"HYBRID SIMULATIONS OF PLANETARY PICKUP IONS & ION CYCLOTRON WAVE GENERATION"

Misa Cowee
LANL

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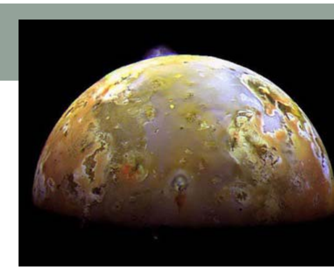
Background

- Plasma waves generated by pickup ions have been seen in many environments (Venus, Earth, Mars, comets, Jupiter, Saturn)

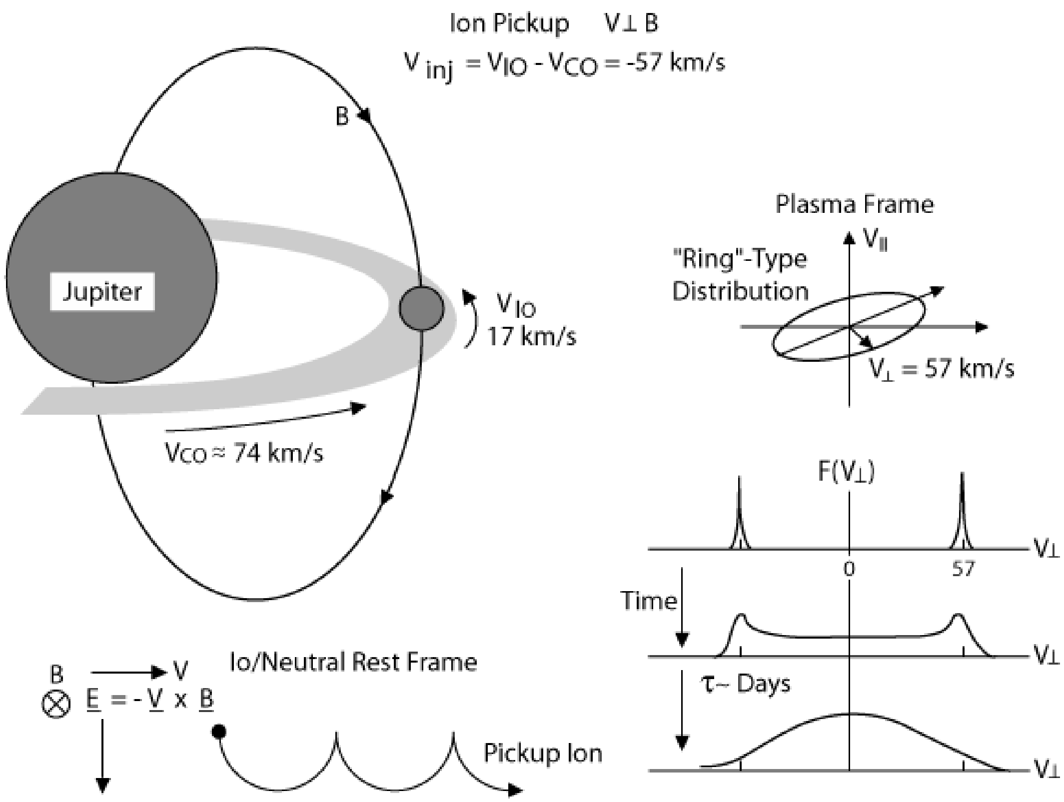
- When newborn ions are created, they can have non-equilibrium velocity distributions which excite short wavelength normal modes of the plasma (micro-instabilities)
  - The waves act to scatter the pickup ions and the background ions, reducing the free energy, and creating a more stable velocity space configuration

- The characteristics of the waves as detected by spacecraft can be used to infer the properties of the pickup ions and the distribution of neutrals in the various planetary environments

Example: Ion pickup at Io



- Jupiter's moon, Io, is volcanically active, adding estimated 1 kg/s of material to the surrounding space
  - Atm primarily SO and SO_2
- To first order, the jovian magnetic field is oriented perpendicular to the plane of the plasma torus (at Io's orbital distance 5.9 R_J)
  - Pickup velocity is 57 km/s
- Newborn ions, gyrating around the magnetic field, will form rings in velocity space in the frame of the corotating torus

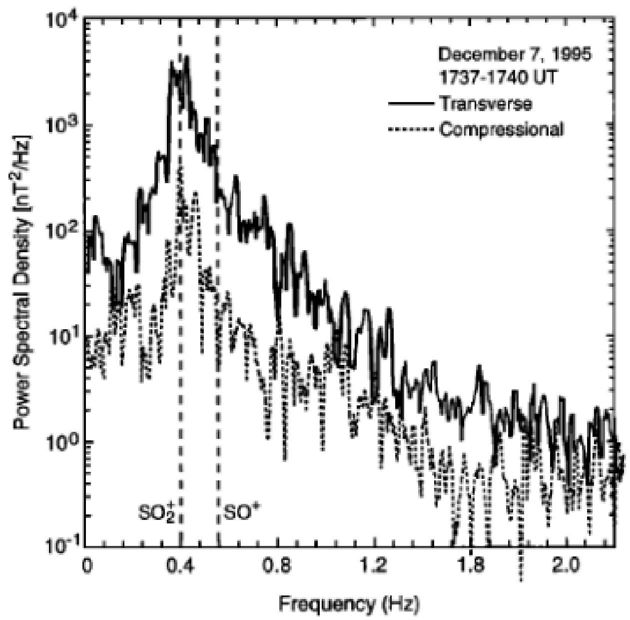


Huddleston et al. (1997)

