INVITED TALK TO THE 8TH ANNUAL RF IONOSPHERIC INTERACTIONS WORKSHOP 15-18 APRIL, 2012
SANTA FE, NM

INJECTION OF SHEAR ALFVEN WAVES IN THE INNER RADIATION BELT USING THE ARECIBO HEATER

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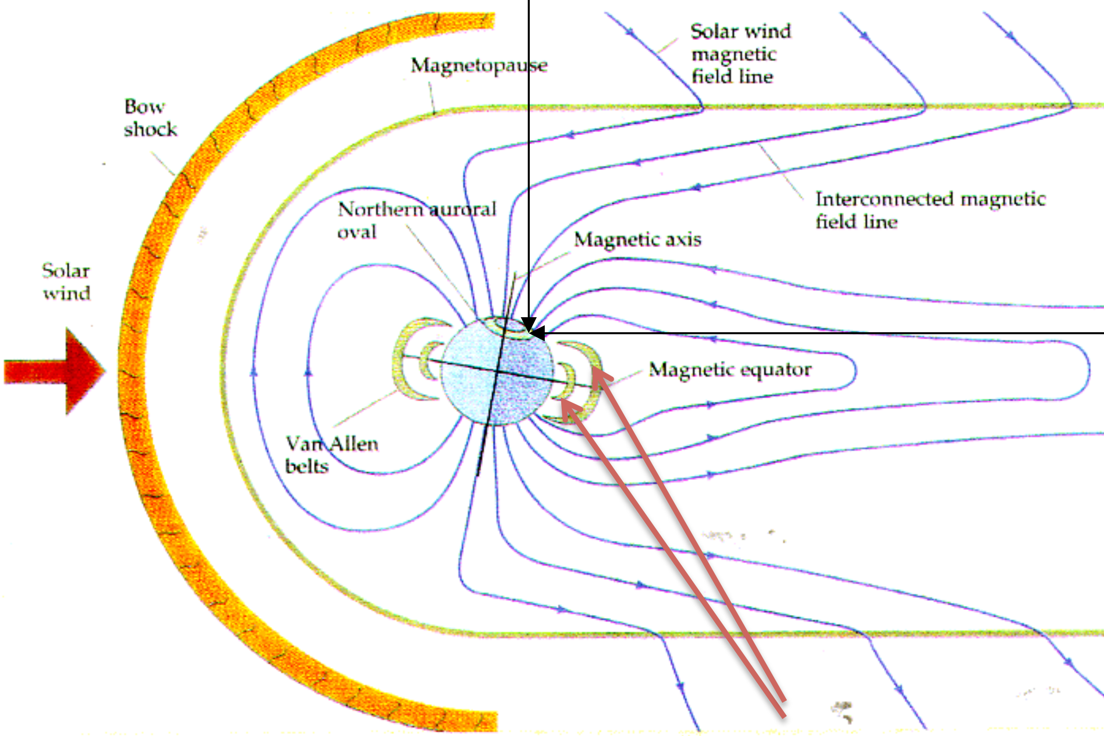
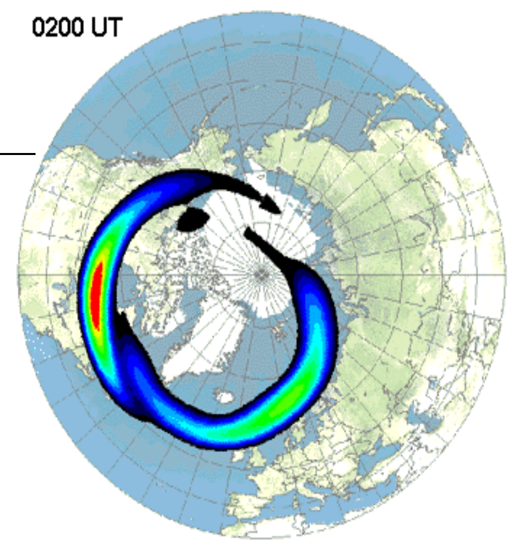
C.L.CHANG BAE SYSTEMS - BRIOCHE
U. INAN STANFORD - MURI
W. GEKELMAN UCLA - MURI

The Venue
Space Plasma Environment

Ionosphere



Electrojet

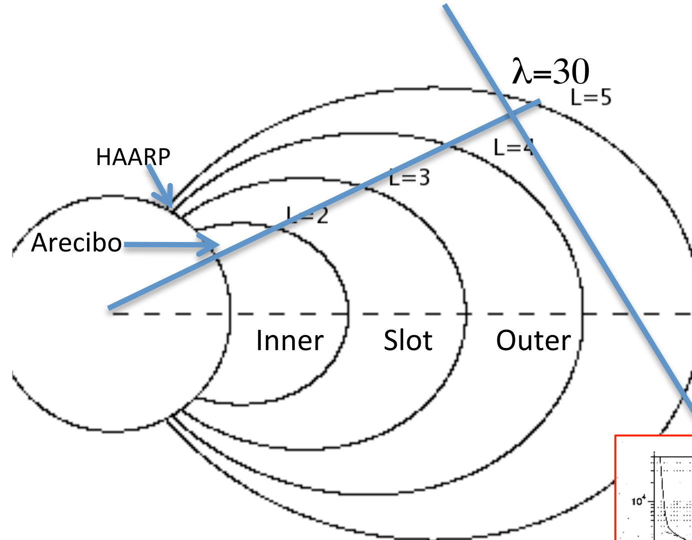


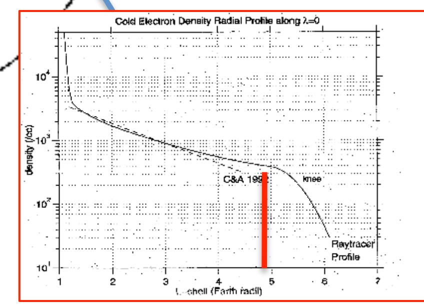
Radiation Belts (RB)

RB - BASICS

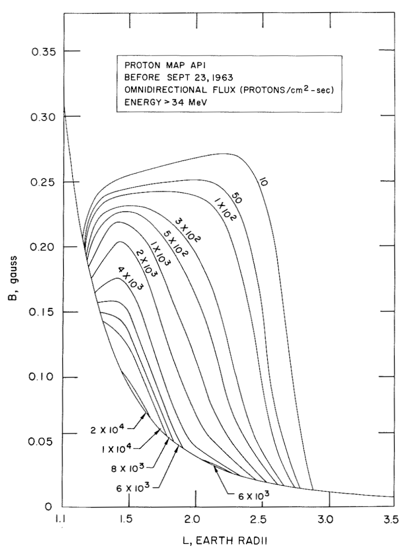
RB contains energetic (keV to MeV) charged particles trapped by the earth's dipole magnetic field and cold plasma (few eV)

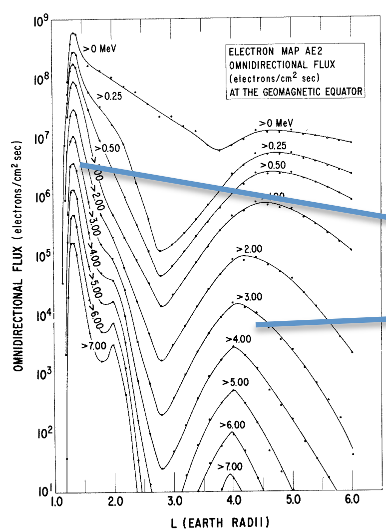
- Magnetic Configuration - Dipole
- L – Shells. $L=R/R_E$ along equator –(L,λ)
- Inner RB (1.5<L<2.2)(MeV electrons & multi-MeV protons – Long lifetime)
- Slot (2.2<L<3) – low electron flux
- Outer (L>3) - Mostly MeV electrons; Very dynamic relatively short lifetime

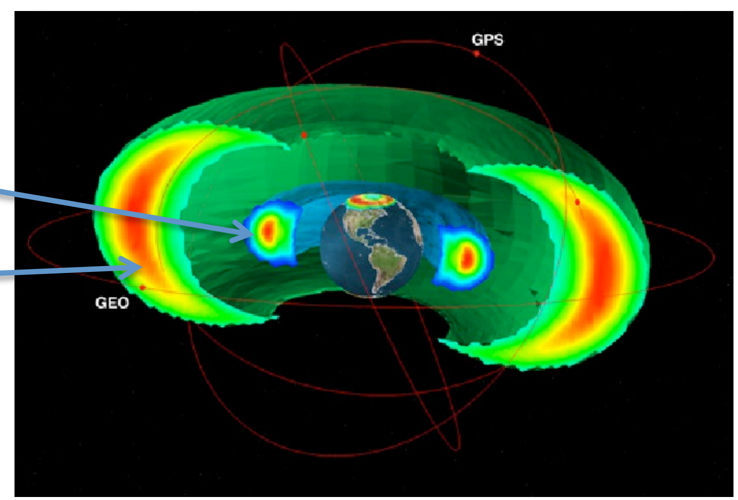




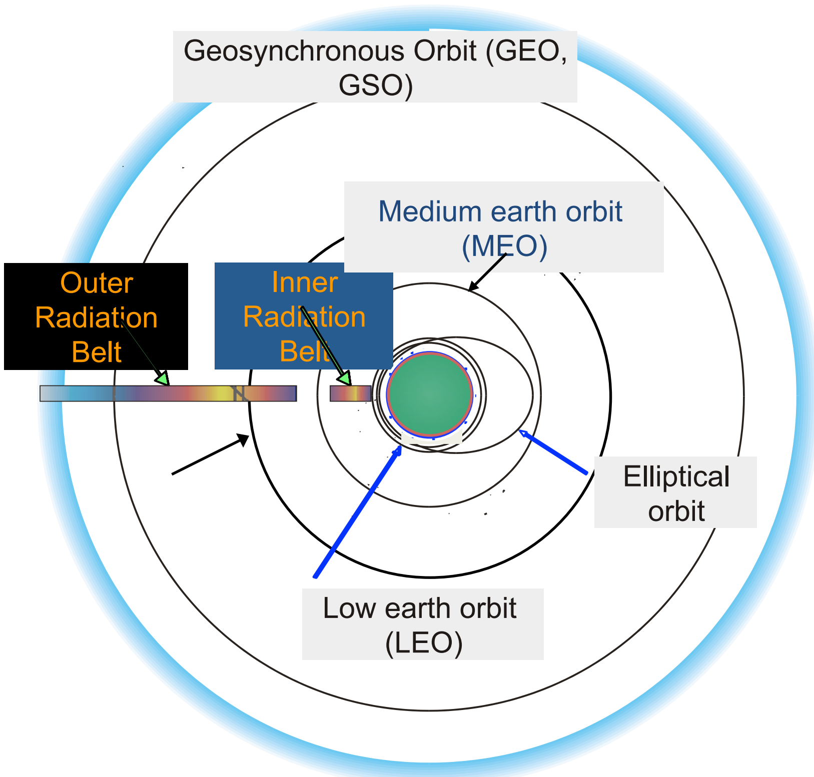
Electron flux – bimodal
Proton flux monotonic

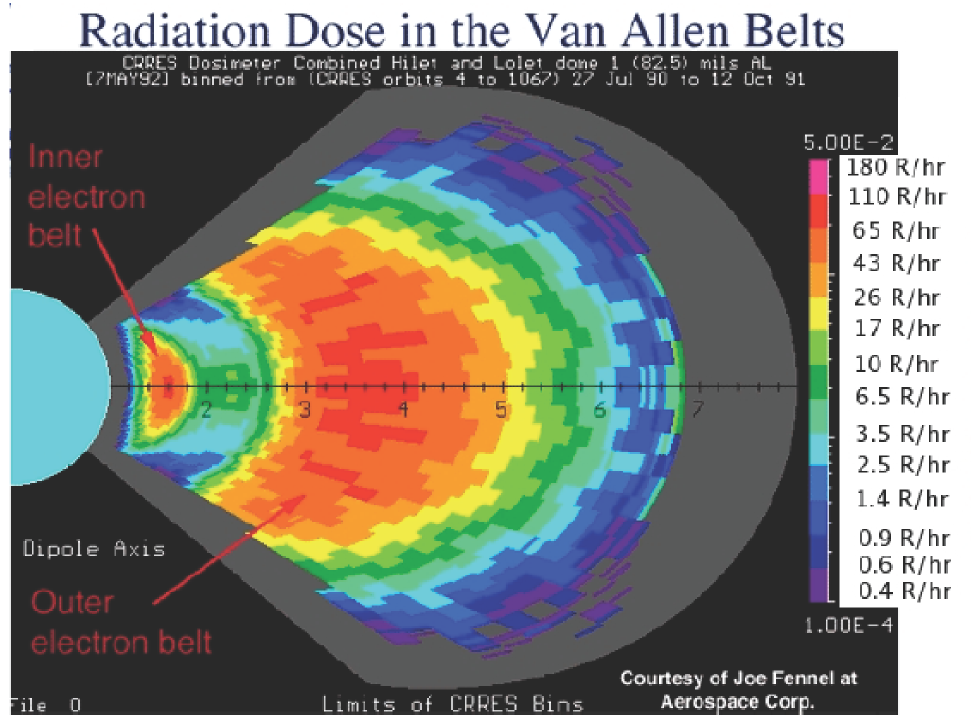






Why Care About RBs ?



