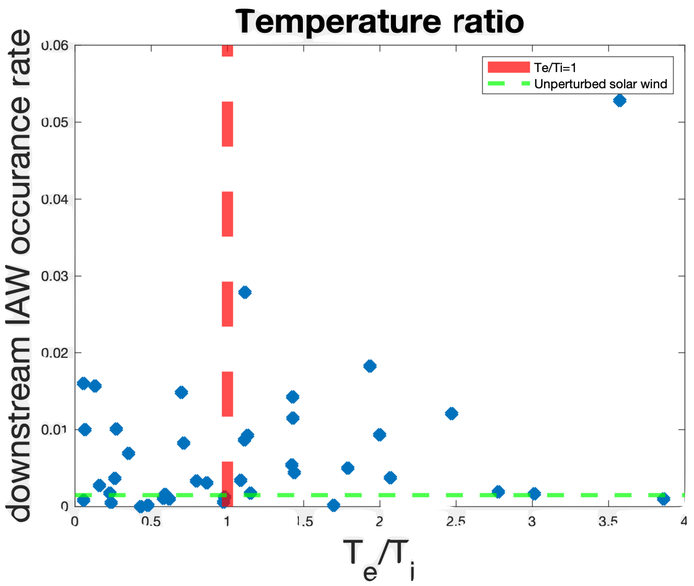




Temperature ratio



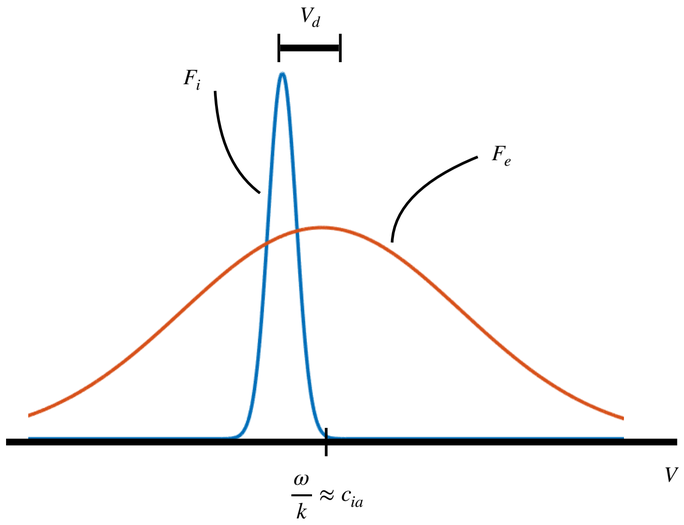




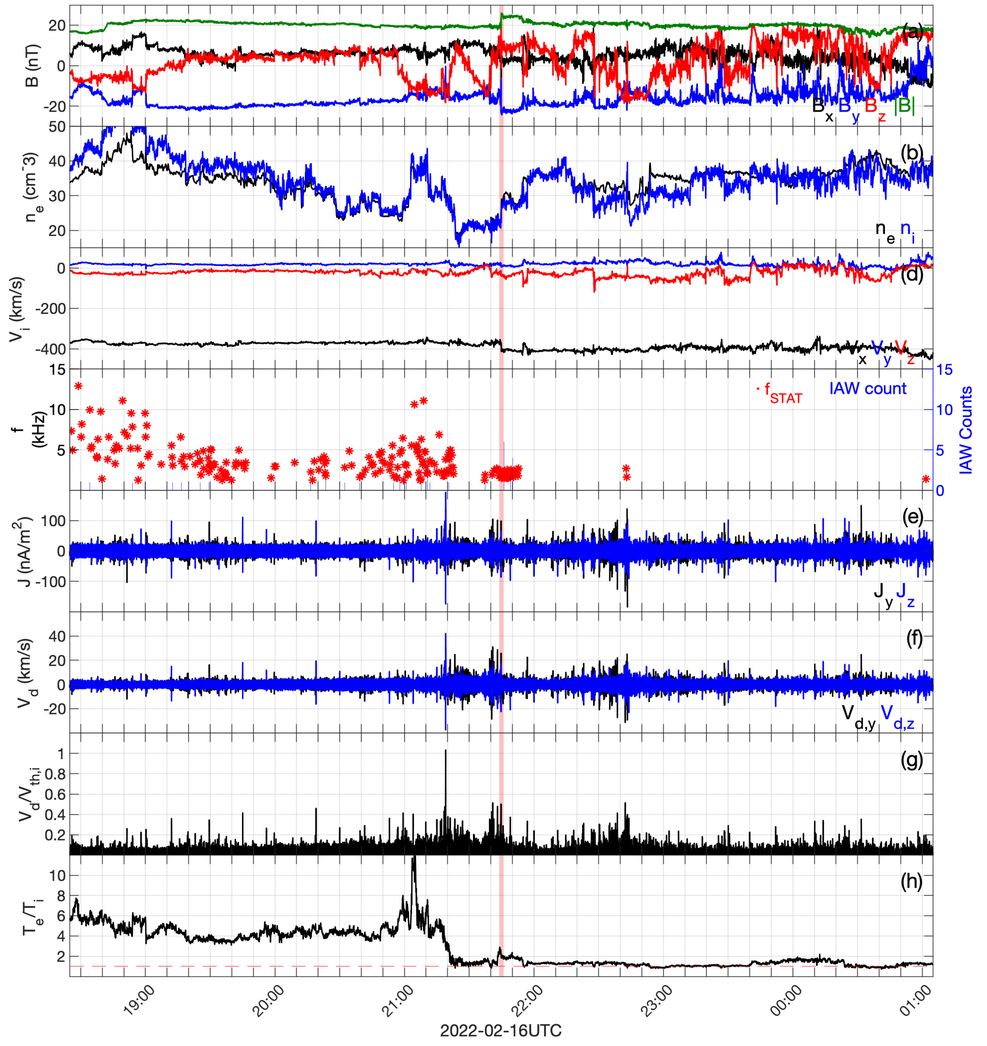
- In several cases an increased occurrence rate is observed when Te/Ti < 1, where a strong damping is expected.
- This is more clear in the downstream region.
- There are cases where higher Te/Ti is estimated, but no clear enhancement in O.R. is present.