- These ring distributions are unstable to waves at the cyclotron frequency of the pickup ion species, which then scatter and thermalize the newborn ions

Galileo ion cyclotron wave observations at Io

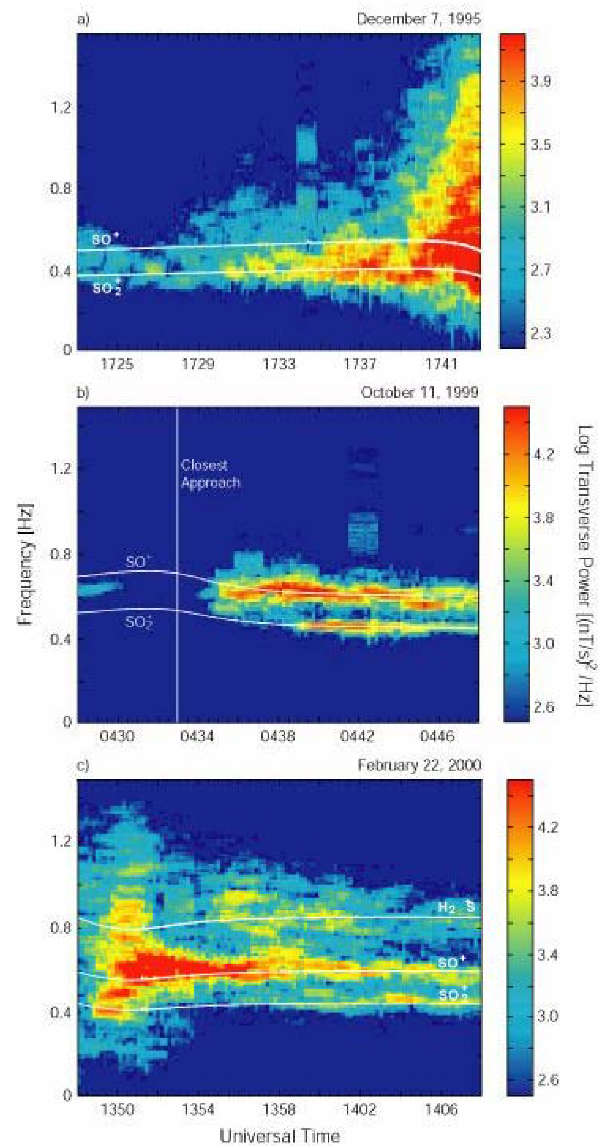
- Galileo collected good magnetic field data on five flybys:
  - Fluctuations primarily left-hand, transverse, parallel propagating, near the SO_2^+ and SO^+ gyrofrequencies
  - Identified as ion cyclotron waves generated by Iogenic pickup ions



- Waves detected mainly downstream of Io as far as ~10 R_{Io} inward and ~20 R_{Io} outward of Io

- Wave power decreased as s/c moved away from Io, suggesting decreasing pickup ion density

- Linear theory predicts that ICW amplitude should be proportional to the initial energy of the pickup ion population -- but what is the relationship?

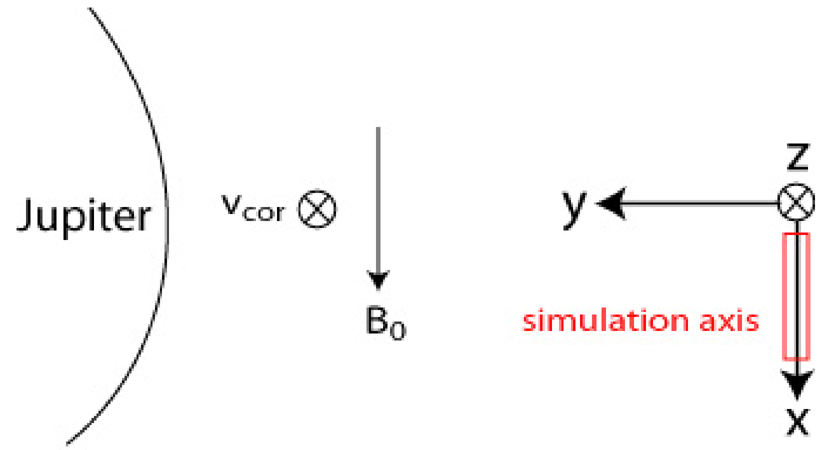


Russell and Kivelson (2001)

Simulating the ion cyclotron ring instability with the 1D hybrid code

- We use a hybrid simulation (Winske and Omidi, 1993) to simulate the self-consistent growth of the waves.