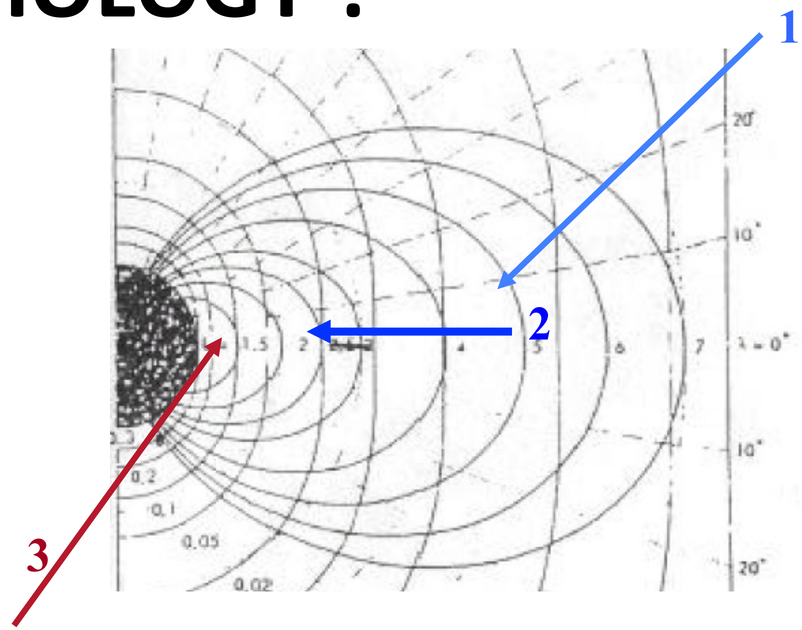


Fennel/Aerospace Corp., 2003

Lifetime and performance of space based assets depends critically on Energetic Particle Fluxes

WHAT CONTROLS THE RB MORPHOLOGY ?

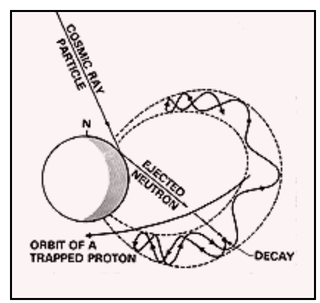
Rate of Flux Change =Sources – Losses



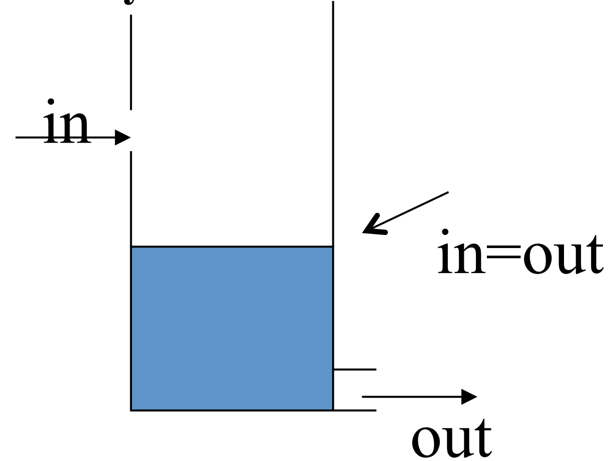
Sources - Natural

- **Solar Wind Particles (outer belt)**
- **Transport –Acceleration (gap)**
- **Cosmic Ray Albedo (inner)**

n→p+e+antineutrino



Leaky Bucket Model

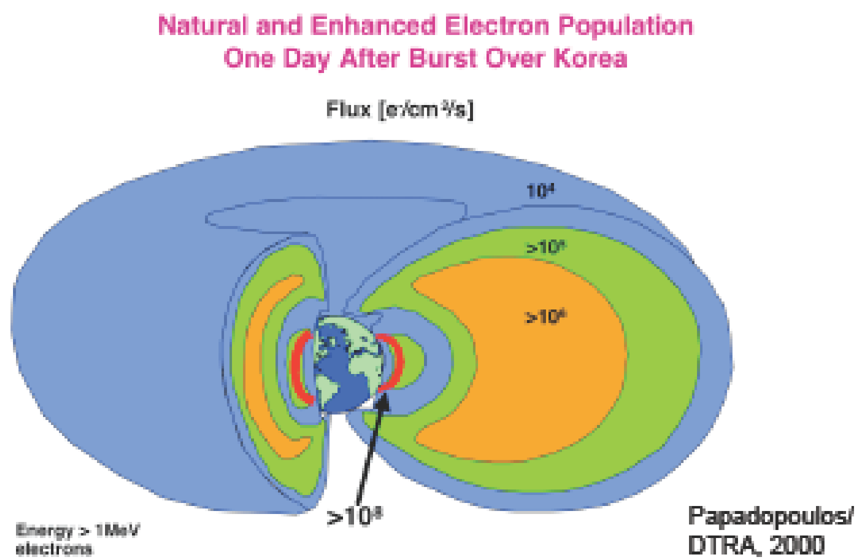


Radiation Belt Remediation (RBR)
What? Why?

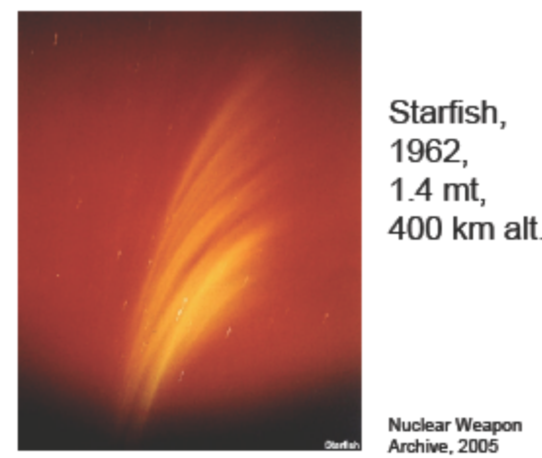
Anthropogenic Sources

High Altitude Nuclear Explosions (HANE)- e.g. ARGUS, Starfish

beta decay of fission fragments creates Mev electrons (10^{25}/MT)



Current Threat: Intercept of nuclear warhead by BMD above 110 km –Iran, N. Korea – leads to loss of LEO satts within a month

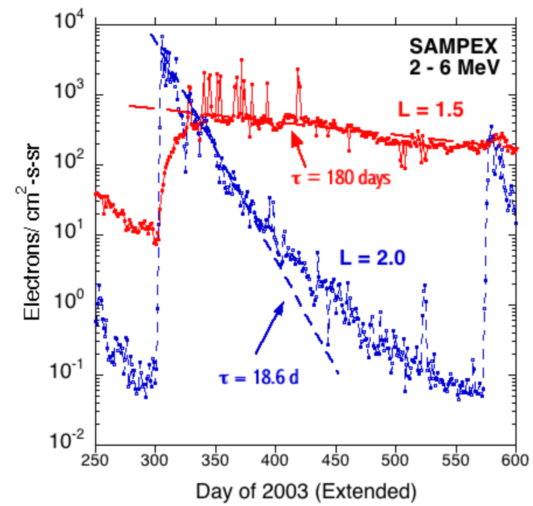


Injected MeV electron trapped in inner RB till 1969

SUPERSTOMS – CARRINGTON EVENTS

FROM 1-10 NOVEMBER, 2003 OUTER BELT CENTERED NEAR L~2.5 AND PLASMASPHERE WAS DISPLACED INWARDS LEADING IN NEW RADIATION BELT POPULATION IN THE SLOT AND INNER BELT.

DECAY RATES DEPENDED HIGHLY ON L VALUE AND VARIED FROM 35 DAYS TO MORE THAN A YEAR



BAKER AND KANEKAL 2007

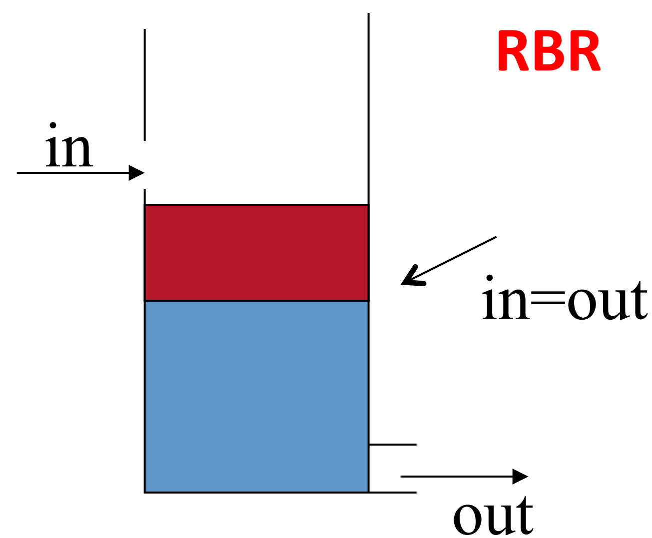
350 nT

TABLE IV

Chronological listing of outstanding geomagnetic storms recorded at Greenwich/Abinger, 1859–1954[a].

Date	Ranges		
	Declination (′)	Horizontal force (nT)	Vertical (nT)
01 Sep. 1859	≫92	≫625	1500
04 Feb. 1872	125	800	>950
17 Nov. 1882	115	>1090	>1060
31 Oct. 1903	119	1175	1440
25 Sep. 1909	193	1710	>1080
14 May 1921	110	≫740	≫460
25 Jan. 1938[b]	126	1055	570
16 Apr. 1938	307	1375	500
24 Mar. 1940	131	1370	1000
01 Mar. 1941	186	1650	1310
18 Sep. 1941	123	1250	1115
28 Mar. 1946	162	1660	920
21 Sep. 1946	136	925	450

[a]Jones, 1955.
[b]This storm was not included in Chapman and Bartels' (1940) list of great storms from 1857–1939.



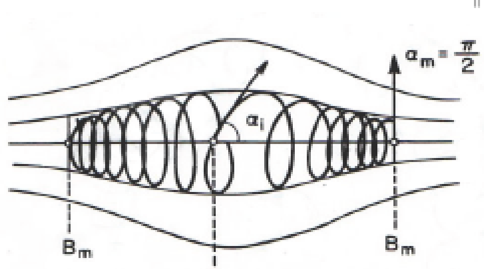
Physics of Loss Rate
Energetic Particle Motion in Dipole Fields
Adiabatic Invariants

Gyro motion:

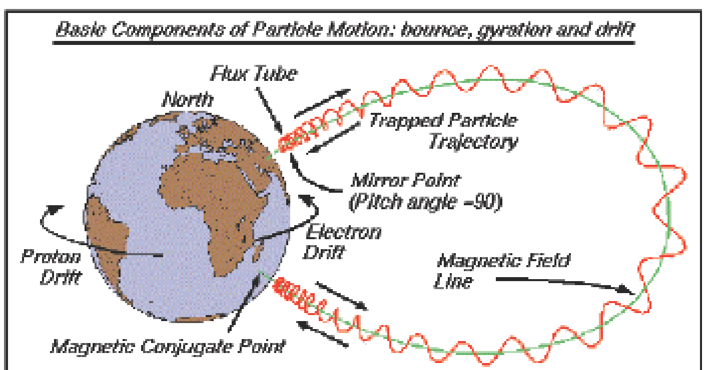
- V x B acceleration leads to gyro motion about field lines
- frequencies ~kHz
- associated 1st invariant μ, relativistic magnetic moment:

$$\mu = \frac{p^2 \sin^2 \alpha}{2 m_0 B}$$

pitch angle α: $\tan\alpha = \frac{V_\perp}{V_\parallel}$

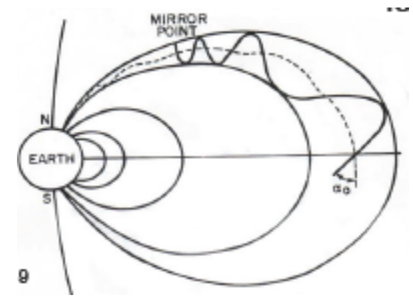


R=100



Bounce motion:

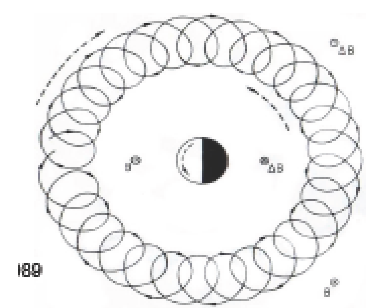
- As a particle gyrates down a field line, the pitch angle increases as B increases
- Motion along field line reverses when pitch angle reaches 90° (mirror point)
- period ~sec
- associated 2nd invariant J, longitudinal invariant:



$$J = \int_{-l_m}^{+l_m} p_\parallel \, dl$$

Drift motion:

- Gradient in magnetic field leads to drift motion around Earth: east for electrons, west for protons/ions
- period ~minutes
- associated 3rd invariant ϕ, magnetic flux:



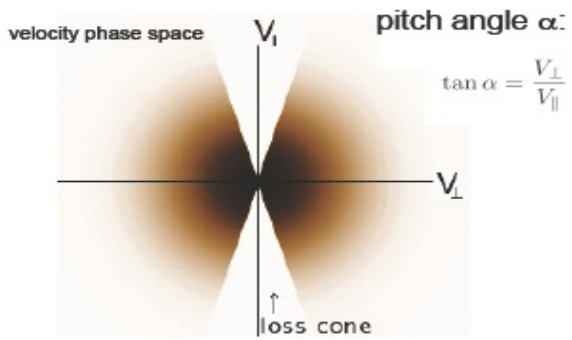
$$\Phi = -\frac{2\pi B_E R_E^2}{L}$$

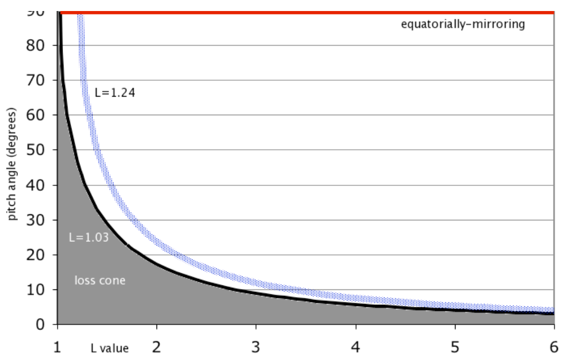
How Are Trapped Particles Lost in RB ? Loss cone

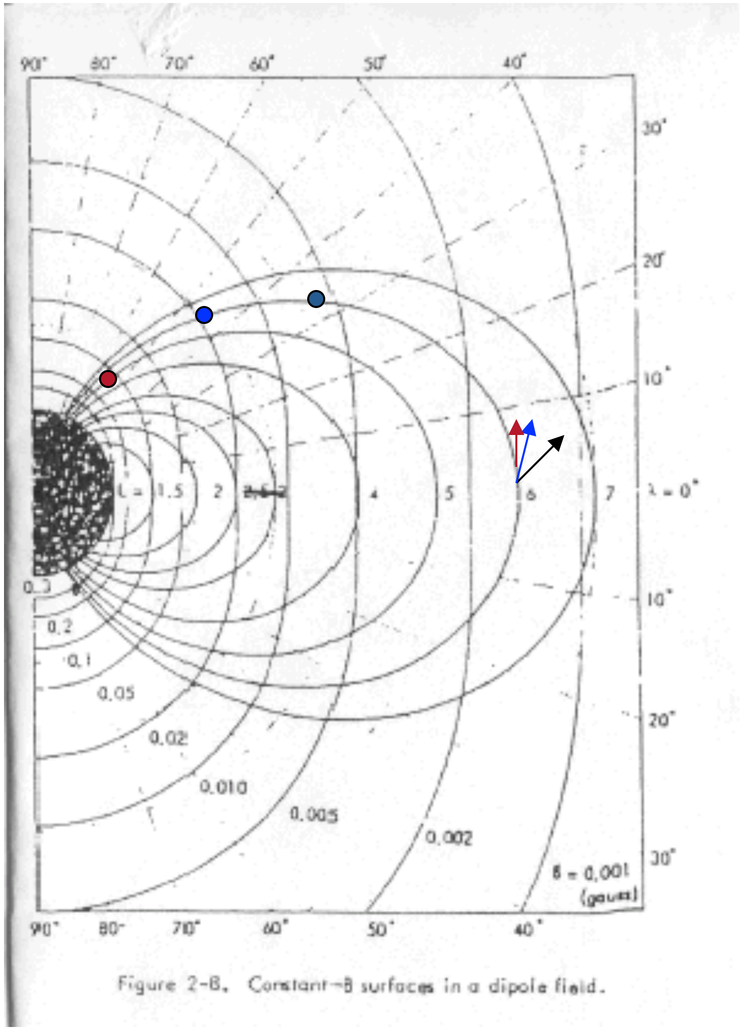
Particles whose mirror point is below 100 km will be lost by precipitation

↓

Loss Cone Distribution



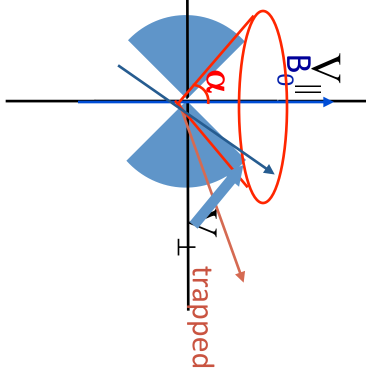




Particles trapped forever unless the change pitch-angle

PHYSICS OF LOSS RATE

1.Collisional Elastic Scattering

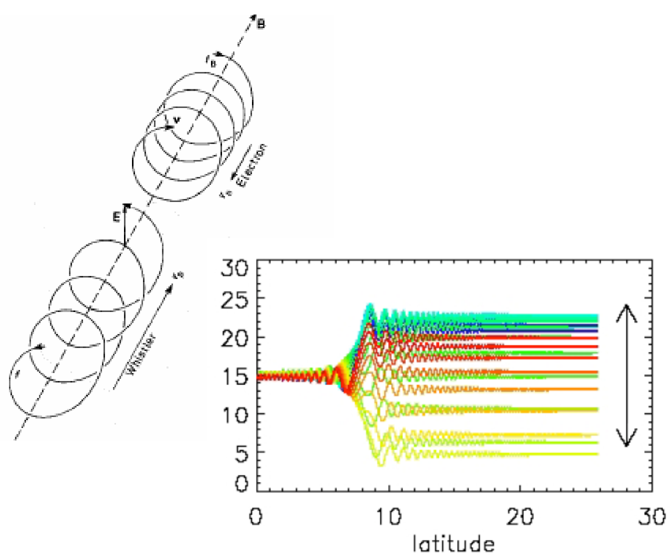


Breaks down first adiabatic invariant **μ** $p_\perp^2 / B$

2.Resonant Wave-Particle (WP) interactions

$$\omega - k_z v_z = n\Omega_e / \gamma$$

$$-k_z v_z \approx n\Omega_e / \gamma$$



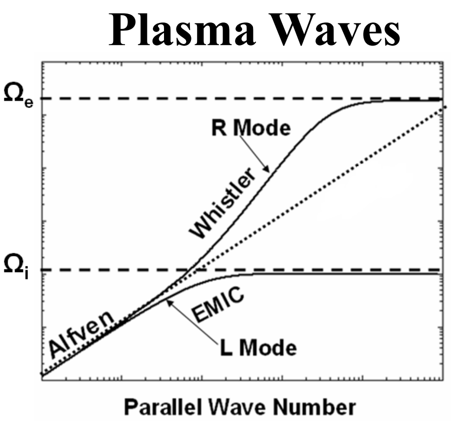
Jay Albert

- All $\omega << \Omega_e$ waves pitch angle scatter electrons if they have the right value of k_z .
- Elastic scattering along energy conserving trajectories (v x b_w)

$$D \equiv < \Delta\alpha\Delta\alpha > / \tau \; ; \; \Omega_e (b_w / B_o)^2$$

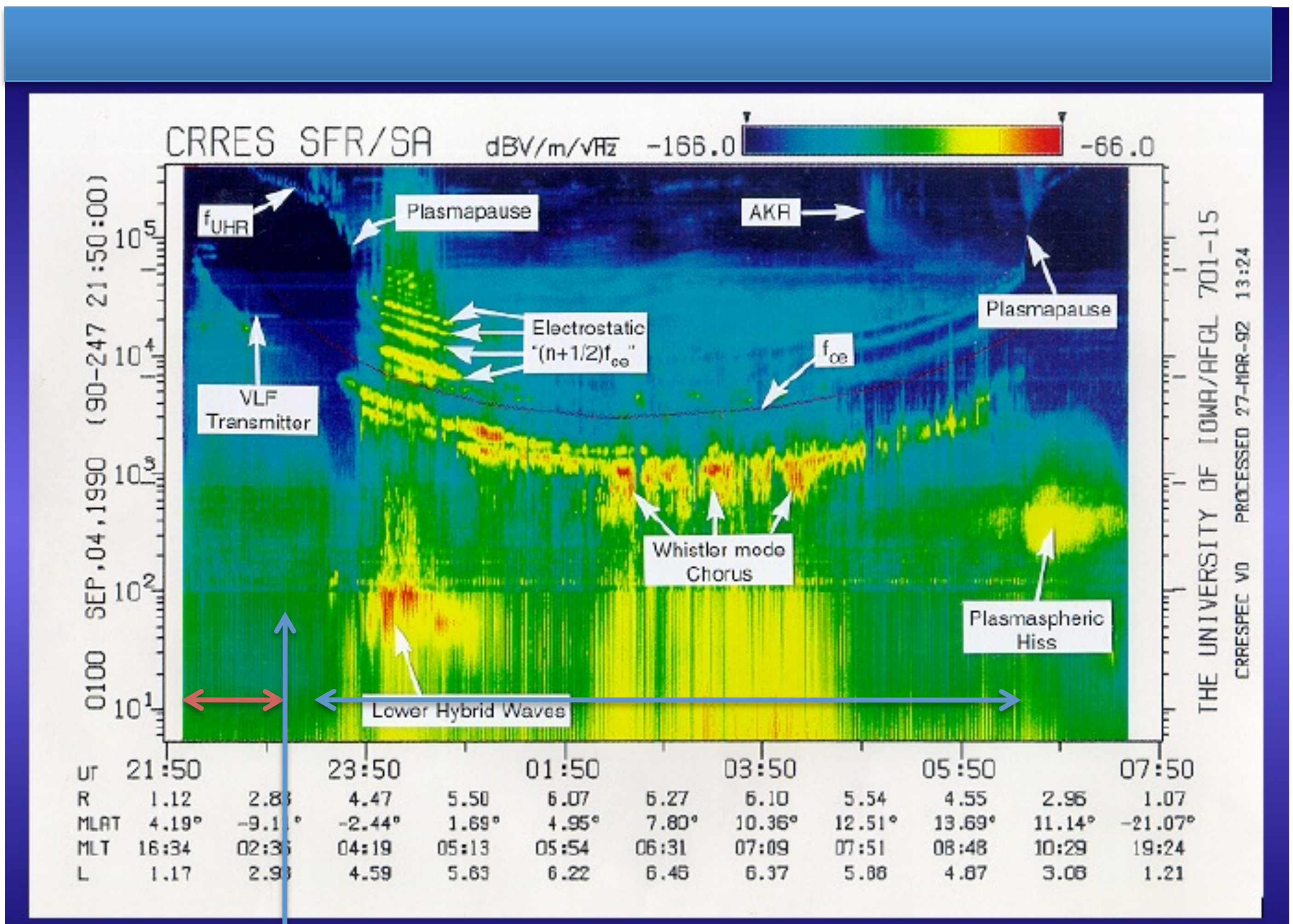
For protons replace Ω_e by Ω_p

Are there waves in the RB?



Whistler: a. Hiss (incoherent, noise-like)
b. Chorus (coherent, discrete, spiky)
MHD: Shear Alfven, Msonic, EMIC, FLR

Barkhausen [1919] heard audible 'whistles' whilst spying on allied communication



Lightning

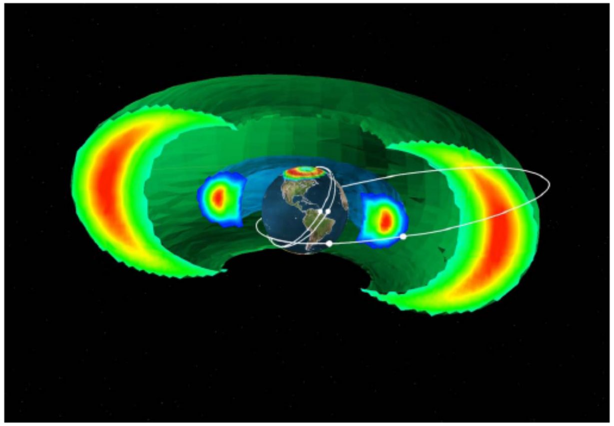
Addressing RB Physics Issues

1. **Conventional System Approach**

- **Simultaneous multi-point sampling at various spatial scales**
- **High quality integrated satellite measurements**

Particles generate waves – waves make particle distribution unstable - **Chicken and Egg Problem**

Radiation Belt Storm Probes (RBSP)



2. System Component Physics Approach

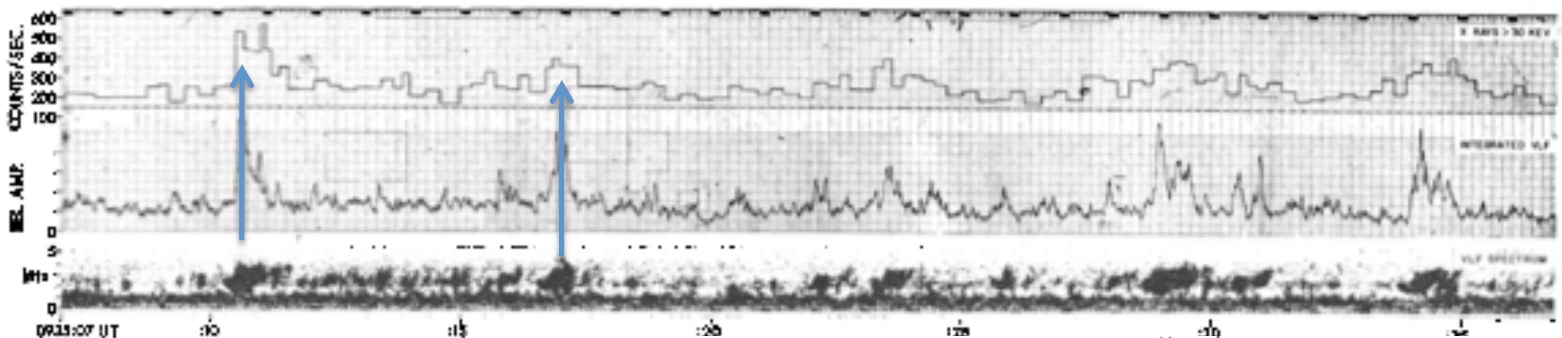
2.1 Laboratory Experiments
2.2 Active experiments by injection of ULF/ELF waves in the RB from ground or space
2.3 Facilitate development of RBR system options