Current-driven instability

- Assuming Maxwellian ions and drifting Maxwellian electrons.
- We calculate the currents to obtain the drift velocity:

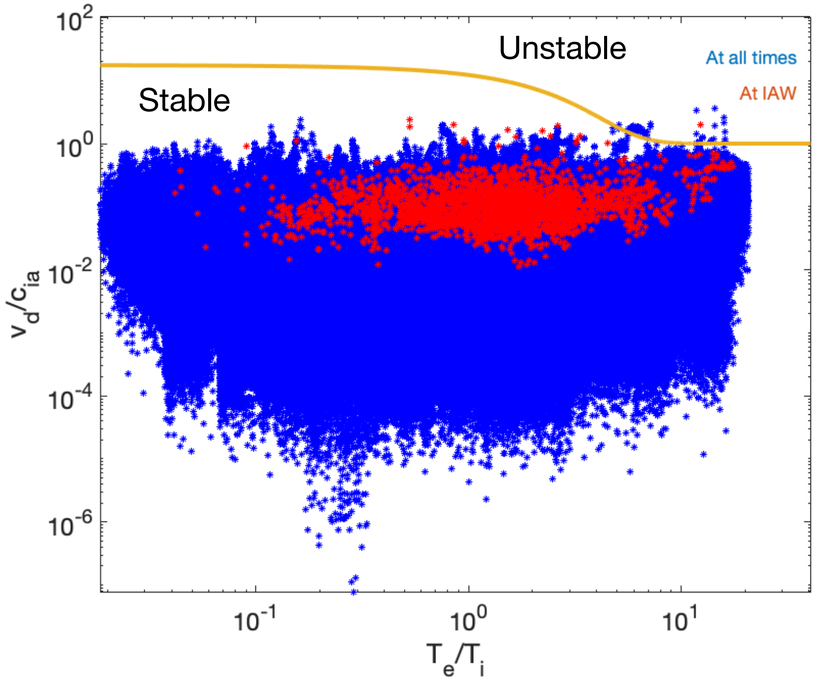


$$J_y = -\frac{1}{\mu_0}\frac{\Delta B_z}{V_{sw}\Delta t} \quad J_z = \frac{1}{\mu_0}\frac{\Delta B_y}{V_{sw}\Delta t}$$