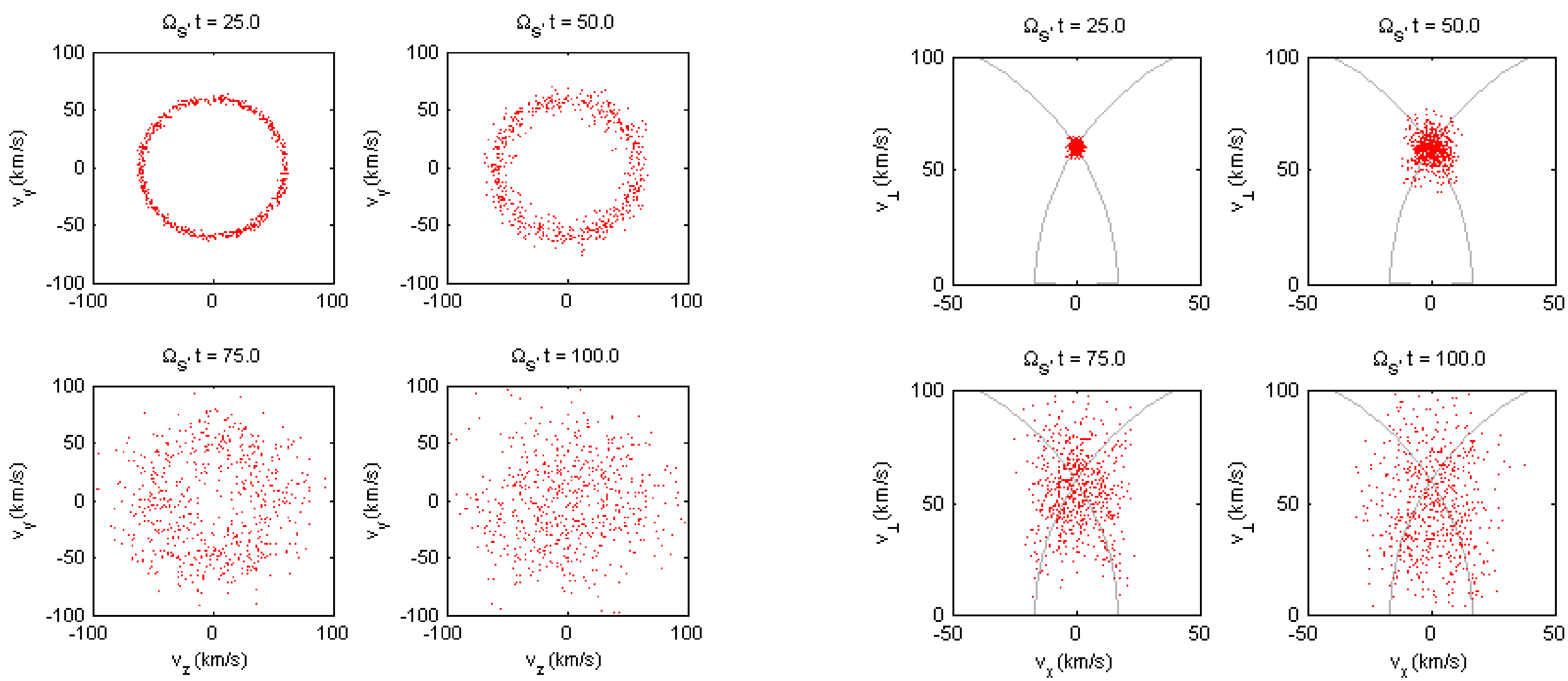
- Nominal initialization:
  - B_0 = 1700 nT
  - n_0 = 3600 ions/cc
  - c/ω_{pS+} = 45 km, Ω_{S+} = 0.8 Hz
  - Perpendicular pickup (no parallel drift velocities)
  - Align simulation axis, x, with B_0 (instability at parallel propagation)
  - injection: no ring ions present at t = 0, ions added at constant rate across the simulation box
    - 0.0162 - 0.162 ions/cc/s



Ion	m/q	Density (cm^{-3})	Tpar (eV)	Tperp (eV)	Tperp* (eV)	v_r (km/s)
O^+ core	16	2800	100	100	-	-
S^+ core	32	800	100	100	-	-
SO_2^+ ring	64	varies	~0	903	~0	60

v_r is the perpendicular ring velocity. Tperp* is perp temperature about the ring.

Simulated ring evolution in velocity space



- Ring spreads in perpendicular and parallel directions over time to a more isotropic state
- As ring scatters, it loses energy in the perpendicular direction and gains energy in parallel direction
- Gray lines show characteristic scattering path for v_{ph} = ±100 km/s
- Core ions scatter up these characteristics as they take energy out of the waves (not shown)

Simulated wave spectra

- Generated SO_2^+ cyclotron waves agree with linear theory predictions for low density warm rings
  - For the injection rates we consider, instability growth is fast compared to the free energy injection rate
  - Peak growth with $v_{ph} \sim 0.5\ v_A$

