Radio Detection of Extrasolar Planets: Present and Future Prospects

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Introduction

In last decade, exciting discovery of extrasolar planets

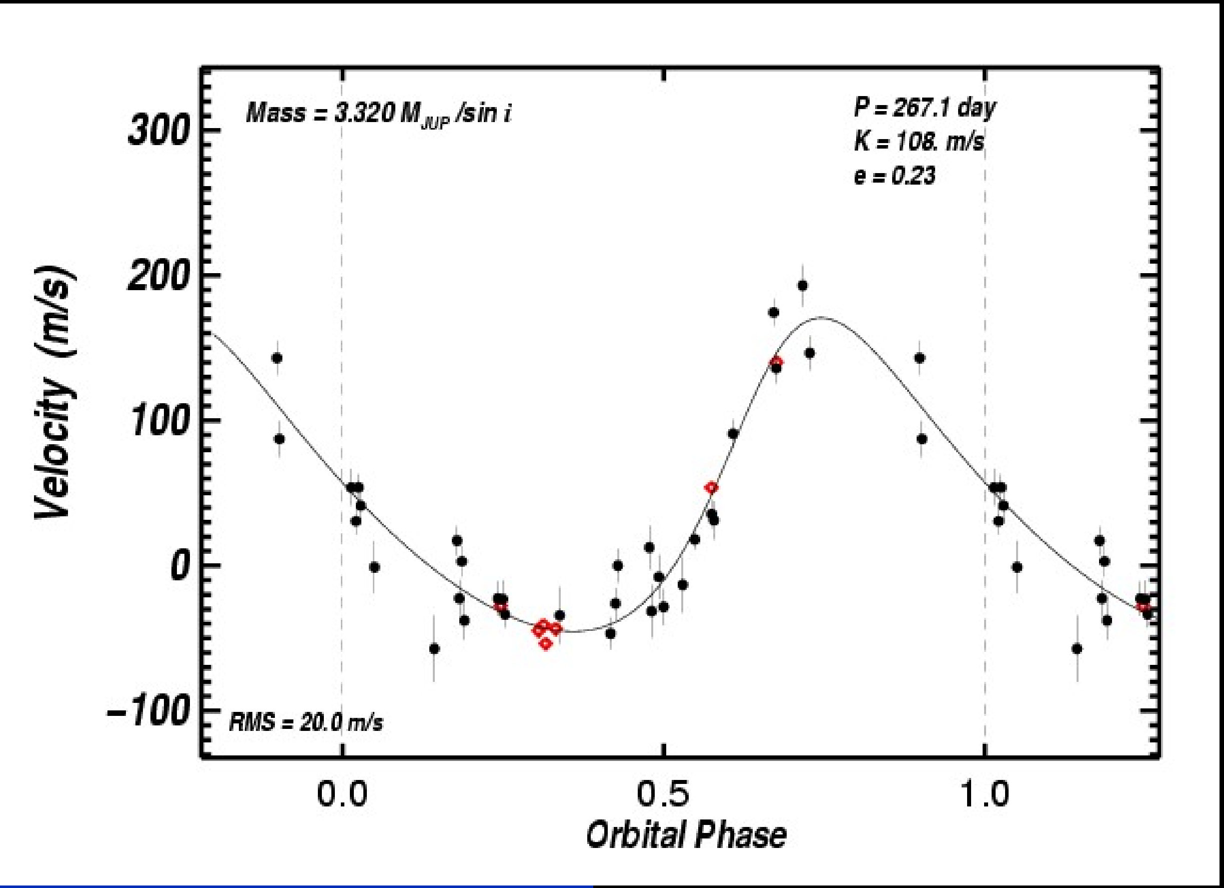
- ~ 100 planetary systems
- Indirect detection via optical signature from host star

Detecting ⇒ characterizing:

- What are their properties?
- Can we detect planets at other wavelengths?
- Implications for habitability of planets to be discovered?

Joint theoretical and observational program focussed on magnetic fields and radio emission

Introduction



HD 40979

3.32 M_J in 267 d orbit (a = 0.811 AU) with e = 0.23 (Fisher et al. 2003)

In last decade, exciting discovery of extrasolar planets

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"Do there exist many worlds, or is there but a single world? This is one of the most noble and exalted questions in the study of Nature."— St. Albertus Magnus, *De Caelo et Mundo* (13th century)

Introduction

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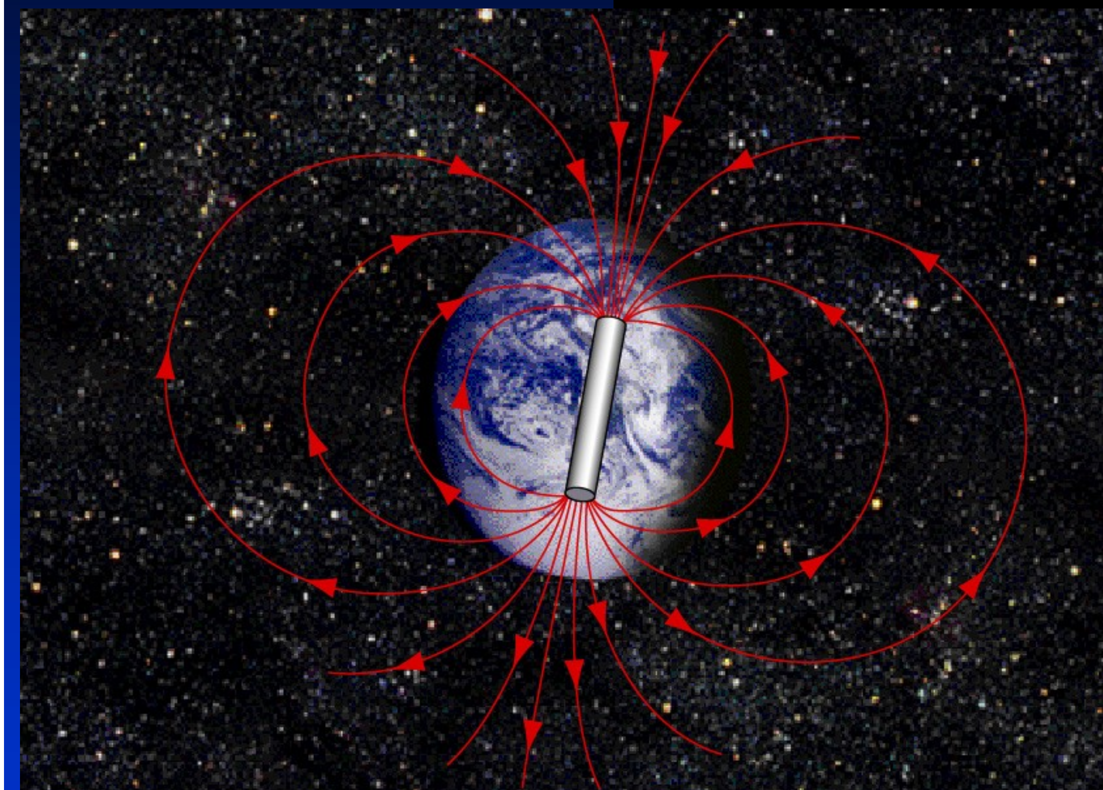
Magnetic Fields and Extrasolar Planets

Why would we care?