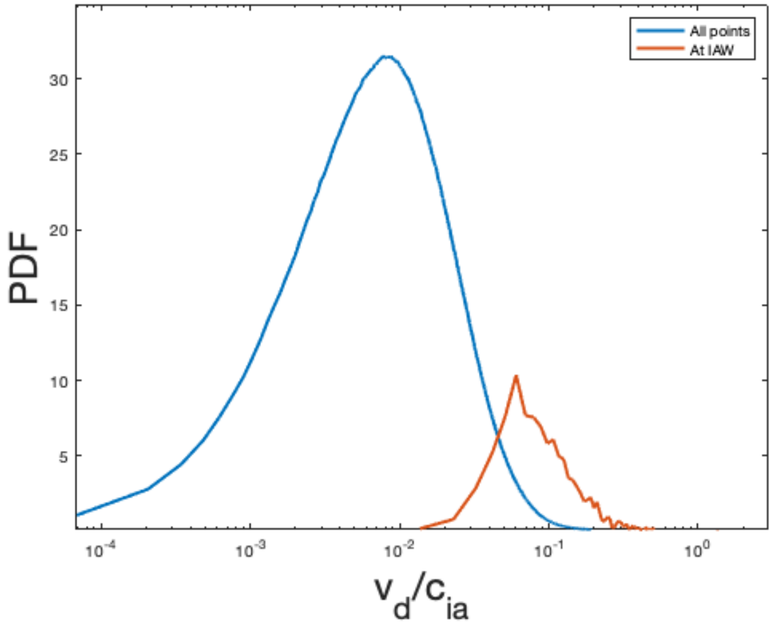
Current-driven instability

- The calculated currents are insufficient to drive the distribution unstable, even at the highest Te/Ti observed.
- However, the waves are observed at regions of higher drift velocities.
- Non-Maxwellian effects could modify the thresholds.