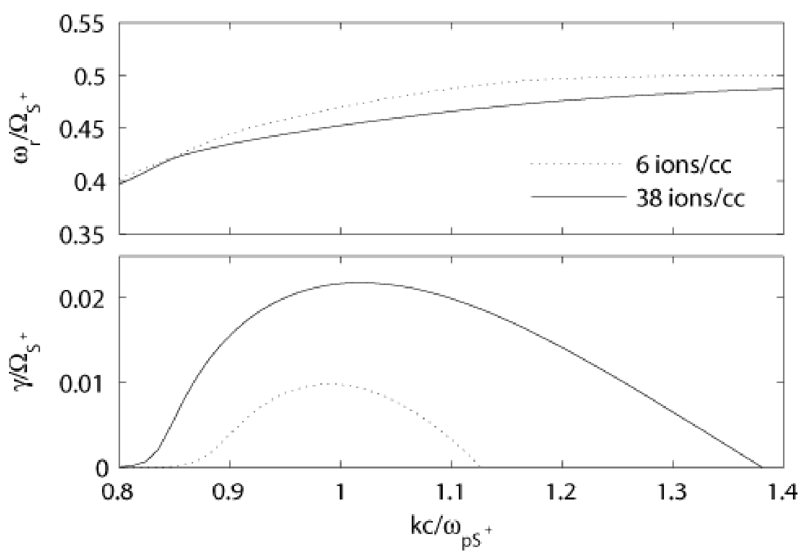


Figure shows dispersion solutions for the generated waves for different pickup ion densities.

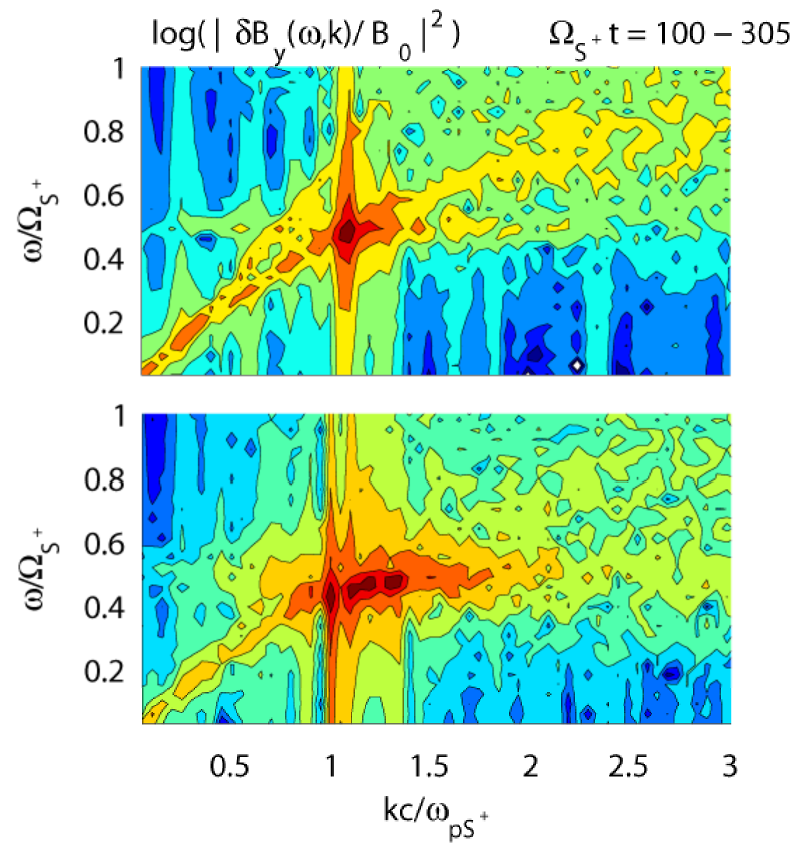
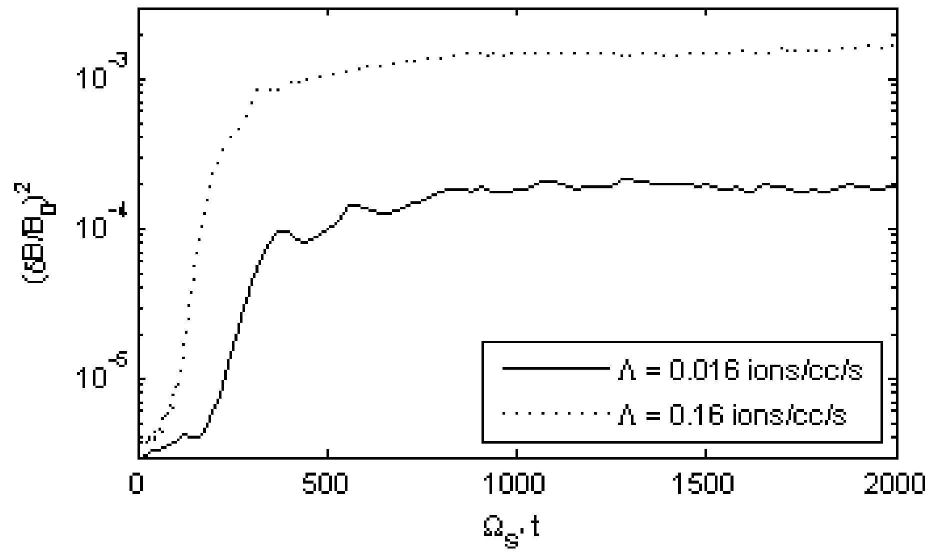
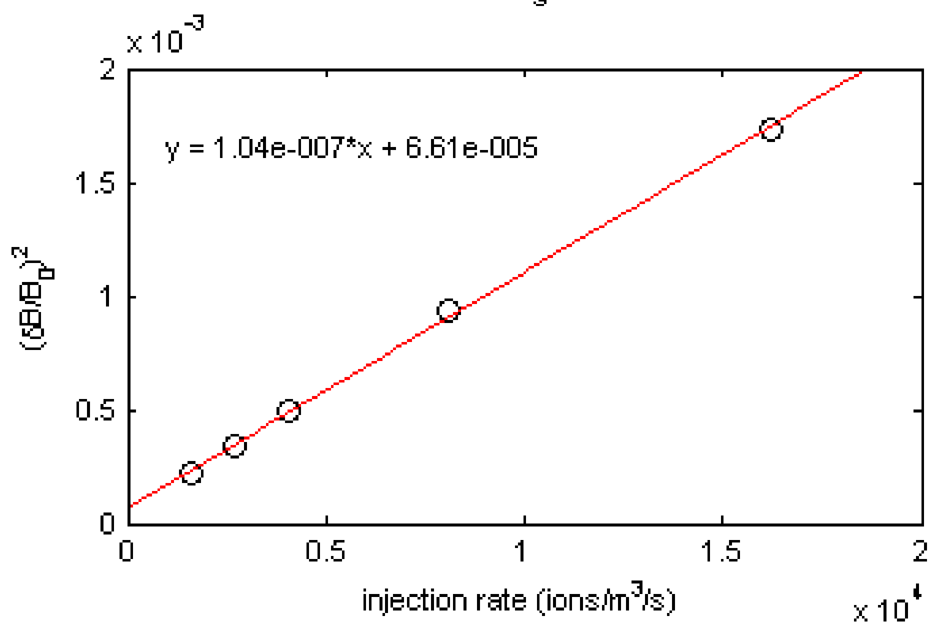