- Presence and strength of magnetic field

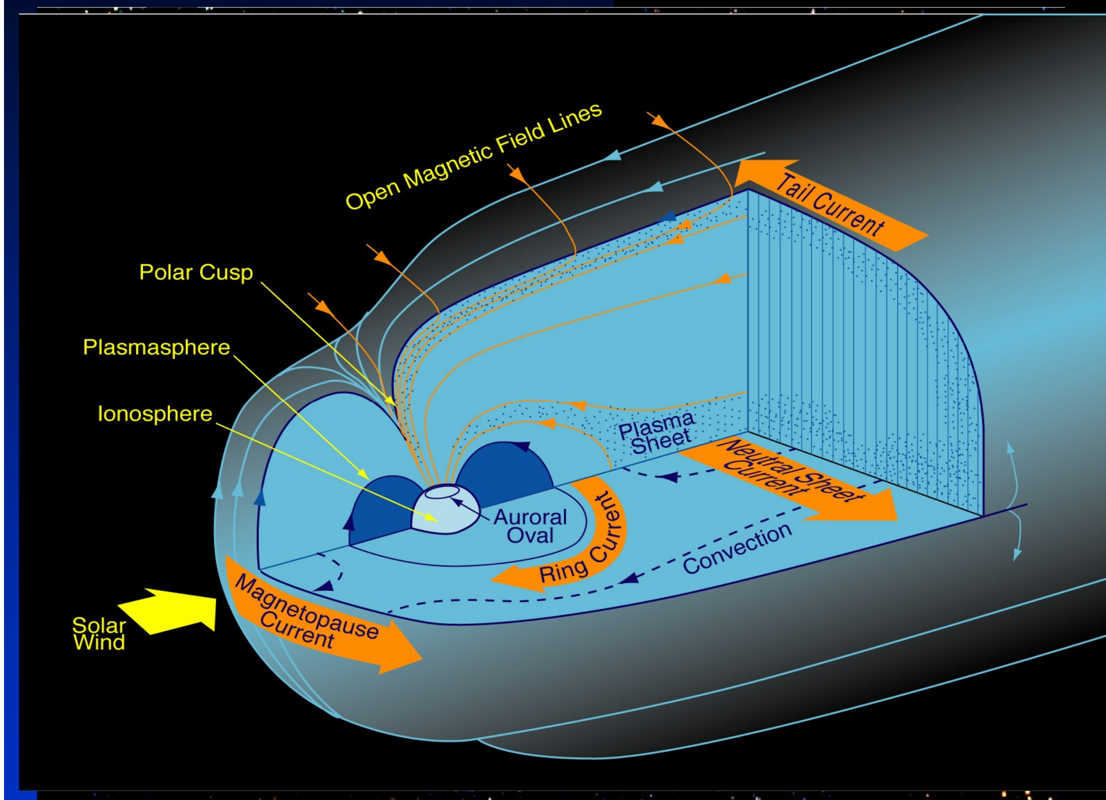
  Composition
- Rotation period
  - Difficult to determine by any other means
  - Defined by magnetic field for solar system giant planets
- Existence of satellites (plus their orbit)
- Estimate of plasma density in the magnetosphere

Planetary Magnetospheres I



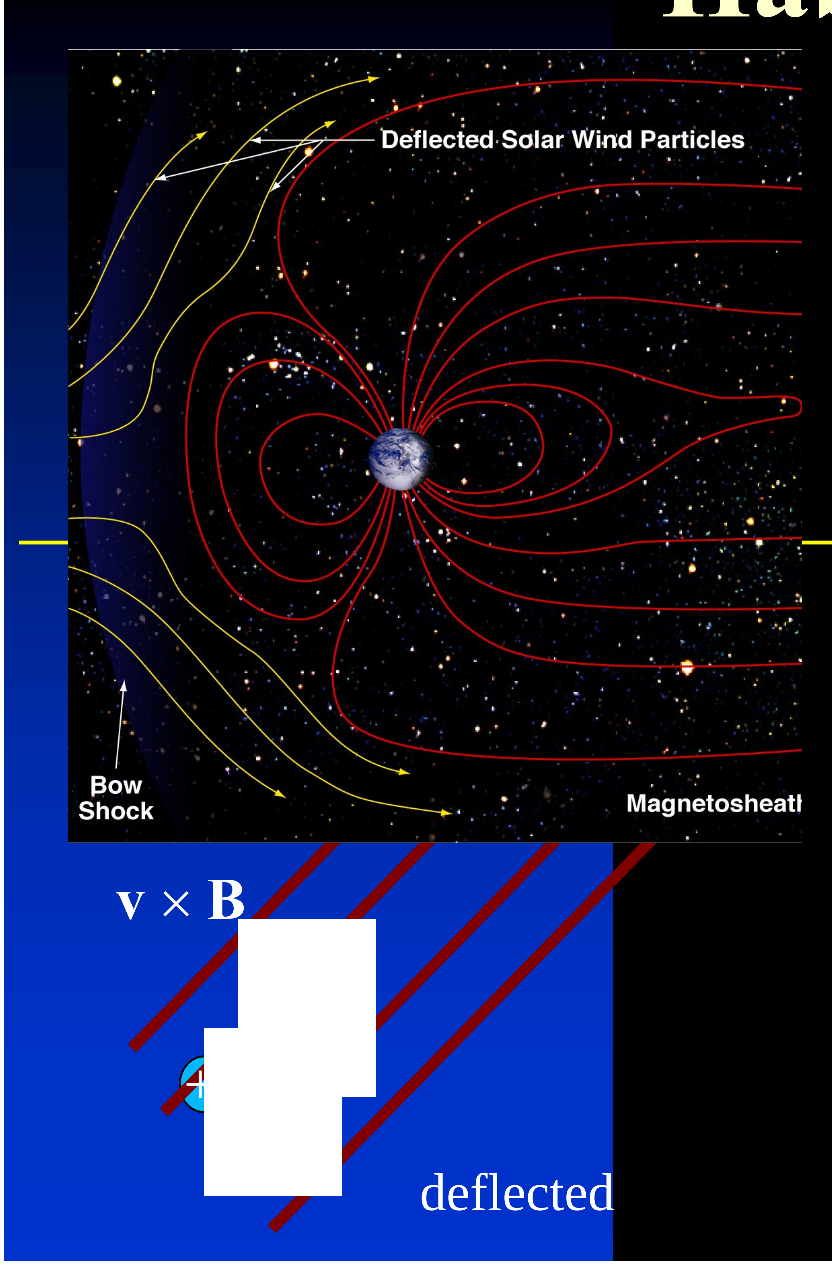
- Planetary-scale magnetic fields:
  - Earth, Jupiter, Saturn, Uranus, & Neptune
- Produced by rotation of conducting fluid
  - ◆Earth: liquid iron core
  - ◆Jupiter & Saturn: metallic hydrogen
  - ◆Uranus & Neptune: salty oceans

Planetary Magnetospheres II



- Planetary magnetic field immersed in solar wind.
- Solar wind is high-speed plasma with embedded magnetic field.
- Pressure from solar wind impacts and deforms planetary magnetic field.
- Magnetosphere
  - *Large* objects, e.g., Jovian magnetosphere is 5x diameter of full Moon