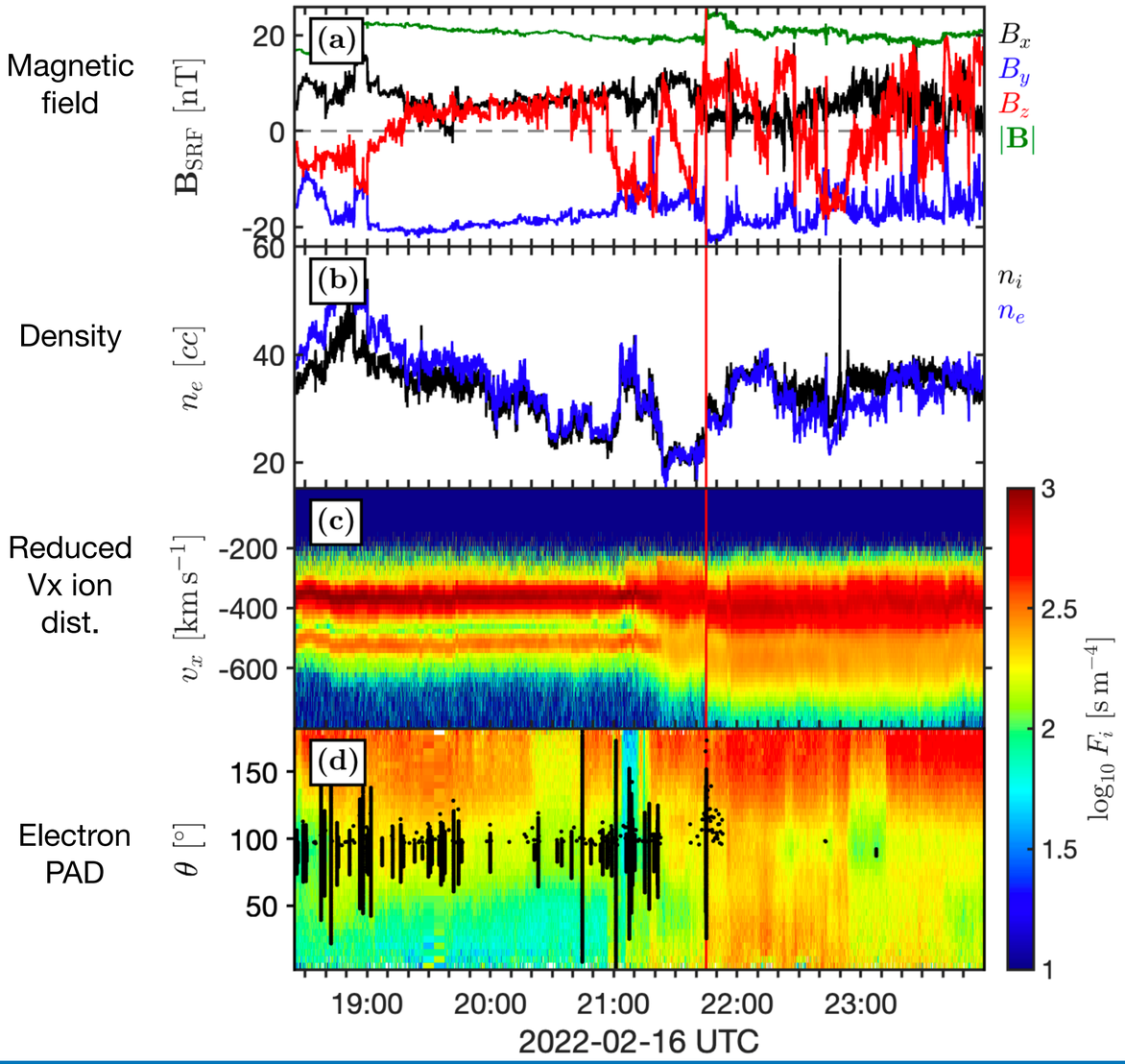


$$\gamma_{ia} = \left(\frac{\pi}{8}\right)^{1/2} \frac{\omega_{ia}}{(1+k^2\lambda_D^2)^{3/2}} \left[\left(\frac{m_e}{m_i}\right)^{1/2}\left(\frac{kv_d}{\omega_{ia}} - 1\right) - \left(\frac{T_e}{T_i}\right)^{3/2} \exp\left(-\frac{T_e}{T_i(1+k^2\lambda_D^2)}\right)\right]$$