UMD/ONR MURI Approach
PM: Bob McCoy

UMD-Stanford-UCLA-Dartmouth – VA Tech- Mishin

Puzzle: Coupled Whistler-driven Precipitation spikes with ULF (SAW) waves

Rosenberg et al. JGR 76, 8445, 1971; Lanzerotti 6 sec micropulsations



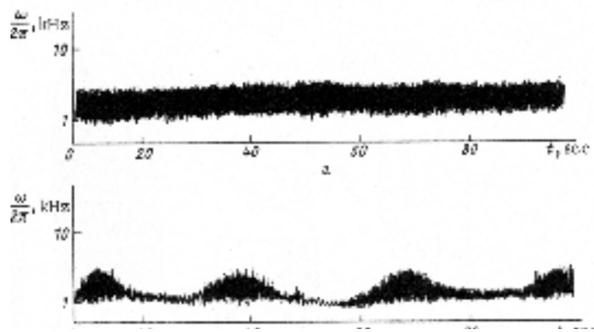
>30 keV

X-rays

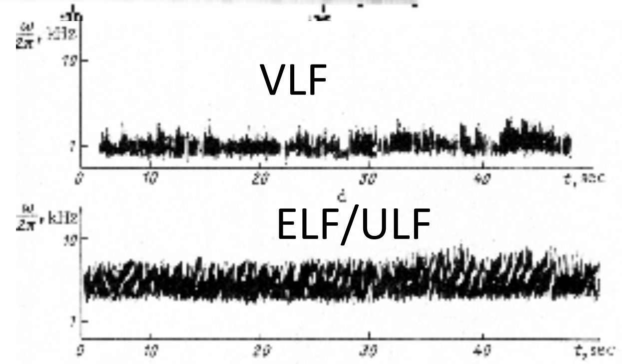
.5-5 kHz

6 sec mod

Ground



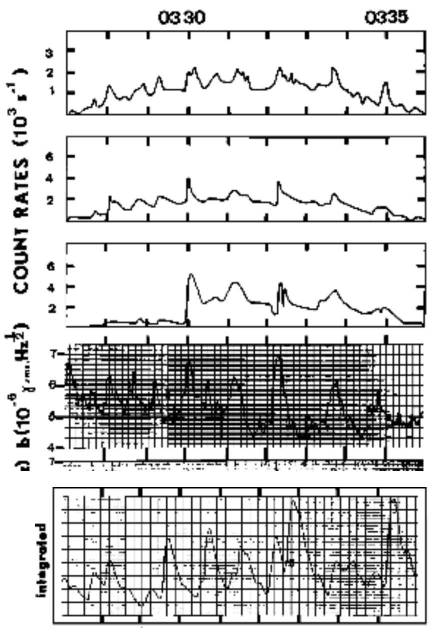
Hiss and q-periodic hiss



Chorus – Coherent hiss

Increase whistler energy density ->increase precipitation –RBR-> Inject whistlers (Helliwell 70's; DSX-Inan et al., 2002, Helliwell 70's) Alternative: Is it possible to inject SAW and use them to amplify whistlers or convert them to EMIC?

Speculation: SAW can lead to amplified whistler spikes



>210 keV

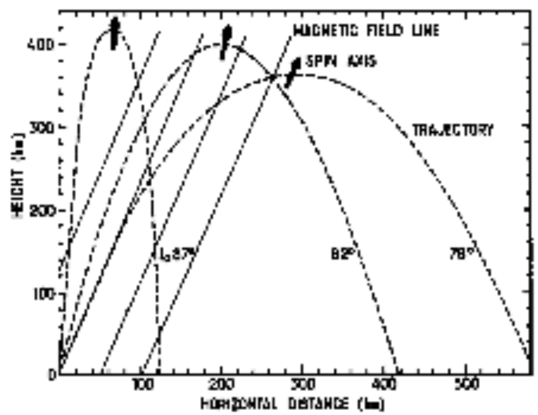
210>E>110 keV

110>E>55keV

VLF

ULF

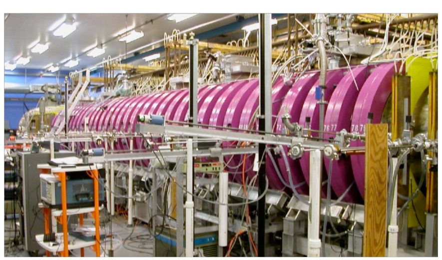
Gedrin et al. JGR, 1970



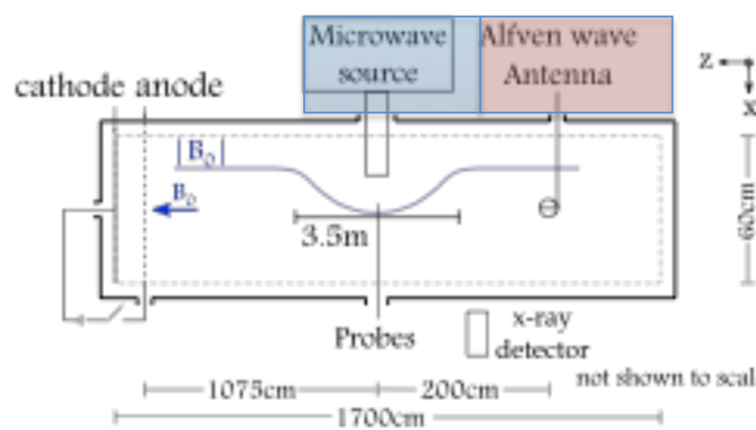
Periodic & quasi-periodic emissions: 100's of papers: Bespalov & Trakhtengerts Rev. Plasma Physics Vol. 10, 1986

MAJOR MURI OBJECTIVE: UNDERSTAND ROLE OF SAW TO MeV Electron Precipitation

Lab experiment UCLA Wang et al. PRL, April 2012

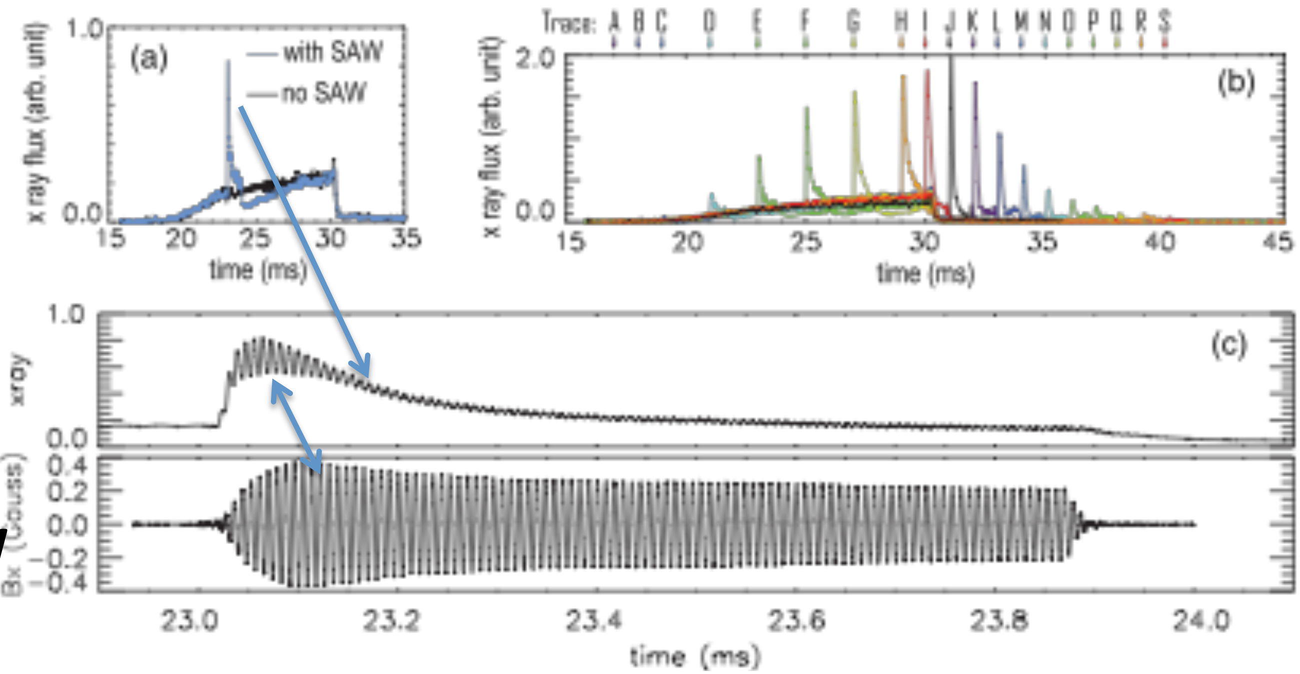


17 m,
10 sections control B
450 diagnostic ports



LAPD Experiment

SAW cannot break μ



Single pulse X-rays

Injected SAW 100 cycles

Physics hypothesis: Loss cone drives whistlers leading to steady state loss (KP)- Injection of SAW couples (?) to whistlers giving enhanced spiky loss

$$\frac{dN}{dt} = -\alpha \varepsilon_w N + J(t)$$

$$\frac{d\varepsilon_w}{dt} = \beta N \varepsilon_w - \nu \varepsilon_w + G_w(t) + \eta \varepsilon_w G_{SAW}$$

$$\nu \equiv \frac{2}{\tau_g} |\ln R|$$

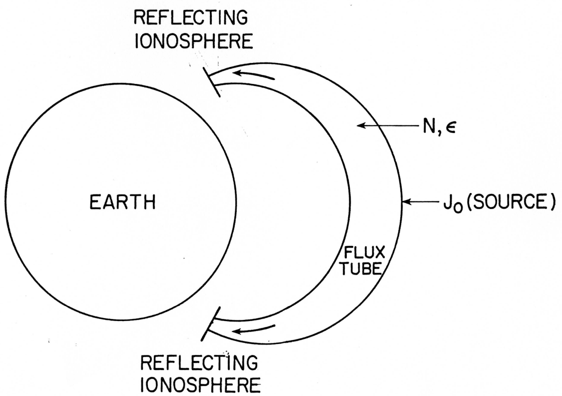
$$\varepsilon_w = (\beta / \alpha \nu) J$$

$$N = \nu / \beta$$

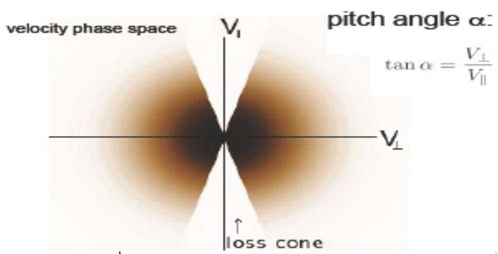
Analogy with Maser. First noted by Trakhtengerts

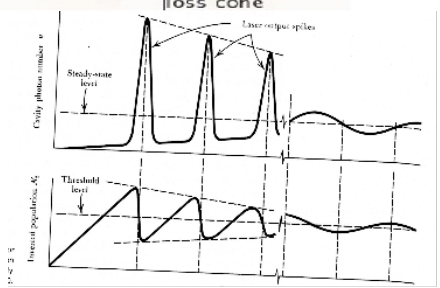
RB AS A MASER WHY ?