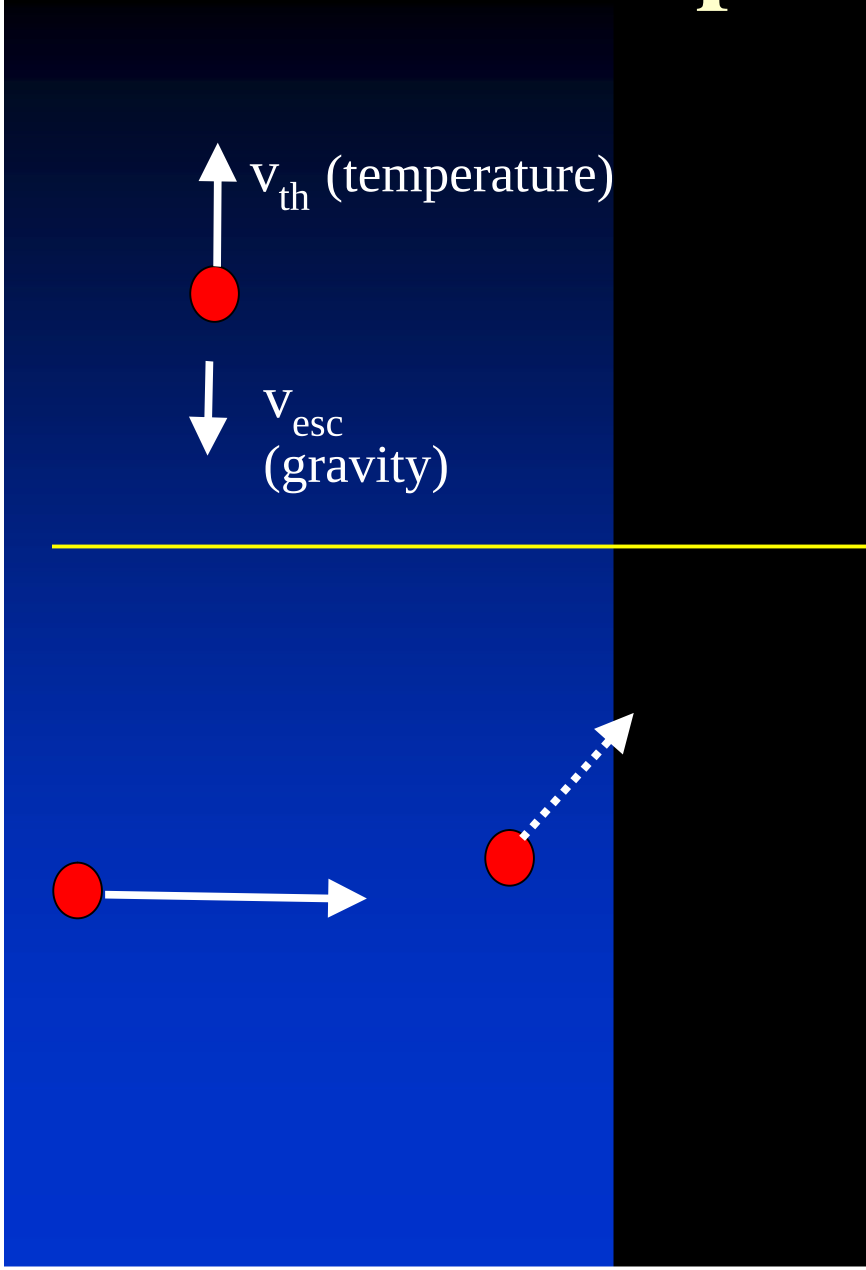
Magnetospheres and Habitability



Solar wind particles deflected at magnetosphere.

- Protects the atmosphere.
- Affects the planet's albedo.
- May protect genetic material of organisms.

Atmospheric Protection

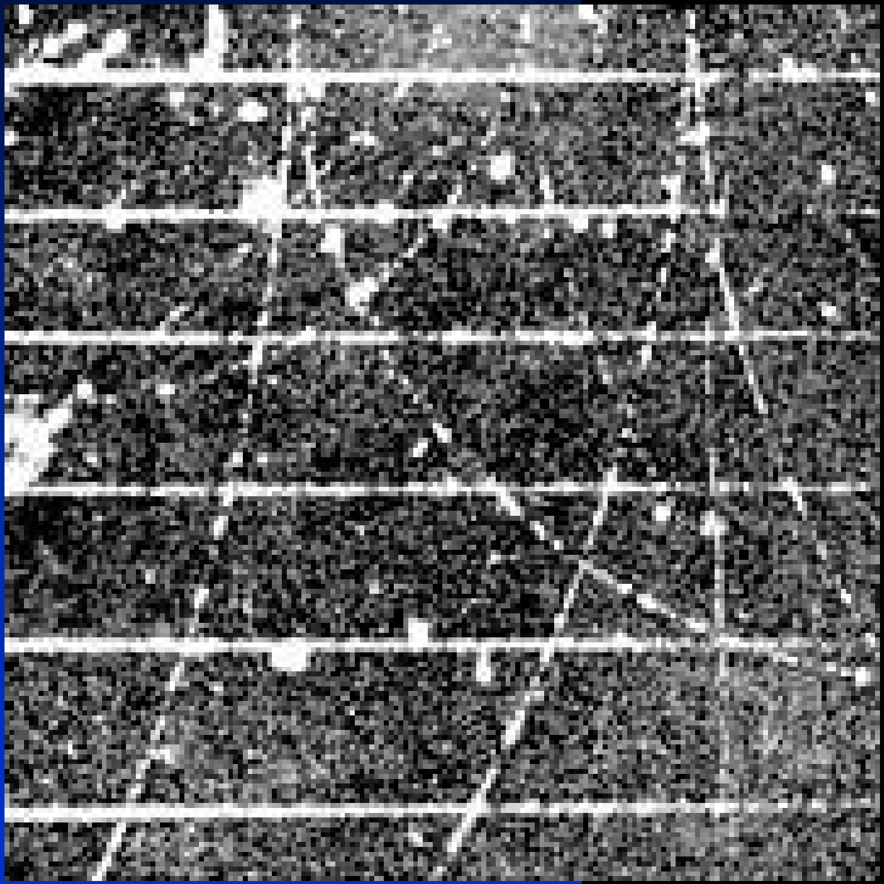


- Thermal vs. Nonthermal atmospheric escape
  - Thermal: Does molecular thermal velocity exceed planetary escape velocity?

    (freshman physics problem)
  - Nonthermal: collisional physics (sputtering, mass loading, ...)
- Implications for water retention?