Figure shows spectra for injection rates of (top) 0.162 and (bottom) 0.0162 SO_2^+/cc/s injection. Note frequency and wave number normalized against S^+.

Varying injection rate

- Simulations show a range of injection rates which generate wave energies in the range observed at Io
- The quasi-steady wave energy level depends on injection rate
    - The continuous injection of free energy maintains the waves against decay
- We can calculate how the injected ion energy is partitioned among the plasma components and the waves
    - Injected ions lose ~30-35% of their initial energy in the process of scattering (assuming no background component of comparable mass to damp the waves)
    - ~2-5% ends up heating the background O^+ and S^+
    - ~30% resides in the waves





Using simulation results and observed wave amplitudes to estimate pickup ion densities

- Assuming the observed wave amplitudes represent a given % of the initial energy of the pickup ion ring (E_R), we infer the pickup ion densities:
  - Assume also v_r = 57 km/s, all SO_2^+ pickup ions

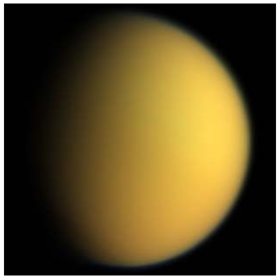
Pass / time	Wave amp (nT)	PLS pickup ion density (ions/cc)		SO_2^+ density from 20-6% E_R (ions/cc)
J0 / 1741 UT	30	175		20-70
J0 / 1744 UT	100	300		230-760
I24 / 0444 UT	15	65		5-20
I27 / 1354 UT	25	100		14-50

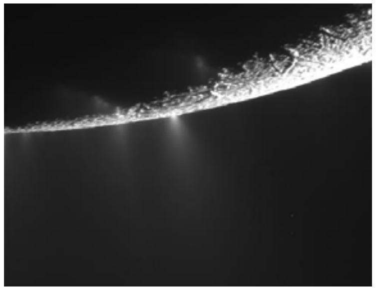
- **For all but J0 1744 UT, the inferred densities are lower than the PLS densities**
  - Possible the PLS densities are too high, as they were estimated based on the pickup ion density at closest approach
  - Possible v_r < 57 km/s, ions are picked up into a slowed flow

Pickup ions at other planets

- We have applied this method of using the hybrid simulation to determine the relationship between the pickup ion rate and ICW amplitude to other planetary environments:
  - Saturn's Extended Neutral Cloud (Cowee et al., 2009)
  - Titan (Cowee et al. 2010)
  - Mars (Cowee et al., 2012; current NASA project with Hanying Wei and CTR)
  - Saturn's moon, Enceladus (current IGPPS project with Hanying Wei, Ron Powell and CTR)