Take a flux tube



Loss Cone Distribution





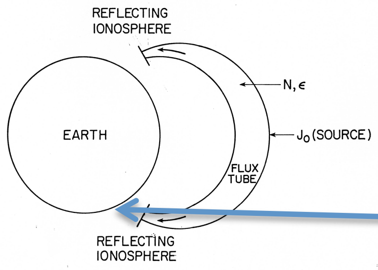
1. Fundamental modes Whistler and Alfven Waves.
2. Magnetic field tube with low density magneto-plasma corresponds to a quasi-optical resonator.
3. High density and conduction ionospheric regions correspond to the mirrors with reflection and transmission coefficients.
4. The active medium is the energetic particle loss cone distribution intrinsically maintained in the geometry – Population inversion
5. Pumping can be provided by sources of energetic particles or waves externally injected or external control of the cavity Q.

$$\frac{dn_p}{dt} = Kn_pN_2 + KN_2 - \frac{n_p}{\tau}$$

$$\frac{dN_2}{dt} = -Kn_pN_2 - \frac{N_2}{\tau_2} + R_p(t)$$

Exhibits relaxation oscillations, spiking, Q switching controlled by the pumping rate R(t)

RB SAW Injection Tests

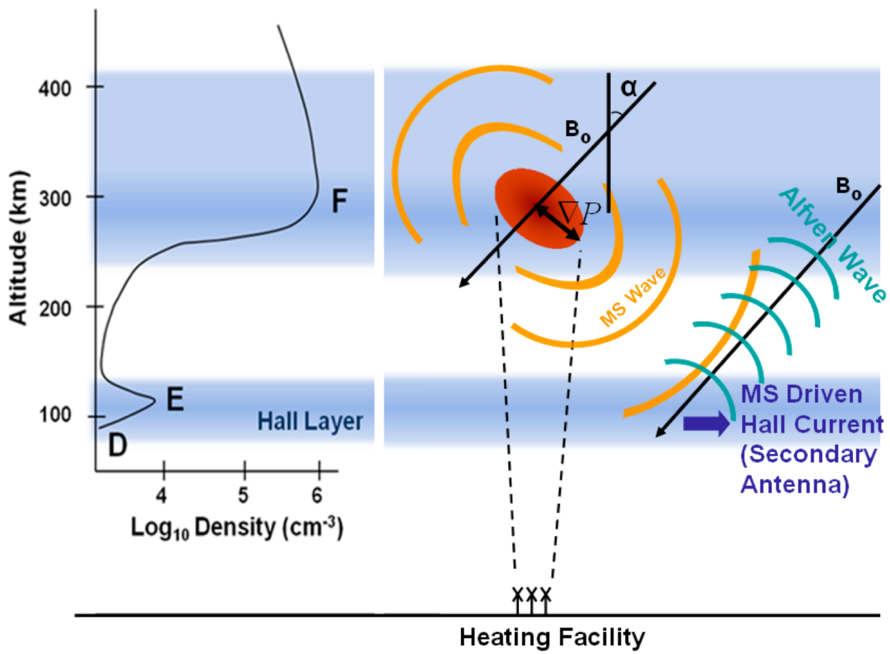


Need Source that can inject SAW into RB Ionospheric Heater

Ionospheric Current Drive (ICD)

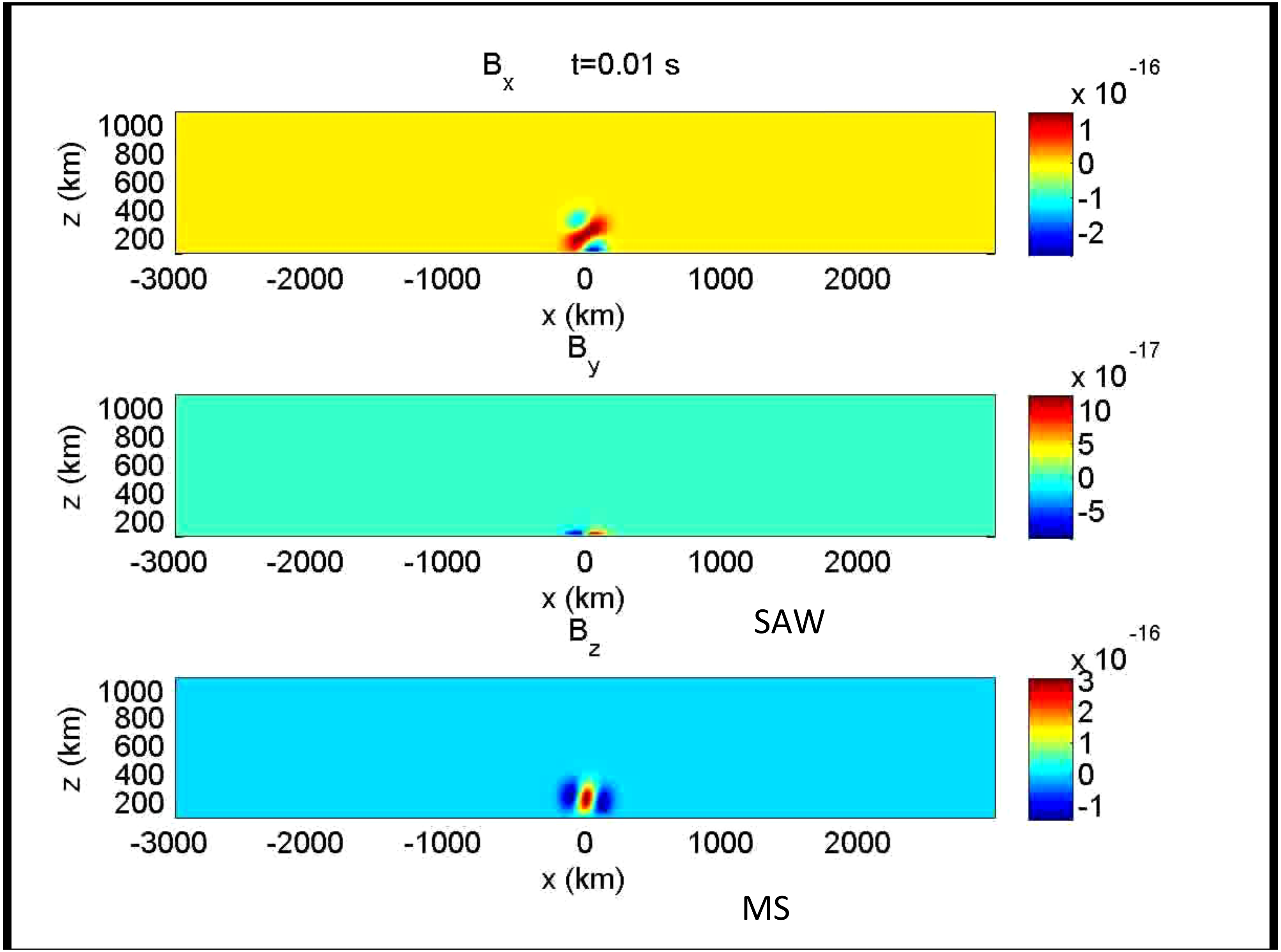
Step 1: $$\Delta J = \frac{B \times \nabla \delta p}{B^2} \exp(i\omega t)$$ Diamagnetic current -> MS wave

Step 2: E field of MS wave drives Hall current in E-region resulting in secondary antenna



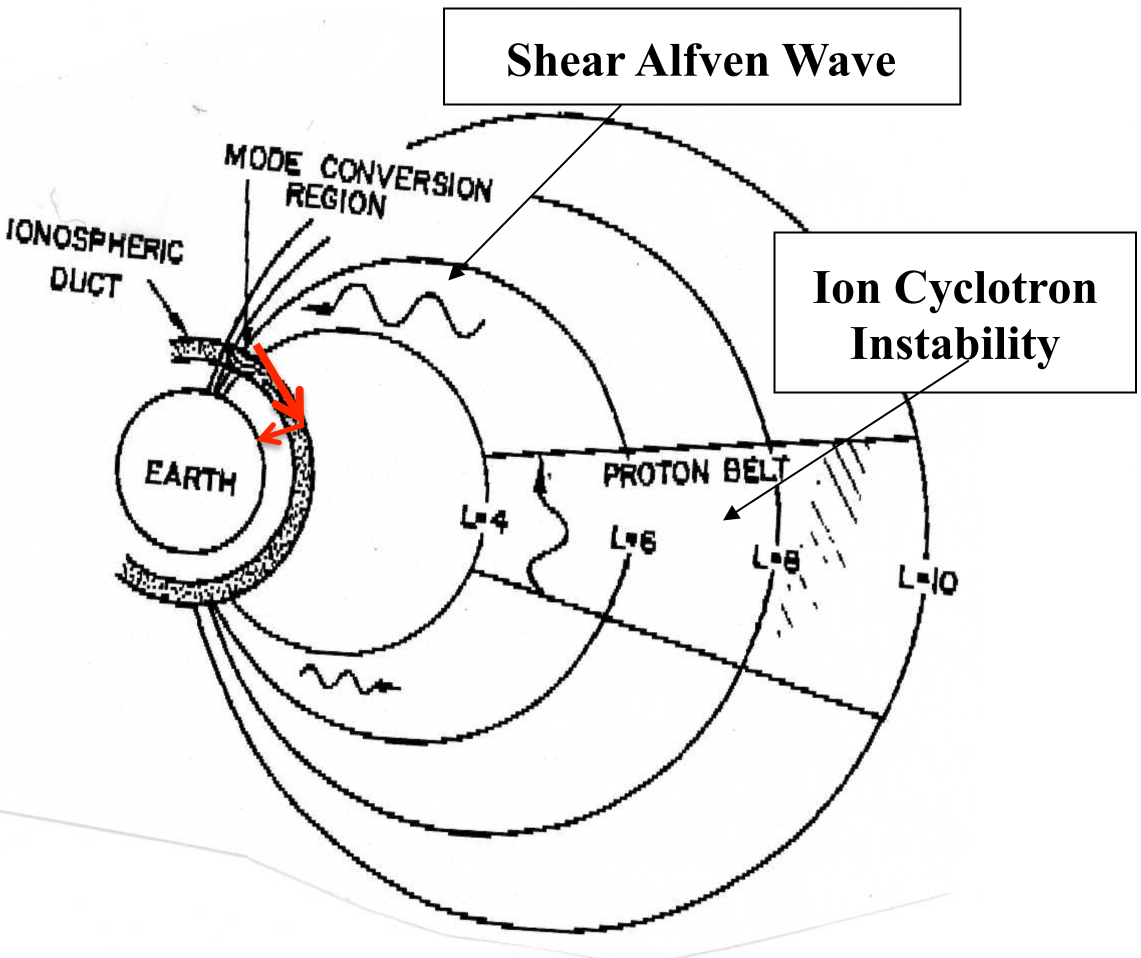
Injects SAW upwards and ELF in the Earth-Ionosphere Waveguide

ICD Inner RB Injection - Arecibo



Lateral Propagation of SAW signals as MS Waves

Lysak 1998



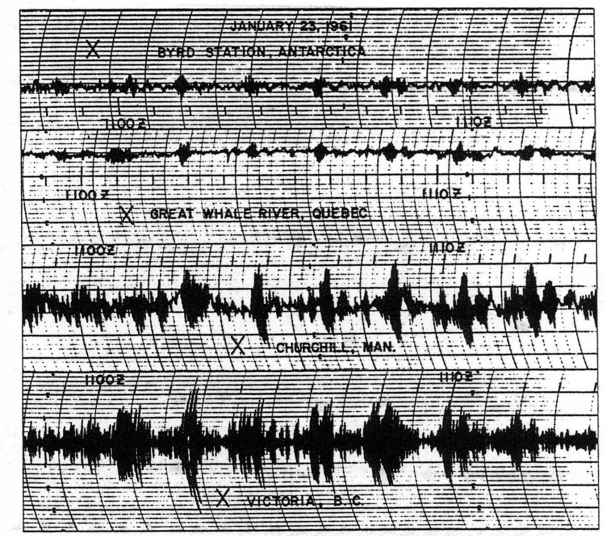


Fig. 2.1. Example of Pc 1's (pearls) recorded at four stations simultaneously. (After J. E. Lokken, J. A. Shand, and C. S. Wright, DREP photograph 2751)