(Shizgal & Arkos 1996, *Rev. Geophys.*, **34**, 483)

Cosmic Rays and Planetary Albedo

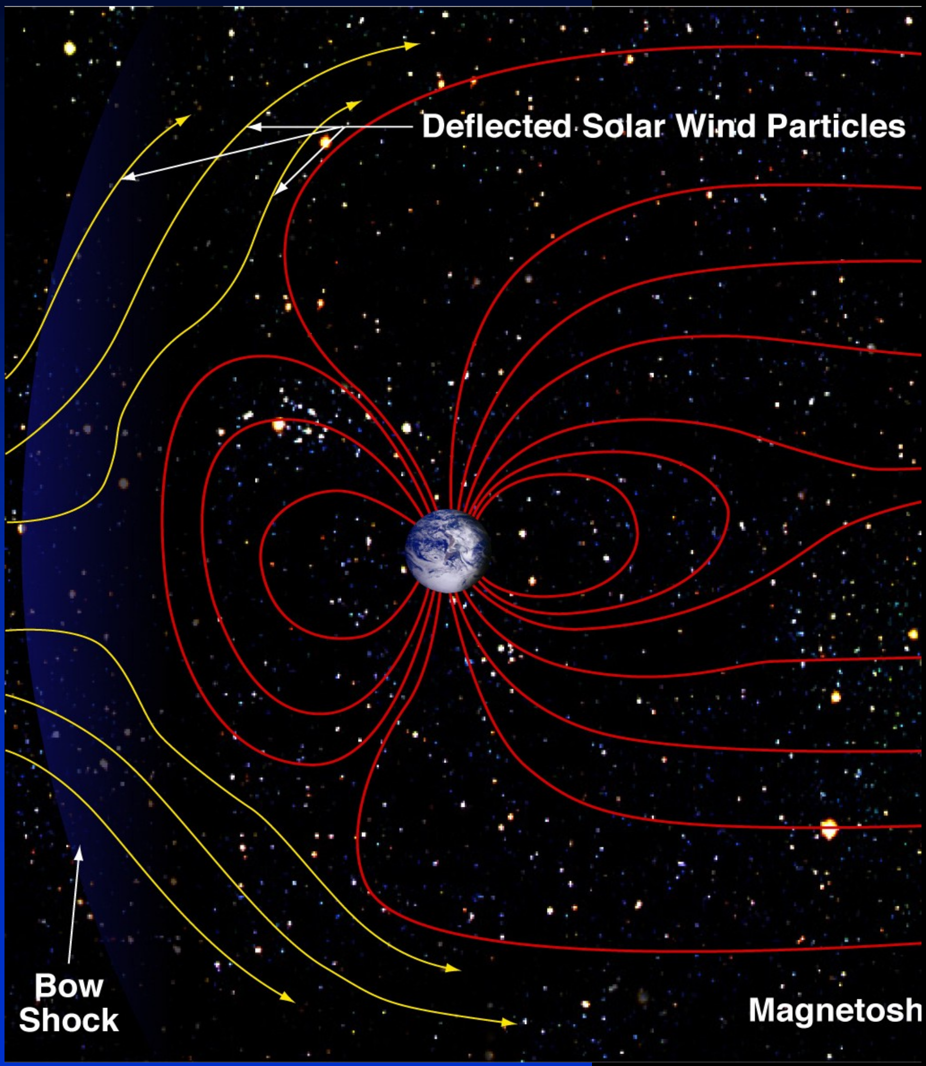


- Cosmic rays induce nucleation in water-vapor saturated air.
- Larger cosmic ray flux $\Rightarrow$ more cloud cover.
- Effect seems to be more pronounced for Galactic cosmic rays rather than solar particles.

(e.g., Svensmark 2000, *Space Sci. Rev.*, **93**, 155)

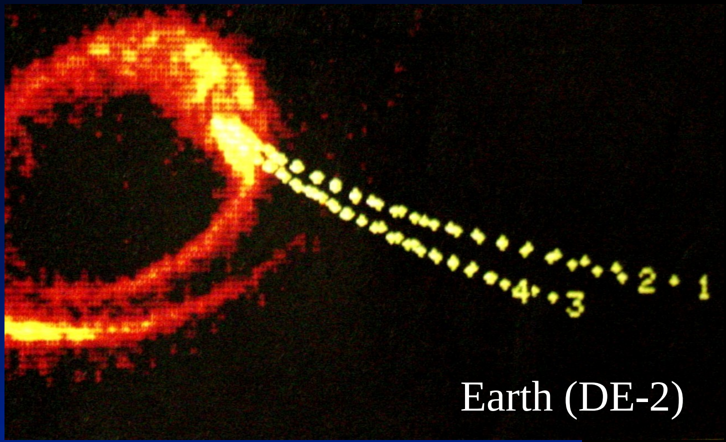
Cosmic Rays and Life

Planetary Radio Emission: From Magnetosphere to Pole



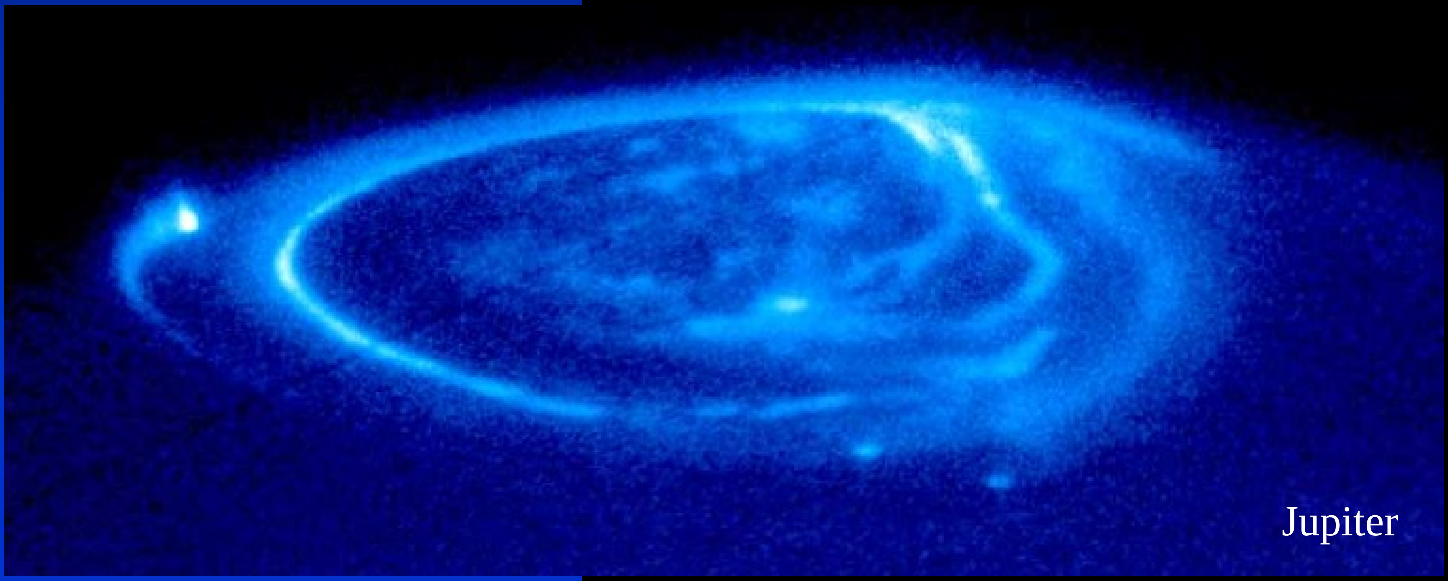
- Solar wind incident on magnetopause
  - Deflect electrons relative to ions and create currents
  - Explosive changes in tail field topology: Reconnection yields $dB/dt \rightarrow I$
- Currents travel down highly conductive magnetic field lines and deposit energy in polar auroral region
  - 1% of auroral input energy to visible/UV aurora
  - 1% of auroral input energy into electron cyclotron radio emission (Gurnett 1974)