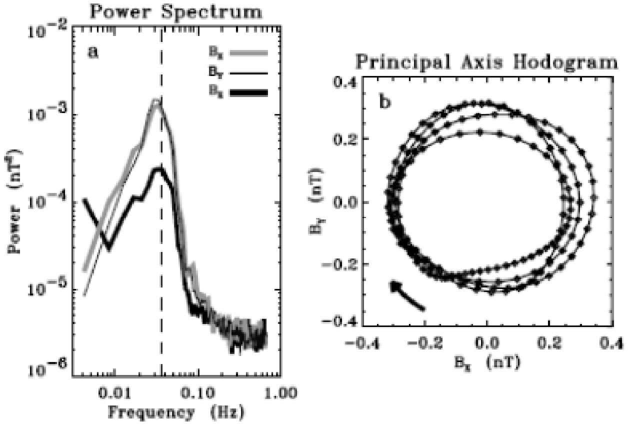
- Work in these other planetary environments has illustrated further complexity in the interpretation of ICW signatures:
  - Wave growth time, and wave convection with solar wind
  - Spatially variable ion pickup rates over large distances
  - Interaction between multiple pickup ion species
  - Non-gyrotropic pickup ion velocity space distributions



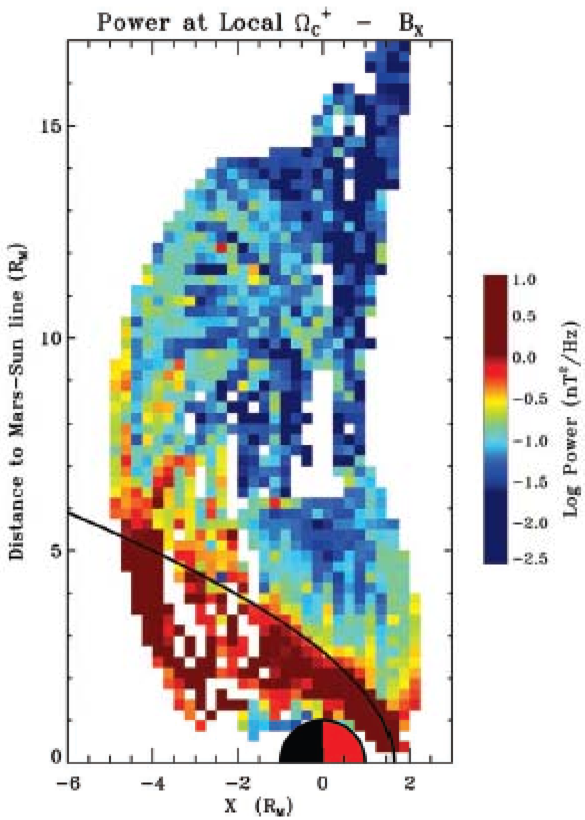


Example: Ion Cyclotron Waves Upstream of Mars

- Proton cyclotron waves observed over a wide range of distances from Mars (MGS data shown)
  - Wave power decreases with distance, consistent with exospheric pickup ion source
  - Can we infer the exospheric structure loss rate from the ICW amplitudes?



Brain et al., (2002)



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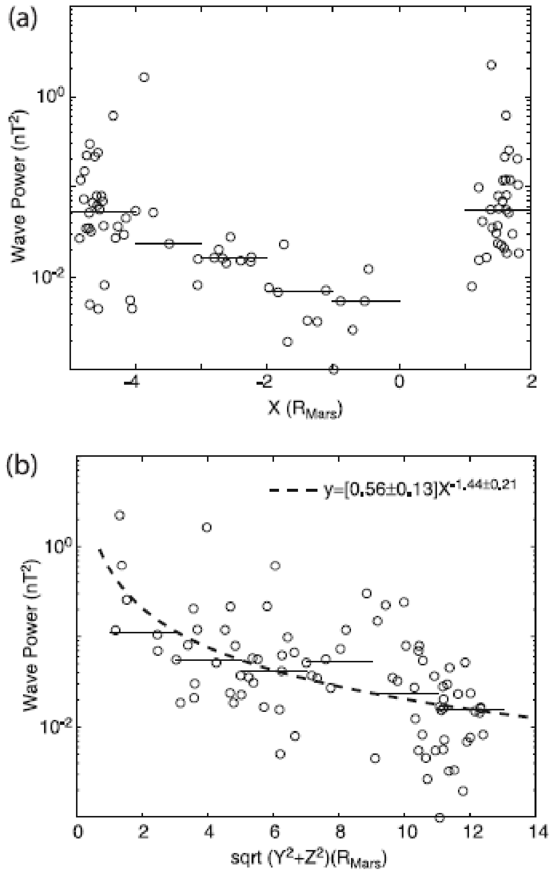
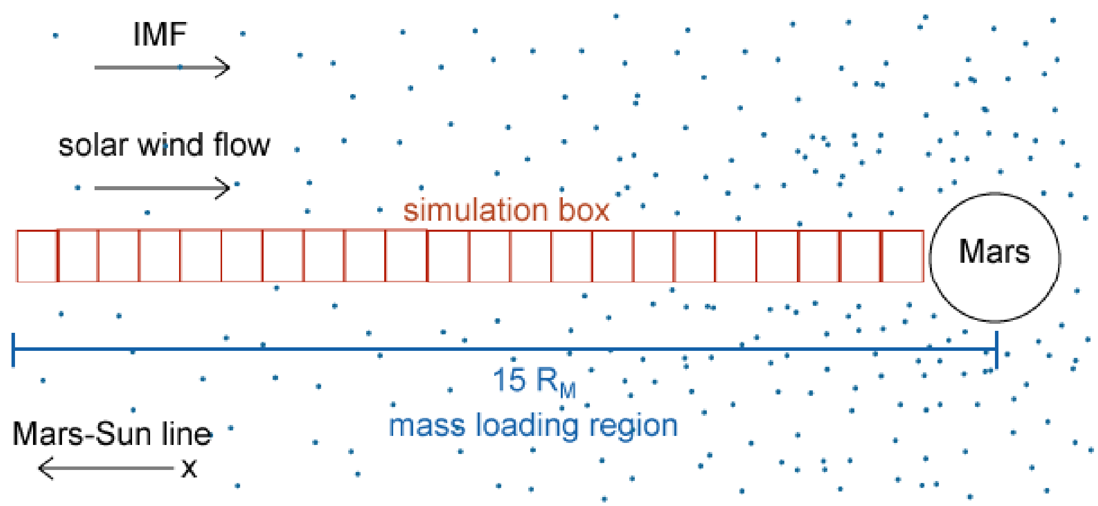