Conjugate stations detect anti-phased pearl wave-packets

Proof of Concept ICD Injection Experiment HAARP/DEMETER

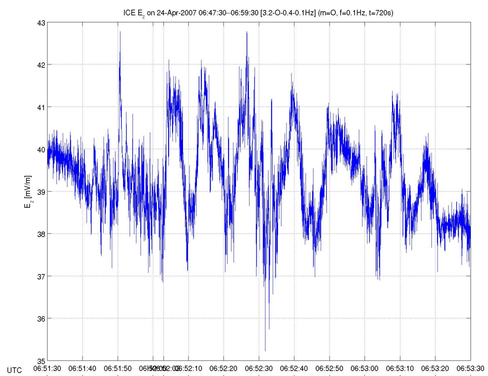
Chang-Lebinsky-Milikh-Papadopoulos

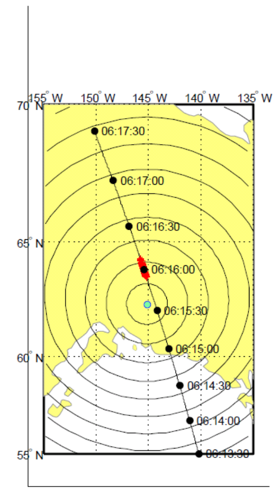
BRIOCHE

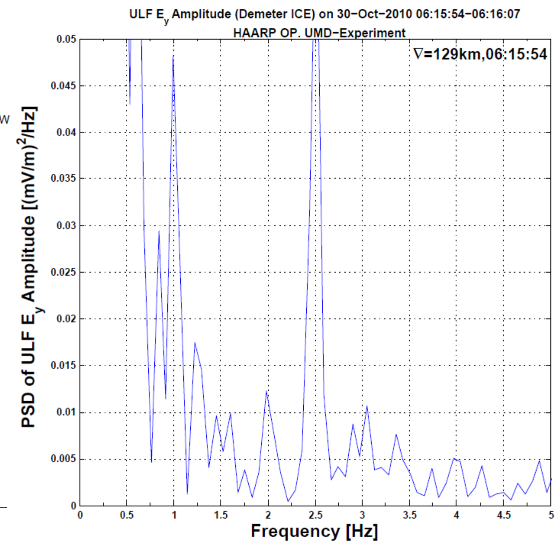
SAW

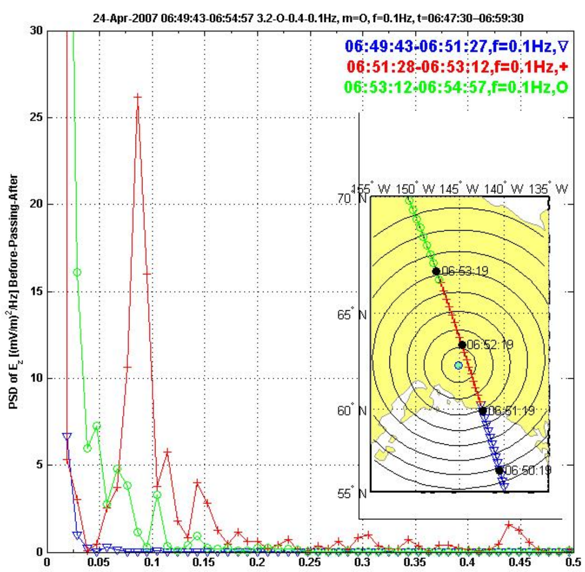
2.8 MHz, O-mode

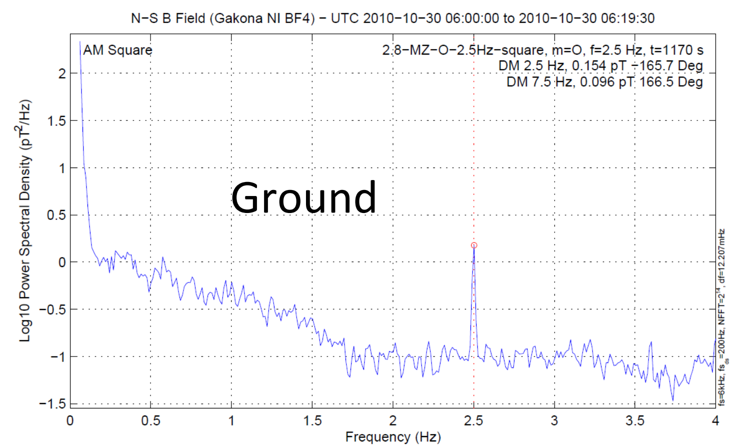
MS





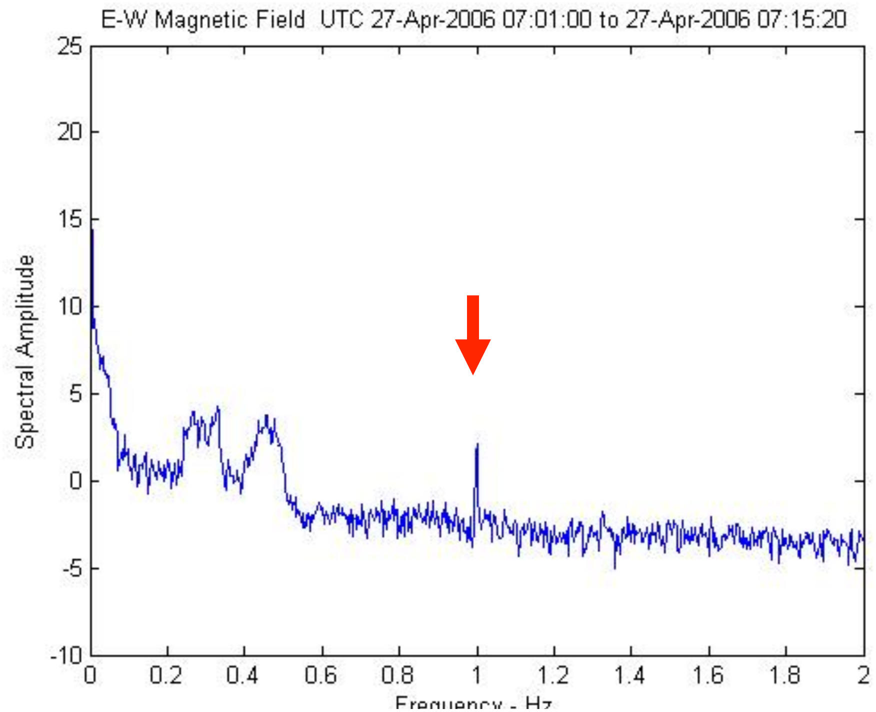


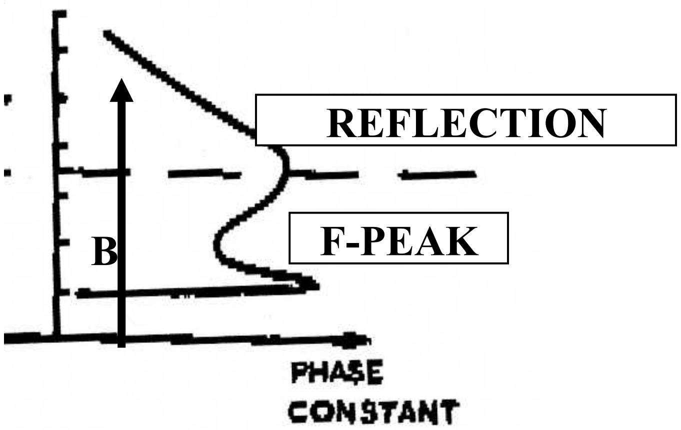


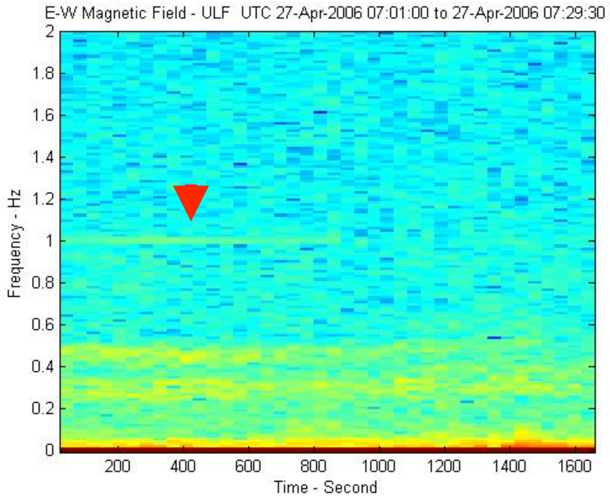


Papadopoulos et al.
GRL 2011a,b

IAR Excitation by the HAARP

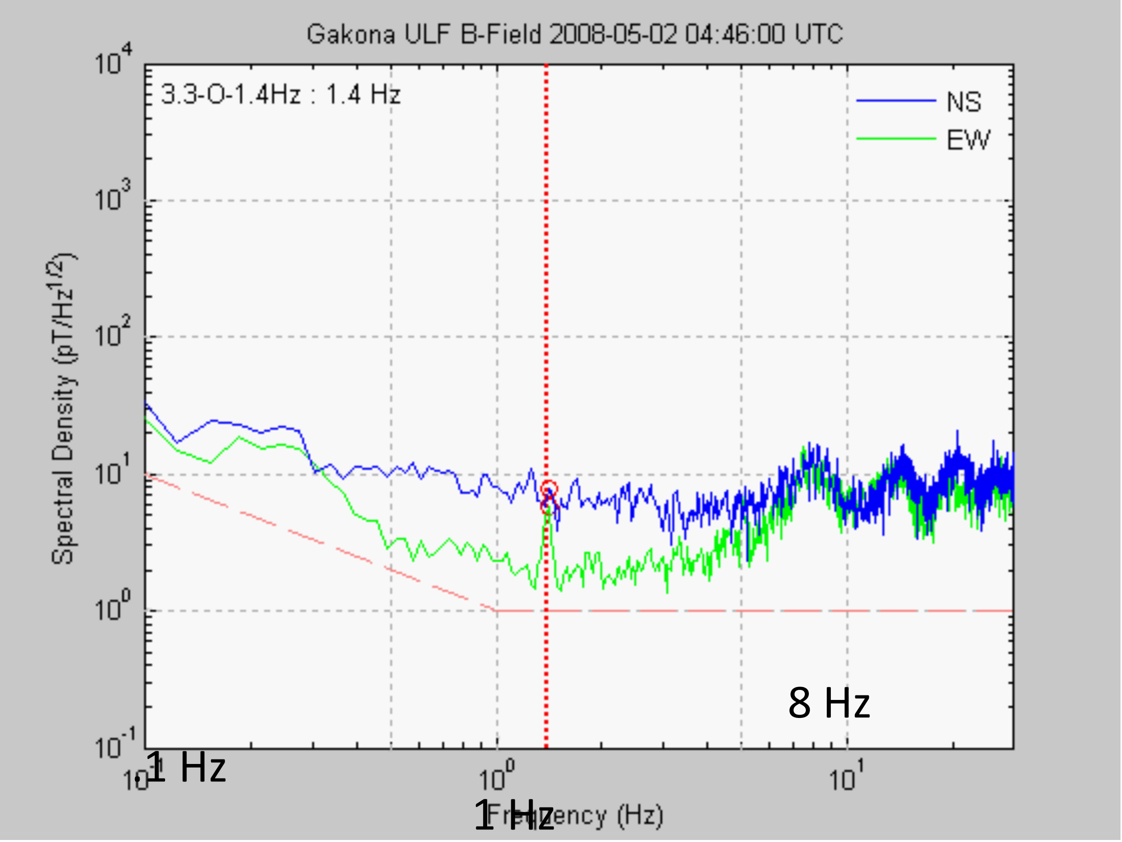




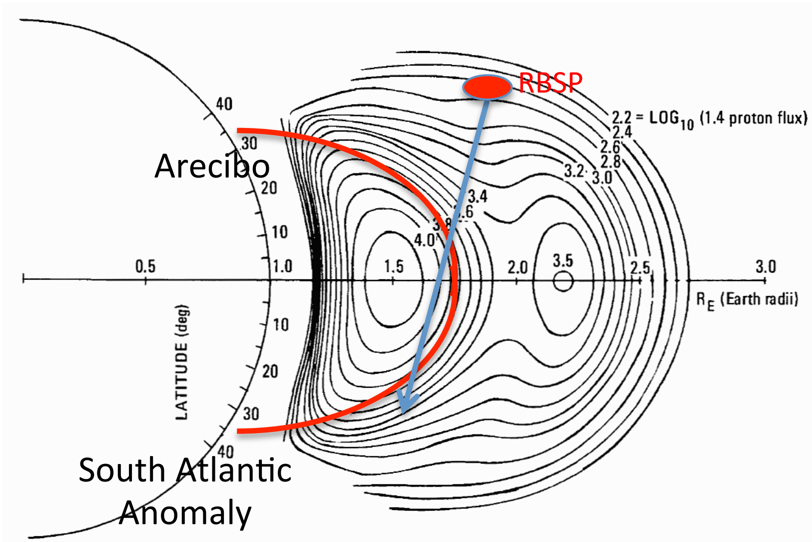


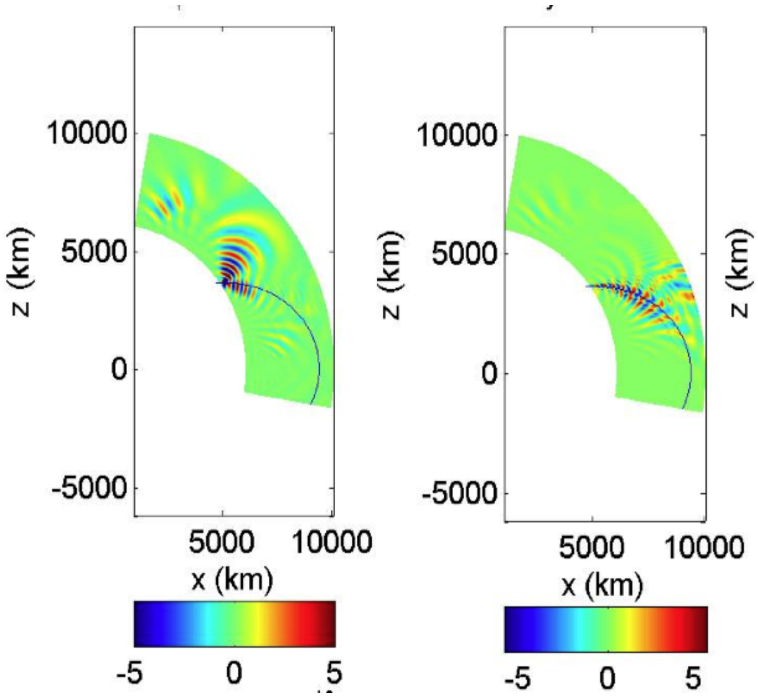
Excitation of the IAR due naturally excited waves at .25 Hz and .5 Hz and by HAARP generated SA at 1.0 Hz.