Planetary Radio Emission From Magnetosphere to Pole



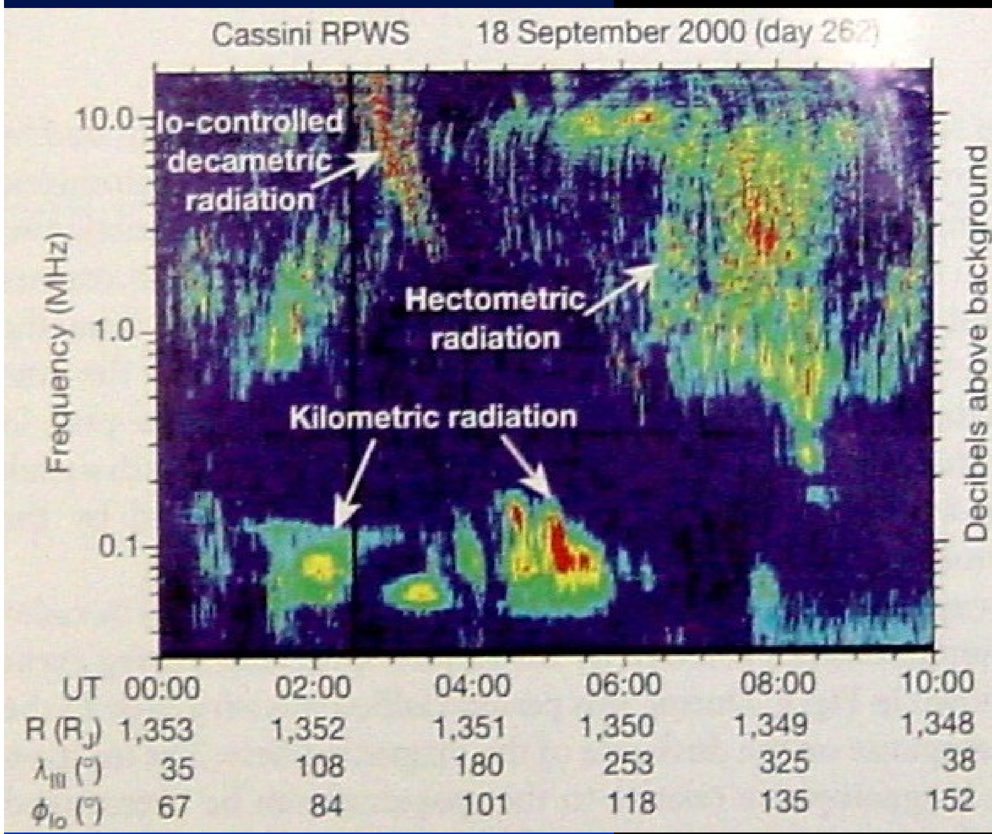
Earth (DE-2)

- Solar wind loading of magnetosphere produces radio emission
- 1% of auroral input energy into electron cyclotron radio emission (Gurnett 1974)
- Auroral radio sources typically map directly to auroral optical sources (Huff et al. 1988)



Jupiter

Planetary Radio Emission in the Solar System



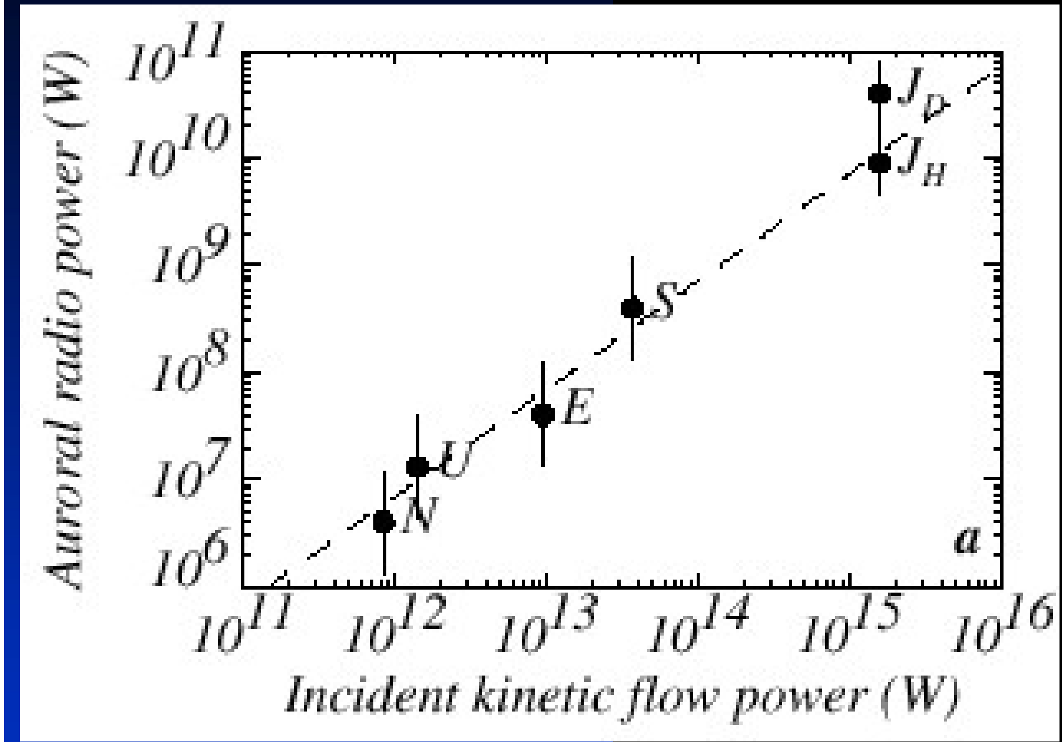
- Burke & Franklin (1955) discover radio emission from Jupiter.
- Late 1960s/Early 70s: Earth's polar region recognized as strong radio source (10^7 W).
- Voyager era: Opens field up.
- All gas giants have strong planetary magnetic fields.
- Gas giants also have stong auroral/polar cyclotron radio emission.
- Jupiter: Strongest at 10^{12} W, Io-driven *and* non-Io component
- Most components driven by solar wind-magnetosphere interaction.

Jupiter at 10 pc

Jupiter (~ 30 MHz)	**Flux Density**
4.5 AU	~ 50,000 Jy (~ 50 kJy)
10 pc	~ 0.0000002 Jy (~ 0.2 μJy)

- Hopeless?
- Extrasolar planets have larger radiated powers than Jupiter?
- Variability?
- … ?