Wei and Russell (2006)

Hybrid simulation for Mars: “Long box”

Nominal simulation parameters:

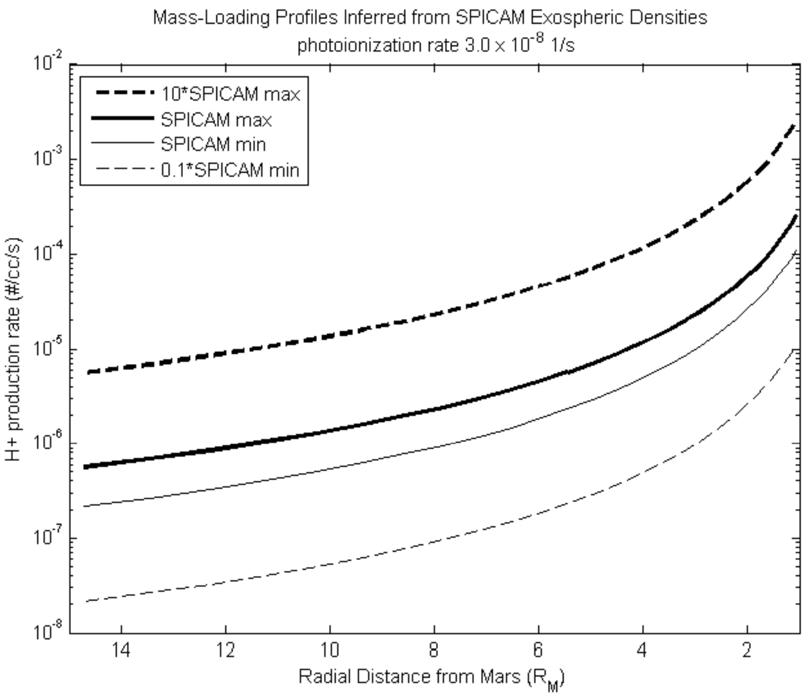
- $B_0 = 3$ nT, $n_0 = 3$ ions/cc
  - $c/\omega_{pi} = 131.5$ km
  - $\Omega_i = 0.046$ Hz (~22 s period)
  - $v_A = 37.8$ km/s
- Background Solar Wind H^+:
  - $V_{sw} = 400$ km/s
  - T = 4 eV maxwellian
  - $n/n_0 = 1$
- Pickup H^+:
  - Injected at rate Λ
  - Injected at zero velocity
- V_{sw} anti-|| to B_0
- 1D axis aligned with B_0, direction of max growth



- To consider the effects of wave growth time and spatially non-uniform ion production we make the simulation box very long and include a radial ion-production profile based on the SPICAM exospheric densities
  - Solar wind, IMF conditions are constant
  - Ion production rates are spatially varying but are constant in time

Mars long box simulation setup (cont.)