HAARP –ELF/ULF Injection



New Opportinuty - Active SAW Probing of Inner RB Using the Arecibo Heater/RBSP





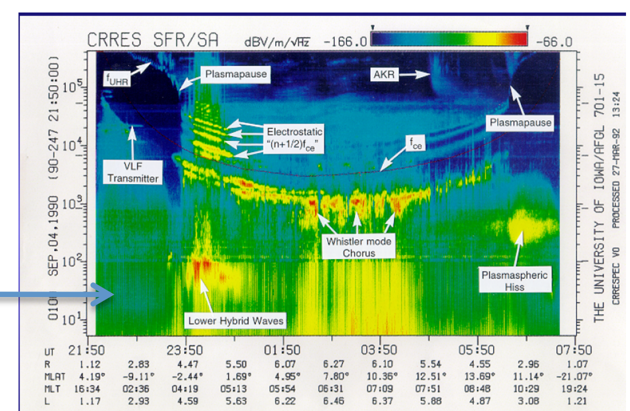
Focus on SAW for protons and EMIC for electrons

Typical inner belt proton lifetimes:

10 MeV – decades

50 MeV – century

No SAW activity
Stacking



Active Probing of Inner RB Using the Arecibo Heater Using ICD – Triggered EMIC

Focus on SAW for protons and EMIC for electrons

$$\omega \approx k_z V_p$$

$$\omega = k_z V_A$$

$$\omega(E,\alpha) \approx \frac{\Omega}{\cos\alpha}\sqrt{\frac{MV_A^2}{2E}}$$

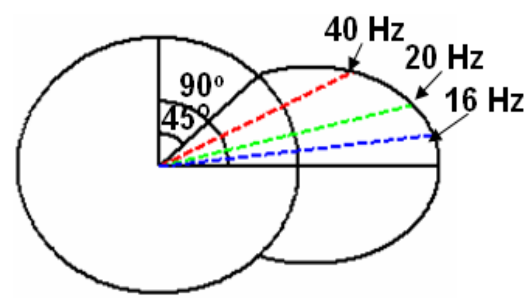
Proton Energy	Resonance Frequencies
30 MeV	6-16 Hz
50 MeV	5-15 Hz
100 MeV	3.5-9.5Hz

$$-k_z v_z = |\Omega_e| / \gamma$$

$$\frac{k^2c^2}{\omega^2} = 1 - \frac{\omega_{pe}^2}{\omega(\omega + |\Omega_e|)} - \sum_{j=1}^{3}\frac{\omega\omega_{pj}^2}{(\omega - \Omega_j)}$$

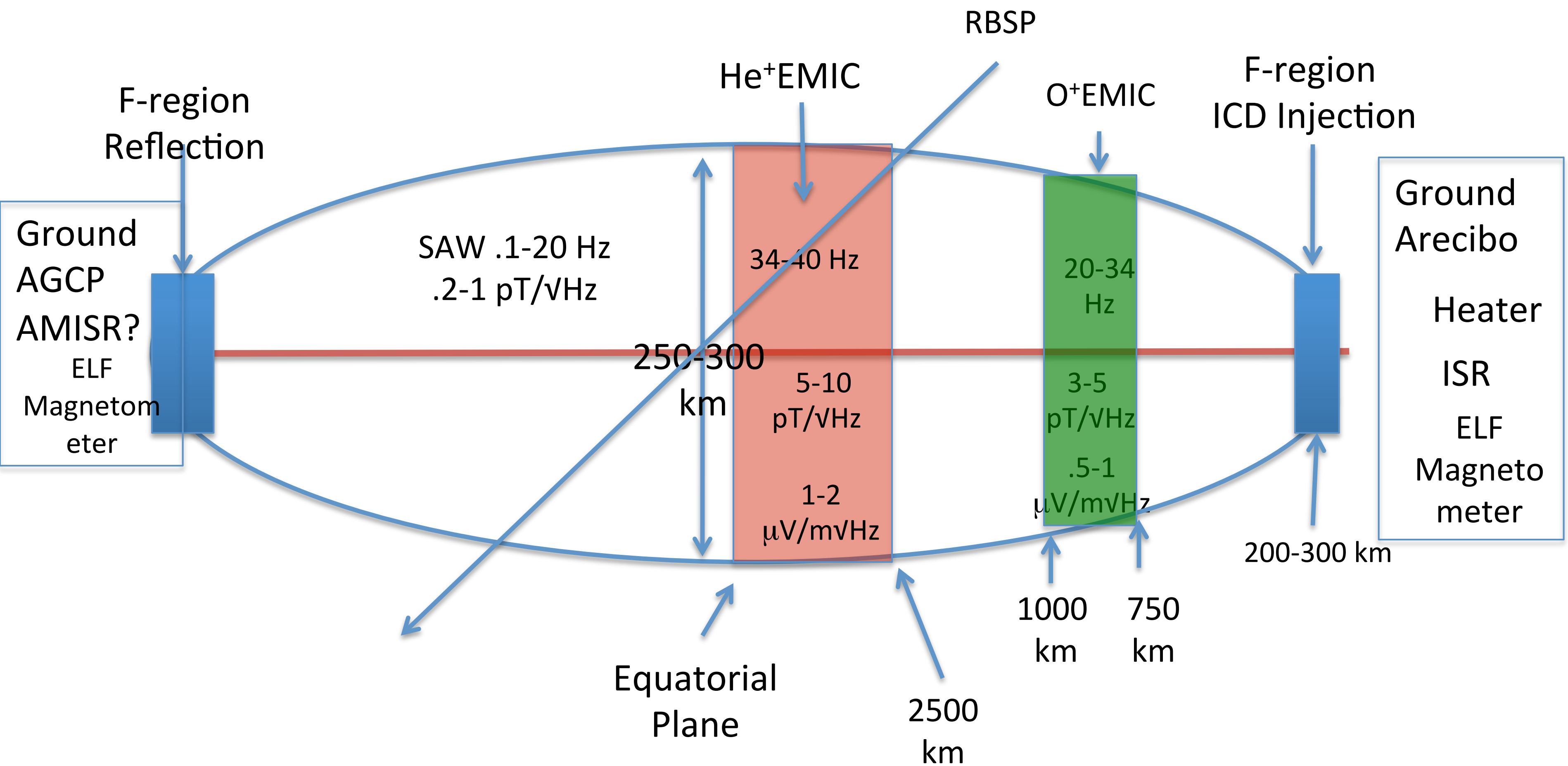
$$\frac{k^2c^2}{\omega^2} \to \infty \text{ for } \omega \to \Omega_j$$

As a result $1/k_z \to |\Omega_e| / \gamma v_z$ before reaching resonance ($1/k_z \to 0$)



HELIUM BRANCH Resonances

RBSP measures the waves and the energetic particles before during and after transitioning the L=1.4 flux tube so that we can use change detection and possibly statistical stacking



Straw-man of Arecibo Heater ICD/ RBSP Investigation

The Future

- **Use Ionospheric heaters (HF) to inject ULF/ELF/VLF waves in the L-shell that spans the heater and diagnose it with RBSP, Resonance, DSX, ePOP**

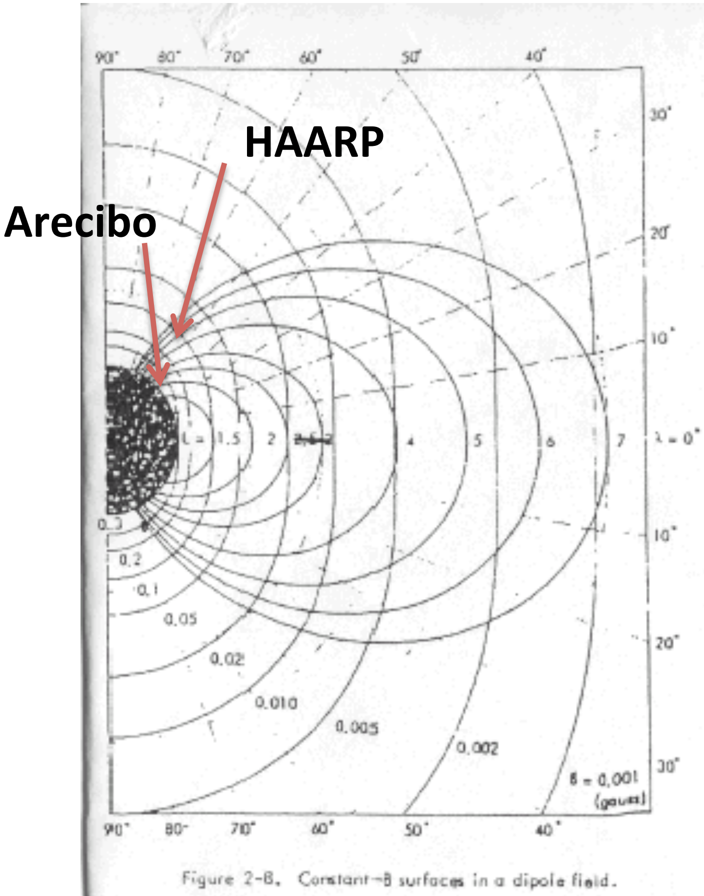
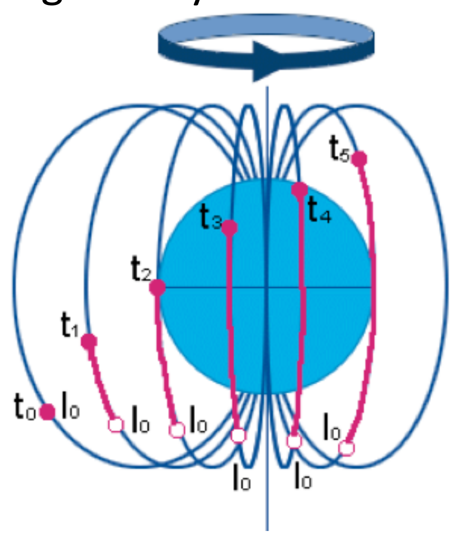


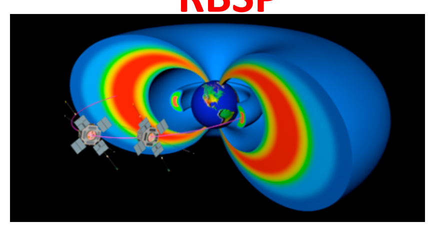
Figure 2-8. Constant-B surfaces in a dipole field.

Ionospheric Heaters
HAARP (L≈4.9)
Arecibo (L≈1.4)
Tromso (L≈5.9)
SURA (L≈2.6)

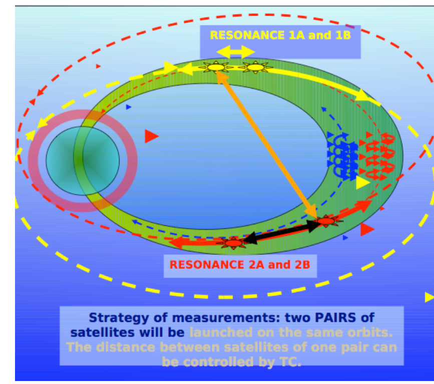
Magneto-synchronous



RBSP

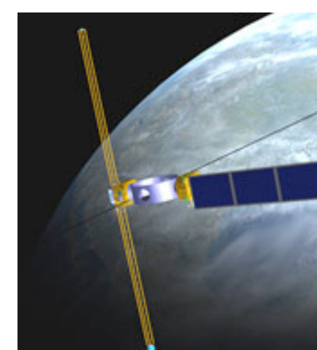


Launch May 18, 2012
2 probes, <1500 kg for both
10° inclination, 9 hr orbits
~500 km x 30,600 km



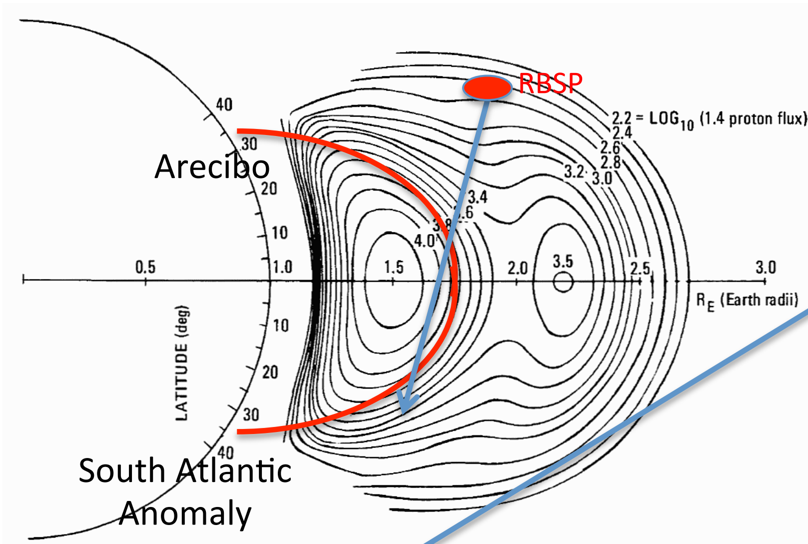
RESONANCE (Russia)
Launch ~2012-14, 4-spacecraft
Orbit:1800x30,000km, ~63° incl.