Treumann & Baumjohann, 1997



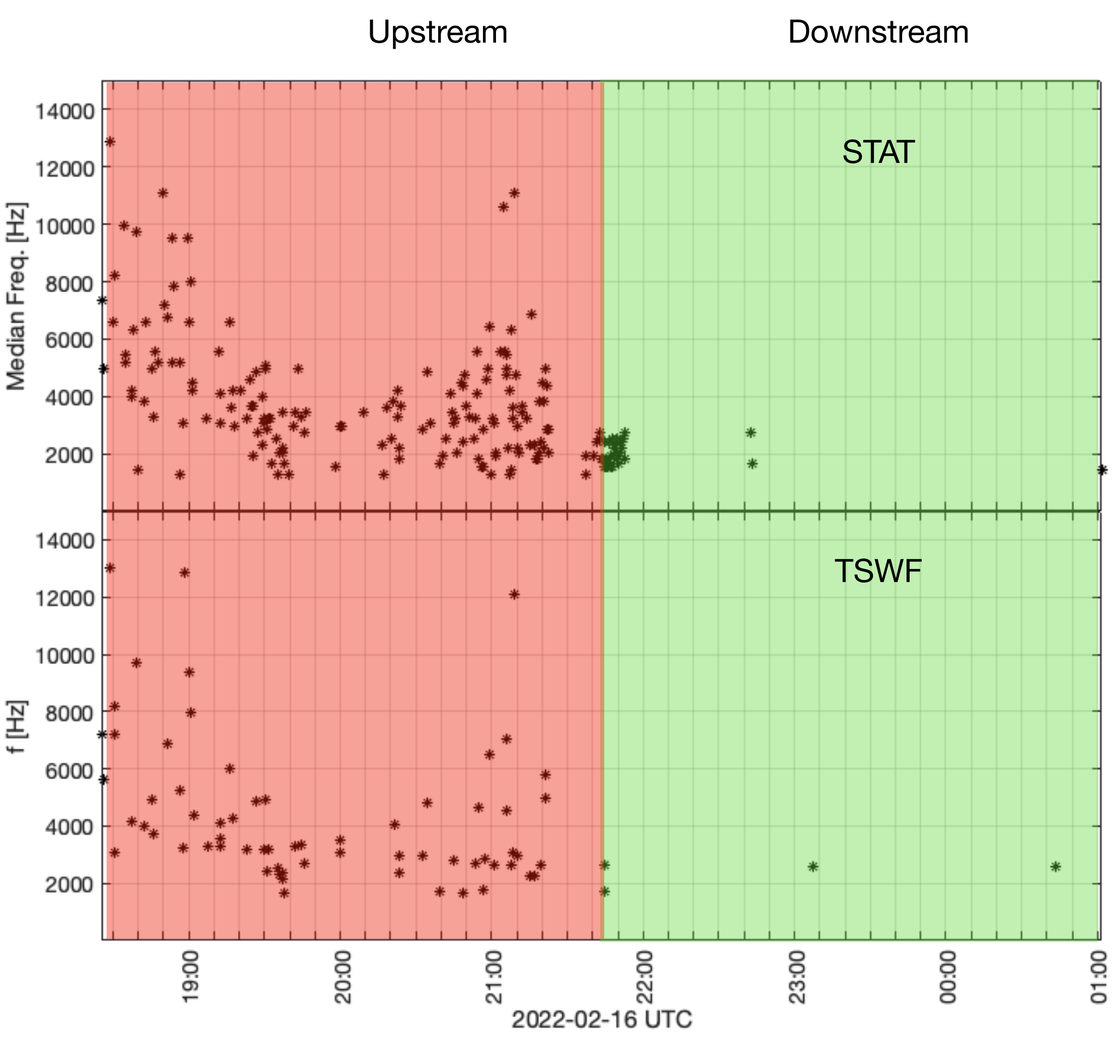
IP shock example

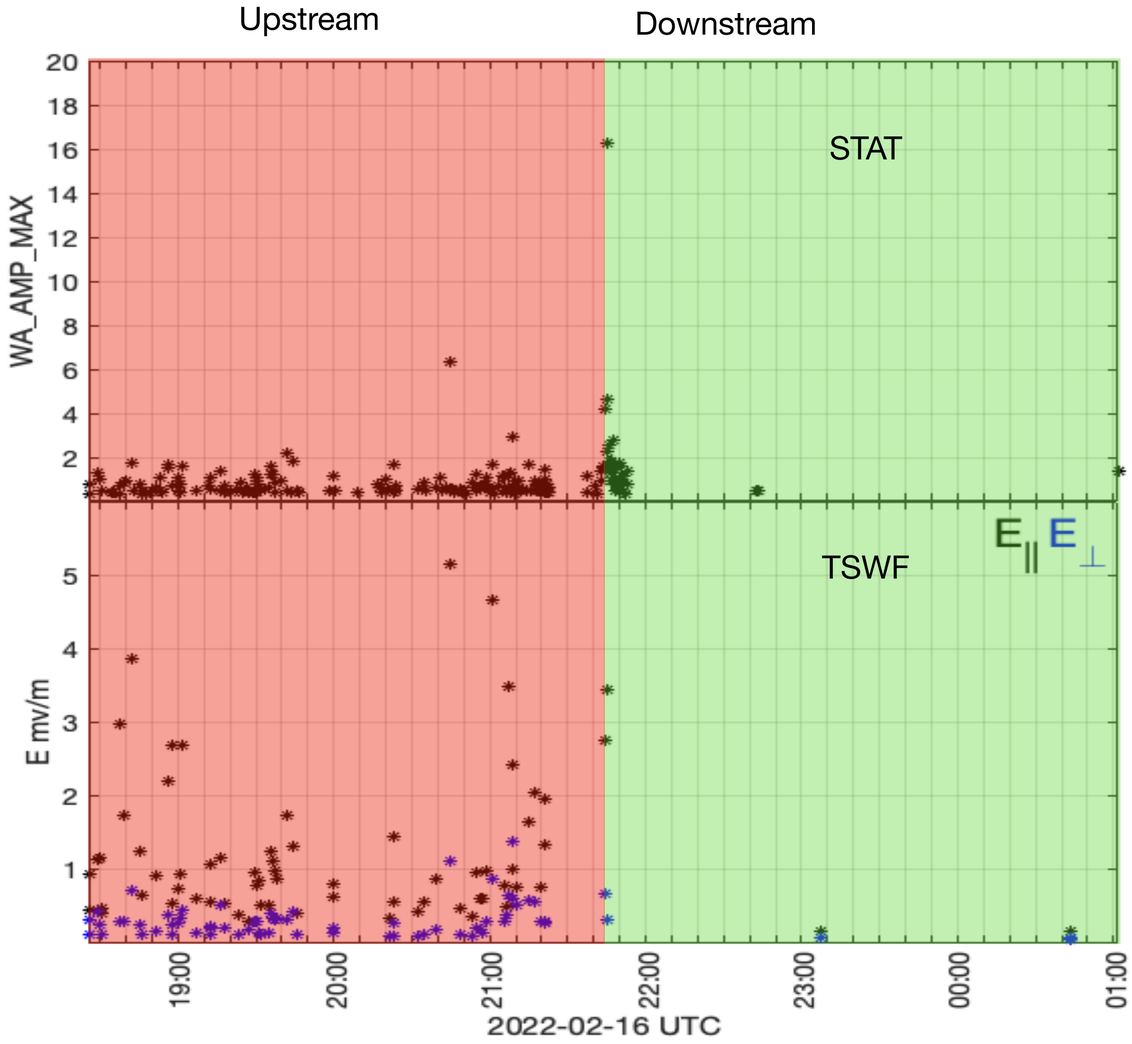


$\theta_{BN} = 44°$, **Ma = 1.8, Vsh = 480 km/s**

- Far upstream - a large set of IAW, large amplitude, decreasing frequency, antiparallel ion population.
- Upstream - another set of ion-acoustic waves. Increasing amplitude, increasing frequency.
- Decrease in the number of waves close to the shock (upstream)
- Ramp - many waves, high amplitude
- Near downstream some waves (only STAT)
- Downstream almost no waves