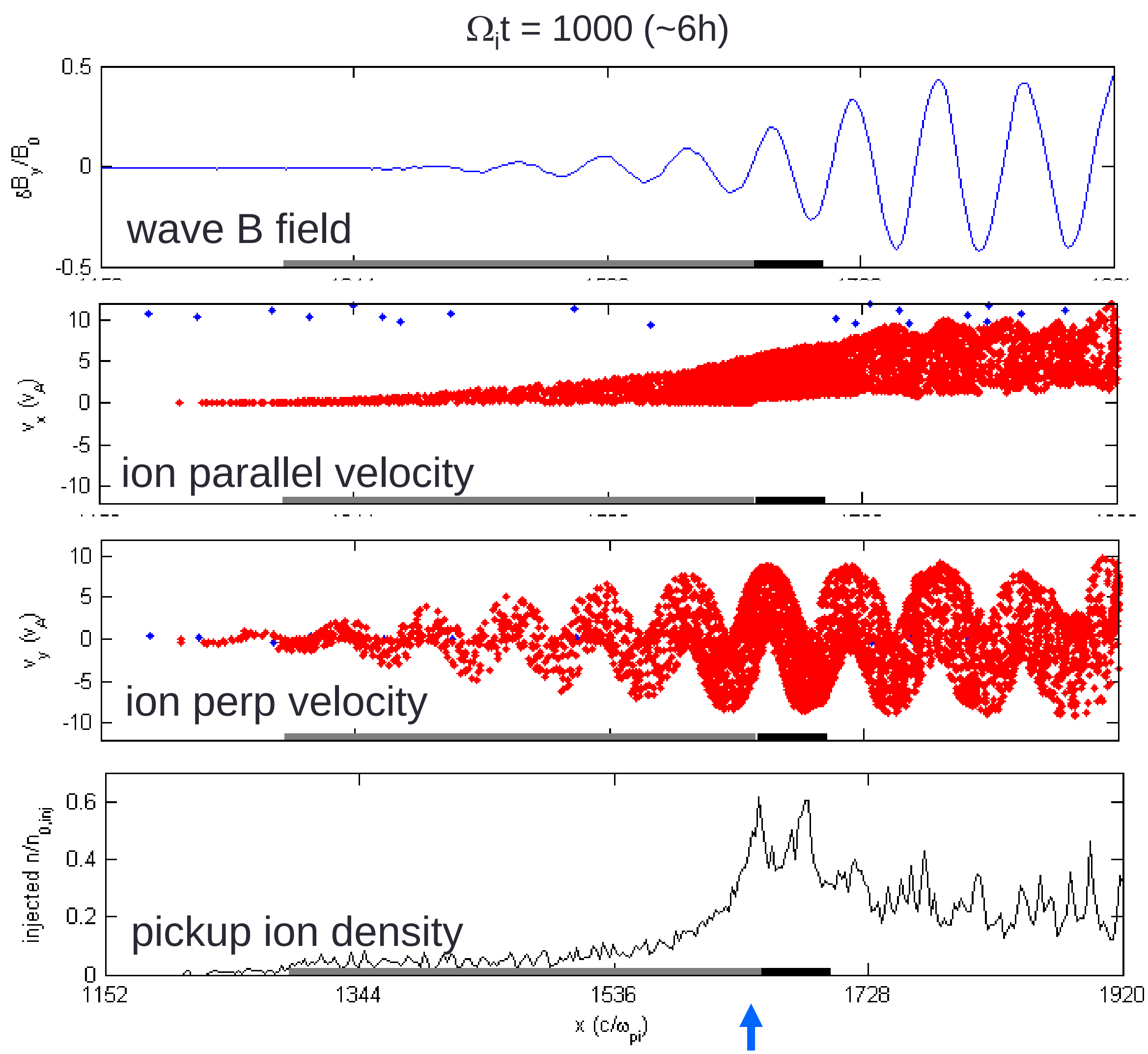
- Cartoon shows the simulation setup:
  - Simulation in the planetary rest frame: SW flows through the box and a newborn ion is created with zero velocity
  - Sim box length >> ion production region
  - Allows us to model the growth of waves as they convect downstream of Mars
  - Mars is not present in the simulation (there is no obstacle to the flow)
- Figure shows exospheric ion production profiles along Mars-Sun line used in the simulation (courtesy J.-Y. Chaufray)
  - Rates from SPICAM min and max densities with photoionization rate of $3x10^{-8}$ 1/s
  - We also use profiles with10x SPICAM max and 0.1x SPICAM min densities



The simulation results shown next using the SPICAM max profile.

Mars long box simulation results

- Figure shows wave B field, SW ions, injected ions, and injected ion density along the simulation axis
  - Mars location indicated by **black bar**, mass loading region by **gray bar**
- Injected ions accumulate until instability grows.
  - Very low densities of newborn ions can drive waves
  - For the exactly parallel pickup conditions here (E = -v x B = 0) newborn ions are not swept downstream by the SW but maintain zero velocity.
- Waves grow and propagate downstream.
  - Wavelength on the order of Mars radius.



In reality, waves will be disrupted here by Mars obstacle!

Mars simulation results (cont.)

- Upstream of Mars, the waves are in a state of growth and the pickup ion distribution is only partially scattered.
  - The increase in wave amplitude closer to Mars, is then not merely due to a stronger exospheric source, but also the growth of the waves over time as they are convected towards Mars

- We cannot assume that the local ICW amplitudes are representative of a local fully scattered pickup ion distribution.
  - No simple “rule-of-thumb” for interpreting local ICW amplitudes in terms of local pickup ion rates and densities.

- ICW amplitudes for ion production rates based on the SPICAM max exospheric densities are in the lower range of MGS observed wave amplitudes at +1 to +2 R_M

- We are currently working on expanding this to 2D simulations and different pickup geometries …

So …

Thank you, Chris!

Thanks for introducing me to an excellent thesis topic, which has continued to yield new and interesting results!

References

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