Radiometric Bode s Law



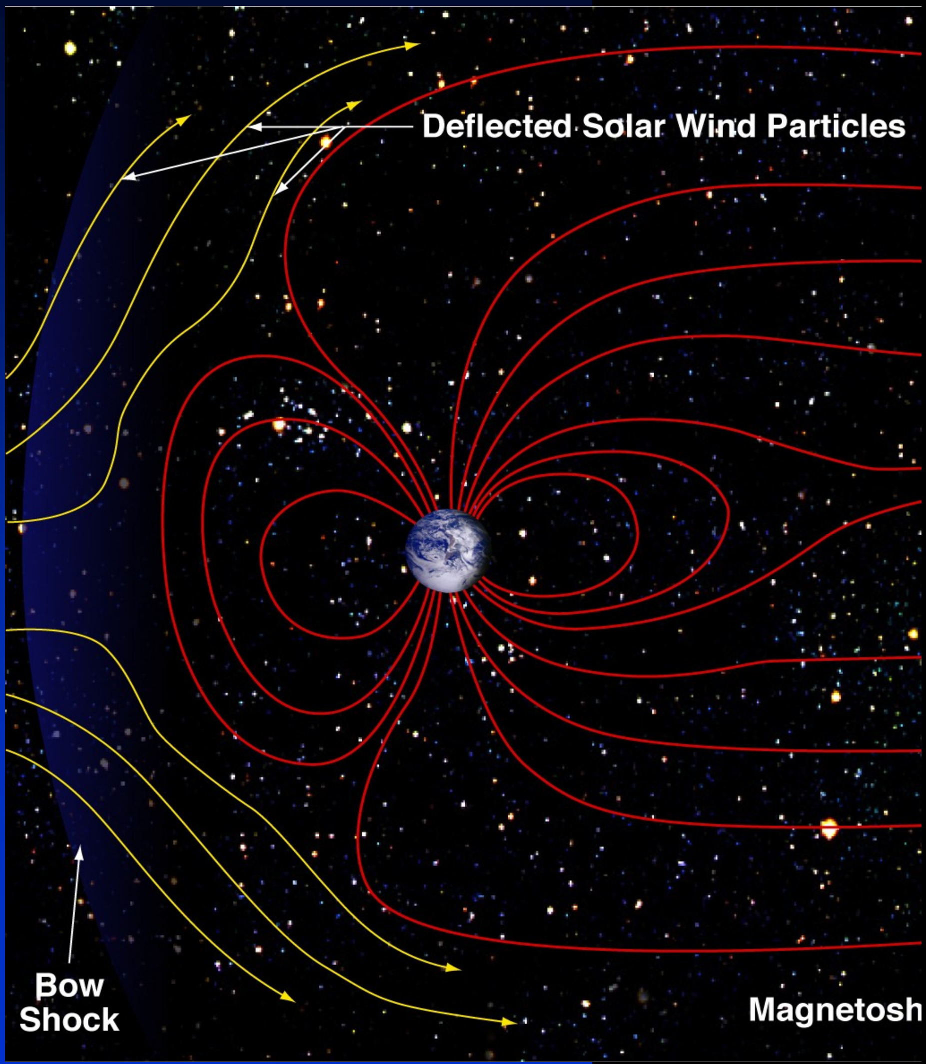
Zarka et al. (2001)

- Planetary magnetosphere intercepts outflowing solar wind power.
- Good correlation between planetary radiated power (P_{rad}) and input solar wind kinetic power (P_{sw})

  $$P_{rad} \sim \varepsilon\, P_{sw}^{\ x}$$

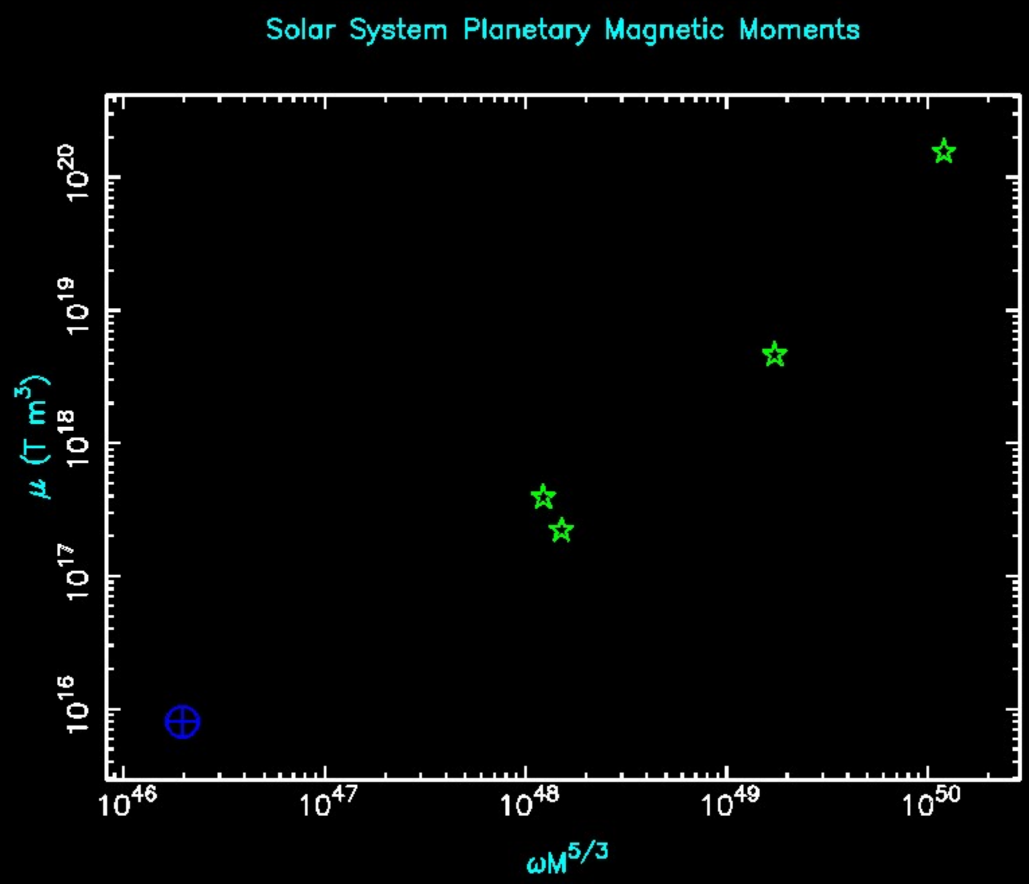
  - $0.9 < x < 1.2$
  - $\varepsilon \sim$ few $\times 10^{-6}$ to few $\times 10^{-3}$
- Desch & Kaiser (1984) recognized system-level pattern $\Rightarrow$ predicted Uranus' radio power before 1986 Voyager encounter.
- Zarka et al. (1997) refined by adding Uranus, Neptune, and non-Io DAM.

Radiometric Bode s Law II



- Planetary magnetosphere intercepts outflowing solar wind power.
- P_{sw} depends on
  - ρ, the solar wind density ($\propto d^{-2}$ for distance to primary d),
  - V, the solar wind velocity, and
  - R_m, the radius of the magnetosphere ($\propto \mu^{1/3} d^{1/3}$ for magnetic moment μ; distance d).

Blackett s Law



- Blackett (1947) noticed relation between angular momentum and magnetic field.
  - Earth, Sun, 78 Vir
  - EM + GR?
  - Jupiter?
  - Anti-gravity?
- Many modern forms, all of approximate form

$$\mu \propto \omega M^{5/3}$$

Emission Frequency

- Earth's ionosphere reflects radiation below about 10 MHz.
- Radio emission from Saturn, Uranus, and Neptune had to wait for spacecraft fly-bys.

- Locally, electron gyrosynchrotron frequency must exceed plasma frequency.