Overview of IAW

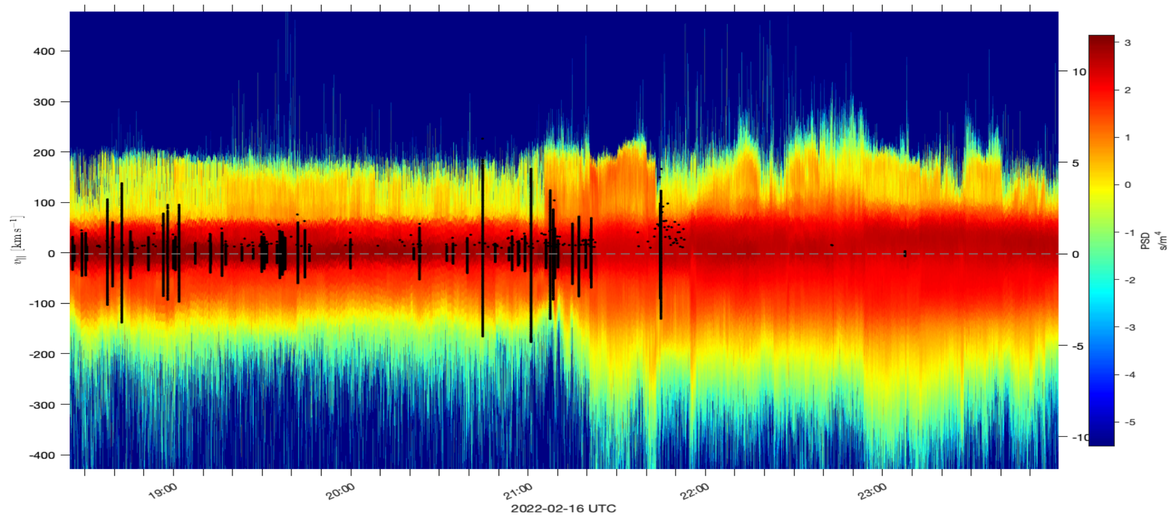




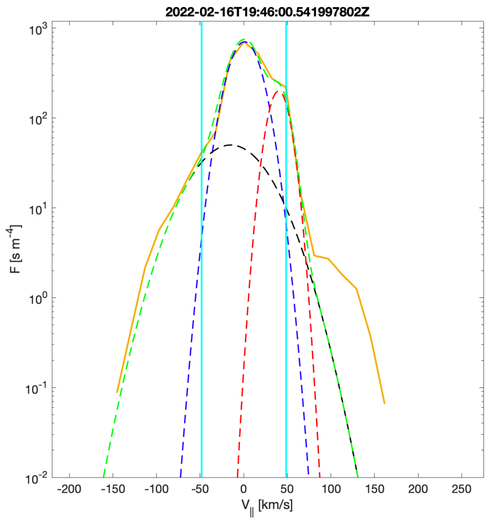
Ion distribution function ($v_{||}$)

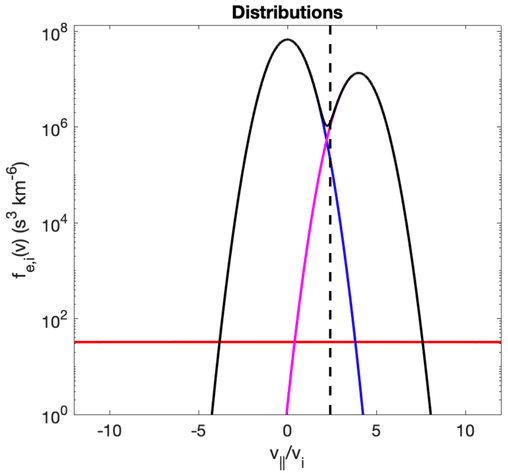
- Antiparallell ion population
- Parallel ion beam population
- The beam population has a velocity close to ion sound speed (c_{ia})

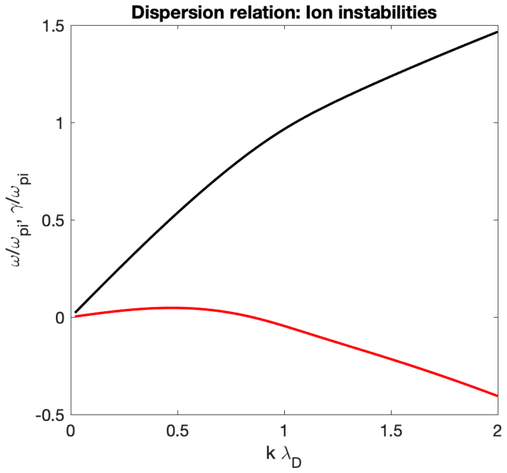
Reduced $v_{||}$ ion dist.



Measured







Alphas have been removed

Conclusions

- The occurrence rate of IAW is increased near interplanetary shocks, with the highest rates at the shock ramp.
- Occurrence rate in the upstream region can be very variable, in the downstream region the O.R. decreases more rapidly.
- The presence of IAW is correlated with enhanced drift velocities between ions and electrons, but the currents are not high enough to reach the theoretically unstable thresholds, even for the largest Te/Ti observed.
- There is no clear dependence of IAW O.R. with shock parameters.