DSX (AFRL)
Launch ~2012
MEO, wave/ particle



THANK YOU

Active Probing of Inner RB Using the Arecibo Heater Using ICD – Triggered EMIC



Focus on SAW for protons and EMIC for electrons

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30 MeV	6-16 Hz
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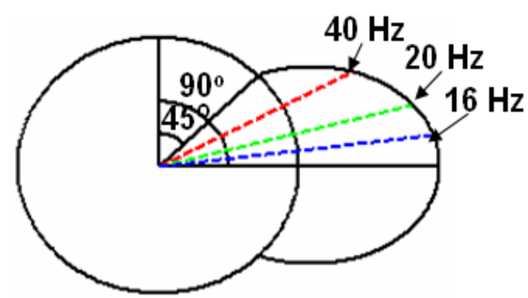
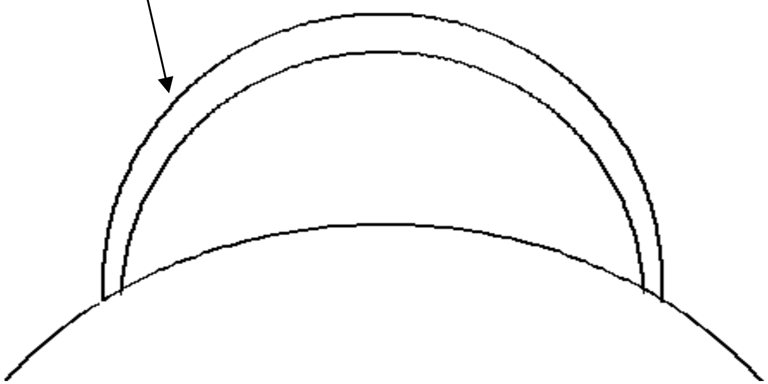


HELIUM BRANCH Resonances

Frequency Selection for Protons

Example for L=1.5

Fill tube with SAW

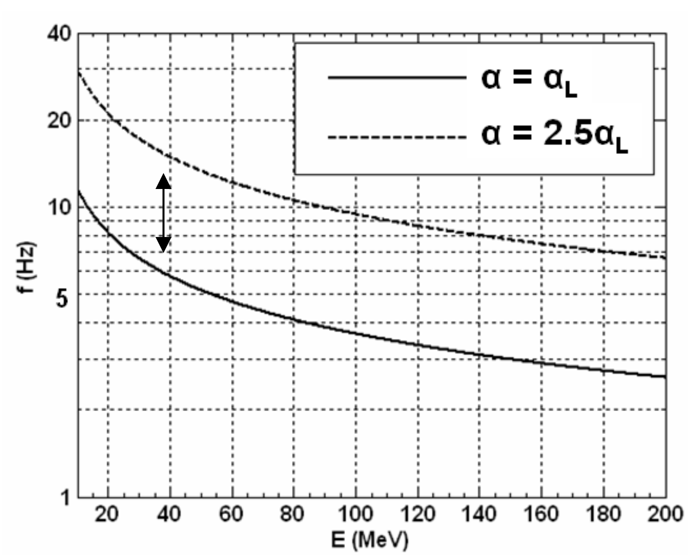


Frequency Selection for Resonance of Protons with SAW

$$\omega \approx k_z V_p$$

$$\omega = k_z V_A$$

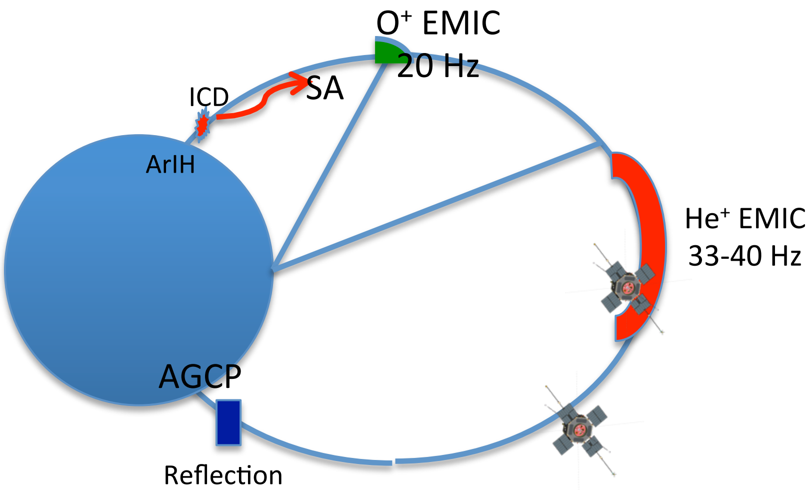
$$\omega(E,\alpha) \approx \frac{\Omega}{\cos\alpha}\sqrt{\frac{MV_A^2}{2E}}$$

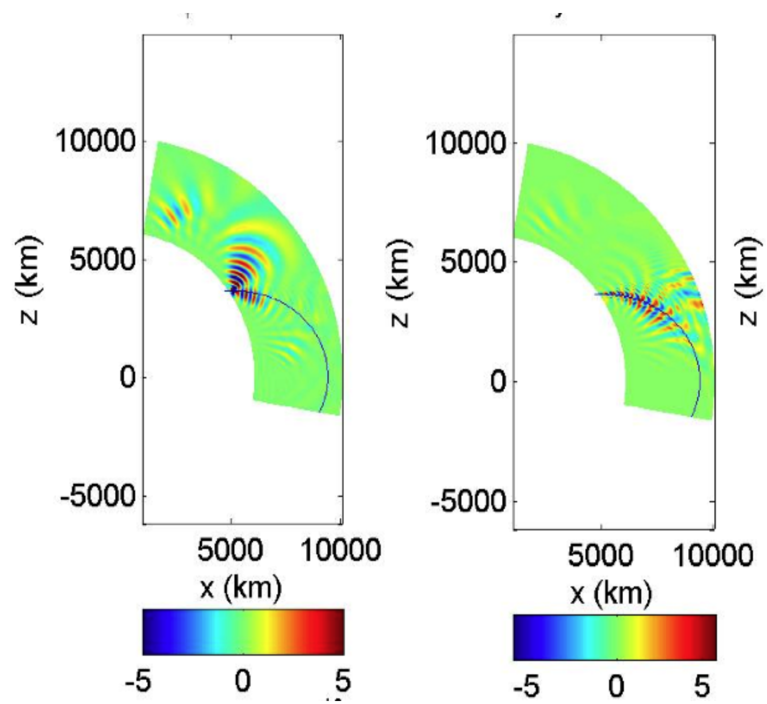


Frequency requirement for equatorial resonance with SAW at L=1.5

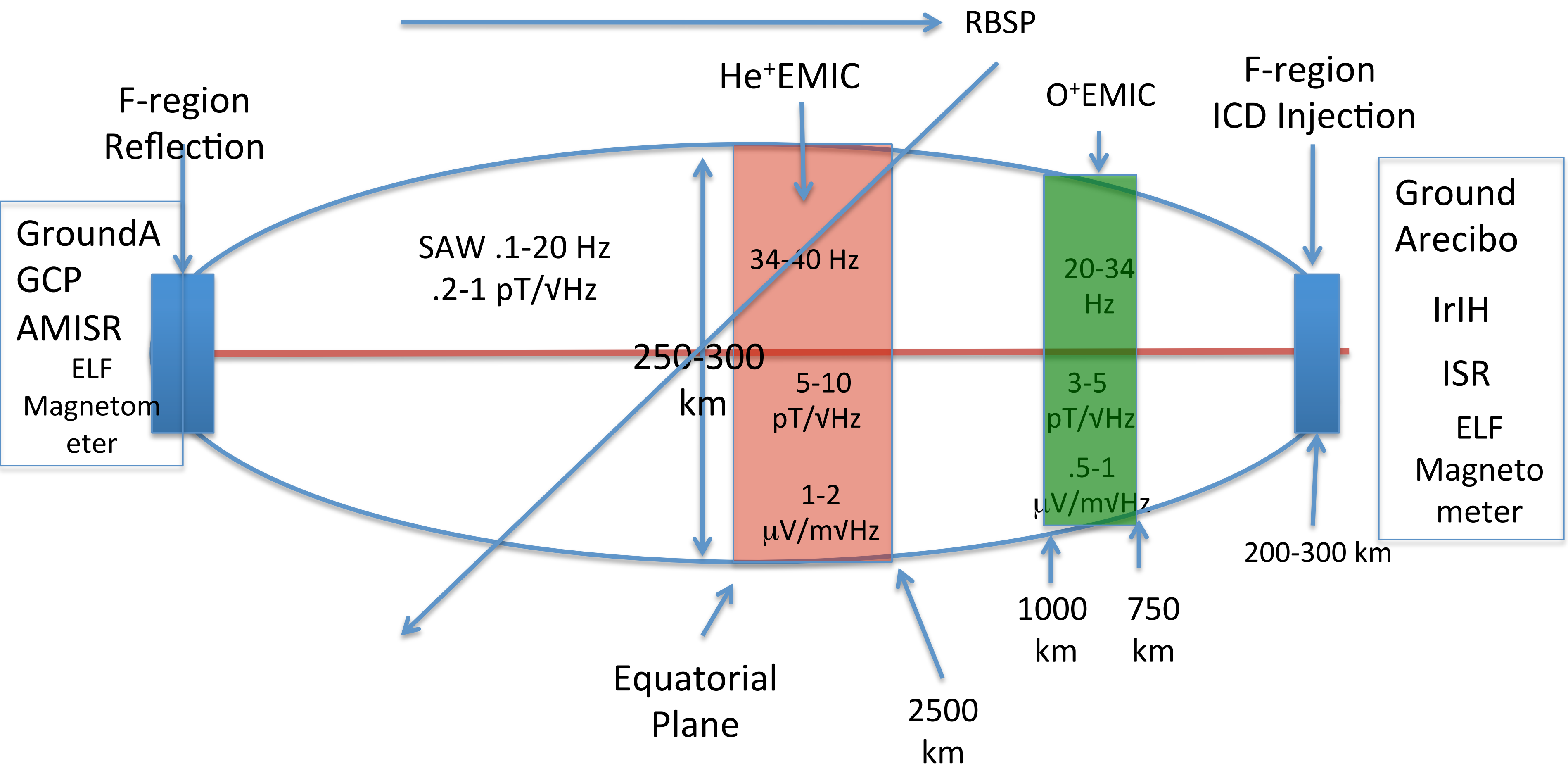
Frequency range 5-30 Hz

Arecibo Heater Experiments



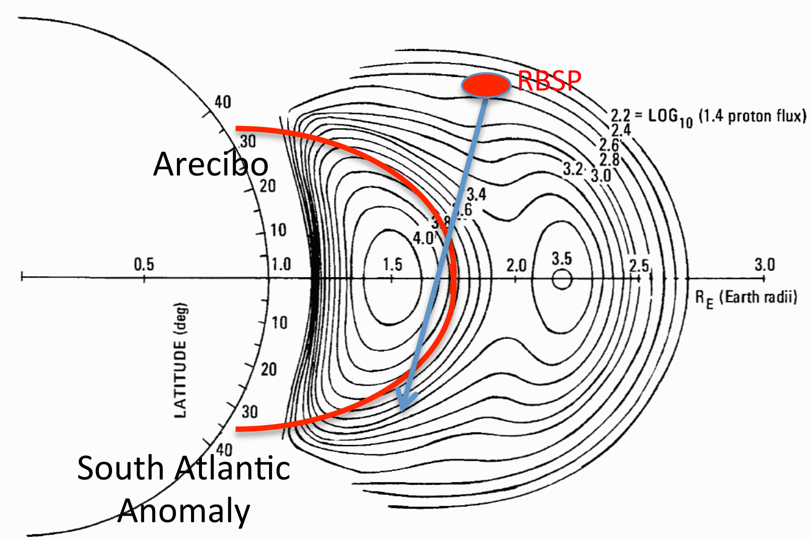


RBSP measures the waves and the energetic particles before during and after transitioning the L=1.4 flux tube so that we can use change detection and possibly statistical stacking



Back of the envelope schematic of experiments with approximate amplitudes to be verified in the experiments. Better calculations to be included in the proposal are in progress. In all experiments the ionospheric state will be measured by the ISRs. The field amplitudes will be recorded on the ground in Arecibo and conjugate (AGCP)

Active Probing of Inner RB Using the Arecibo Heater Using ICD



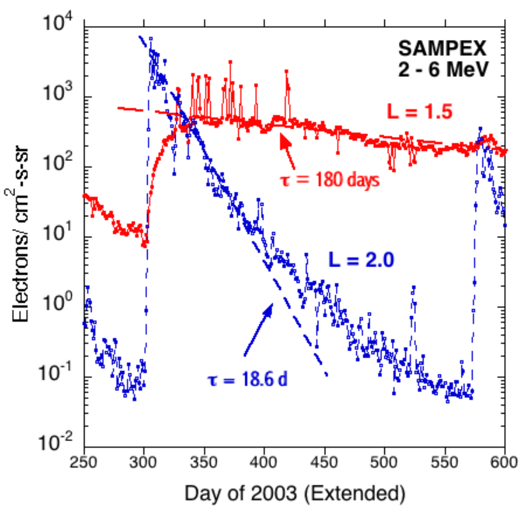
Focus on SAW for protons and EMIC for electrons

WPI critical aspect of RB physics. RBSP will study interactions in the natural environment, A wave injection facility at Arecibo at frequencies that resonate with energetic protons and electrons offers cause and effect understanding of the induced transport processes with RBSP and other satellite diagnostics. Also study of mid-latitude IAR and SAW and EMIC propagation

SUPERSTOMS – CARRINGTON EVENTS

FROM 1-10 NOVEMBER, 2003 OUTER BELT CENTERED NEAR L~2.5 AND PLASMASPHERE WAS DISPLACED INWARDS LEADING IN NEW RADIATION BELT POPULATION IN THE SLOT AND INNER BELT.

DECAY RATES DEPENDED HIGHLY ON L VALUE AND VARIED FROM 35 DAYS TO MORE THAN A YEAR



BAKER AND KANEKAL 2007

TABLE IV

Chronological listing of outstanding geomagnetic storms recorded at Greenwich/Abinger, 1859–1954[a].

	Ranges		
Date	Declination (′)	Horizontal force (nT)	Vertical (nT)
01 Sep. 1859	≫92	≫625	1500
04 Feb. 1872	125	800	>950
17 Nov. 1882	115	>1090	>1060
31 Oct. 1903	119	1175	1440
25 Sep. 1909	193	1710	>1080
14 May 1921	110	≫740	≫460
25 Jan. 1938[b]	126	1055	570
16 Apr. 1938	307	1375	500
24 Mar. 1940	131	1370	1000
01 Mar. 1941	186	1650	1310
18 Sep. 1941	123	1250	1115
28 Mar. 1946	162	1660	920
21 Sep. 1946	136	925	450

[a]Jones, 1955.
[b]This storm was not included in Chapman and Bartels' (1940) list of great storms from 1857–1939.