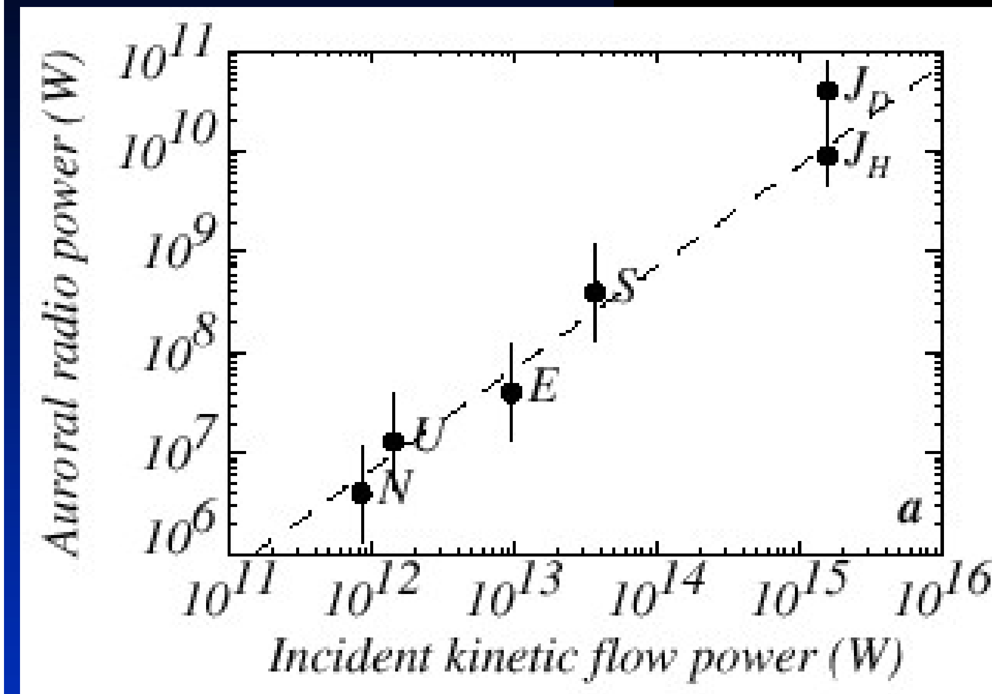
- $\nu_c = 5.6$ MHz μ

  $\mu = 4.2$ G R_J^3

  $\mu \propto \omega M^{5/3}$

- Use Blackett's Law to predict magnetic moment, and therefore emission frequency.

Radiometric Bode s Law

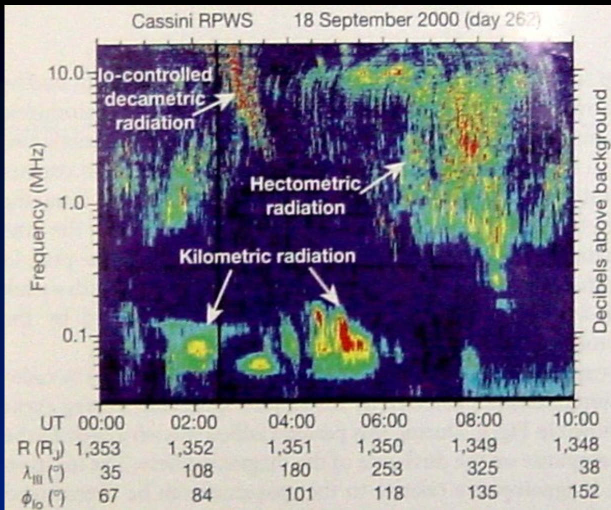


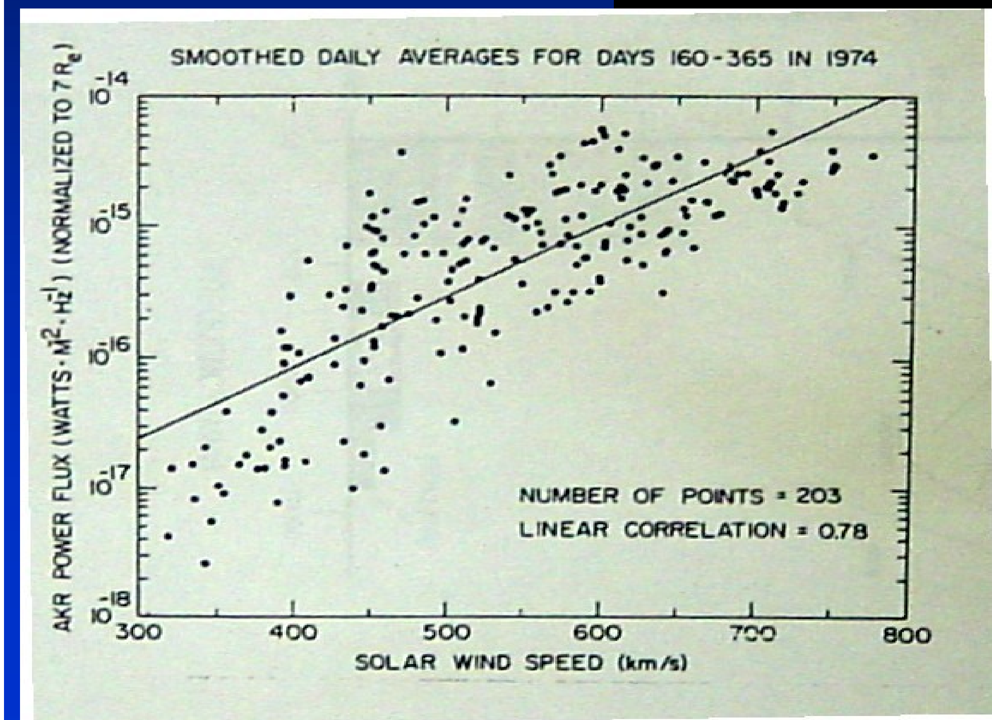
- Predict radiated power levels and emission frequency.
  - M — Doppler measurements
  - d — Doppler measurements
  - ω — 10 hr, assumed, unless tidally locked
  - R— 1 Jovian radius, unless "hot Jupiter" for which 1.25 R_J, viz. HD 209458
  - V, ρ — solar values
- Farrell et al. (1999) extended to extrasolar planetary systems.

$P \sim 4 \times 10^{11}\ \mathrm{W}\ \omega^{0.79}\ M^{1.33}\ d^{-1.60}$

$\nu_c = 23.5\ \mathrm{MHz}\ \ \omega\ M^{1.66}\ R^{3}$

Variability of Planetary Radio Emission

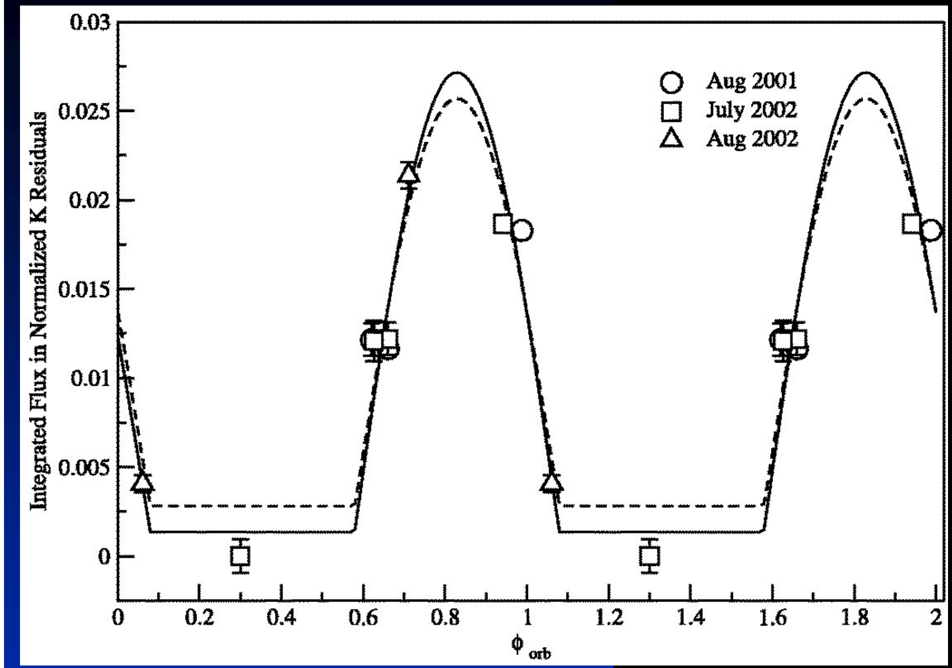


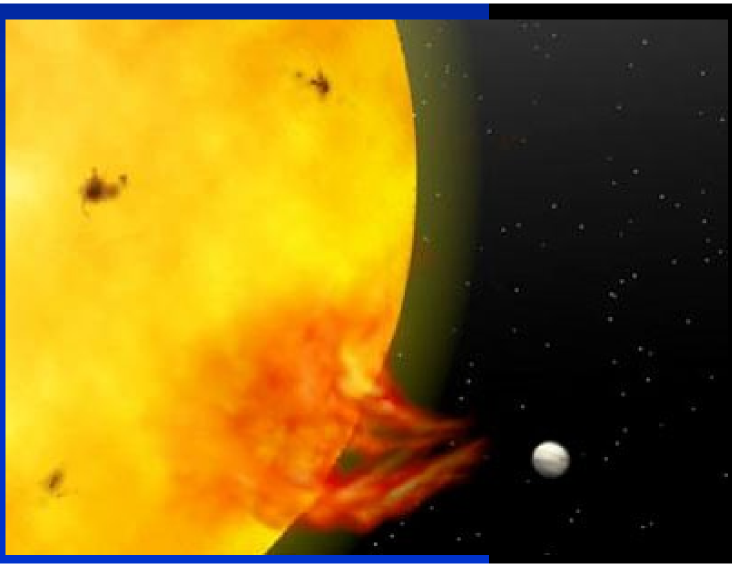


- Planetary radio sources behave as exponential amplifiers (Gallagher & D’Angelo 1979)
- Other stars may have a higher activity than the Sun, i.e., more stellar wind.

Earth cyclotron emission exponential variation with solar wind speed

Extrasolar Planetary Magnetic Fields?





- Observe Ca II H and K lines (393.3, 396.8 nm).
- HD 179949: 0.84 M_J planet in 3.1 d orbit
  - Detect ~ 4% variations in “line strength.”
  - No estimate of the planetary magnetic field strength.
  - Also observed τ Boo, υ And, 51 Peg, HD 209458

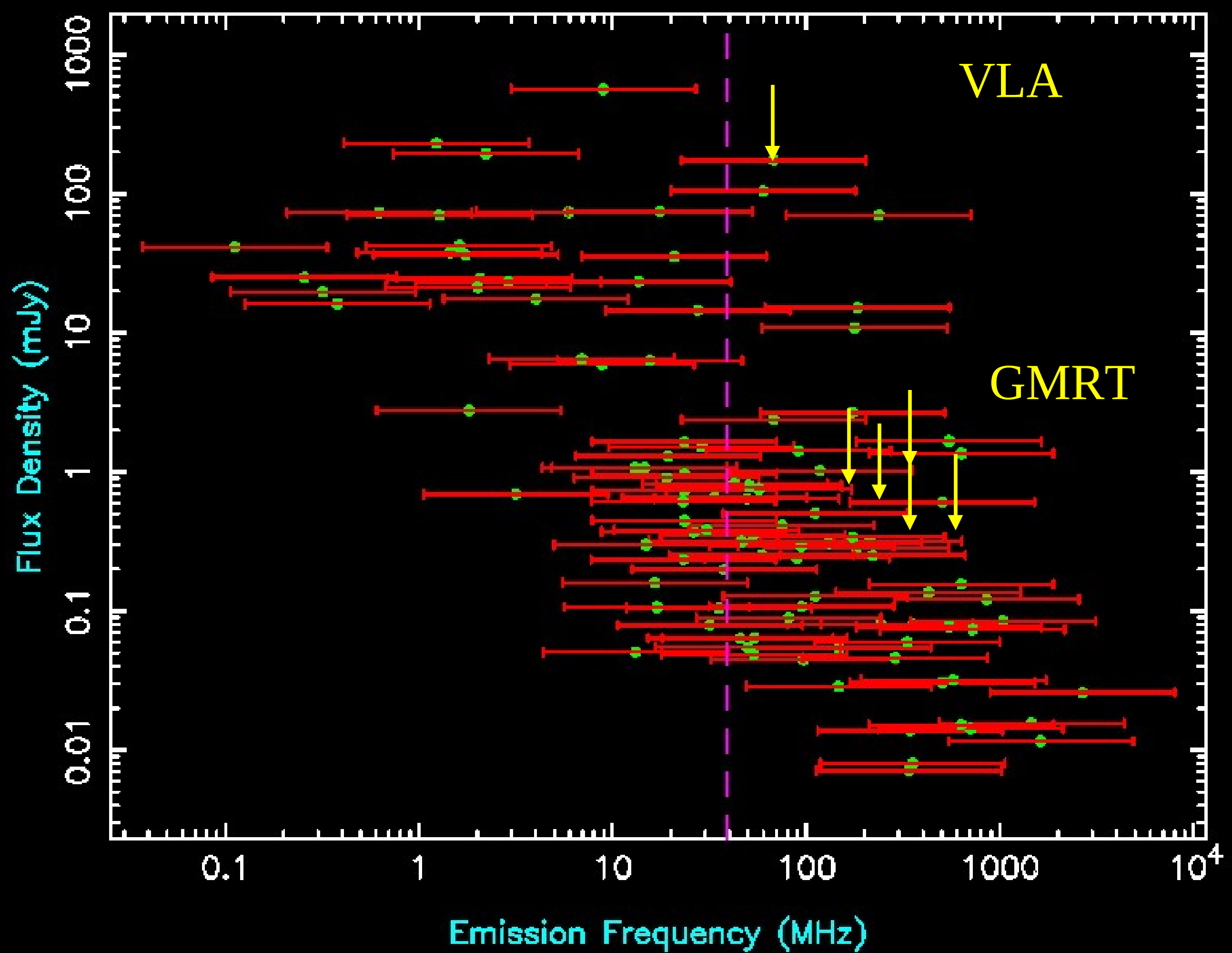
(Shkolnik et al. 2003, *Astrophys. J.*, **597**, 1092)

Nothing New Under the Sun

035-5 A Search for Extra-Solar Jovian Planets by Radio Techniques. W.F. YANTIS, U. Wash. and Goldendale Observatory, W.T. SULLIVAN, III, U. Wash. & W.C. ERICKSON, U. Maryland. - We propose to search for the presence of planets associated with nearby stars through detection of Jovian like decametric radio bursts. Planetary bursts would be distinguished from possible stellar bursts by the presence of a high-frequency cutoff and possibly a modulation associated with the rotation of the planet. A search for such planetary radio bursts at 26.3 MHz is presently being conducted at The Clark Lake Radio Observatory. The sample includes 22 stars within 5 parsecs. The sensitivity limit is 10^{-26} watts m^{-2} Hz^{-1}, about 1,000 times the signal expected from a strong Jovian burst. However, it is expected that the strength of any bursts will depend strongly on the planetary magnetic field and also possibly on the presence of a stellar wind. Initial observations exhibit several non-instrumental features which are under current study. Further results will be reported and monitoring observations are continuing.

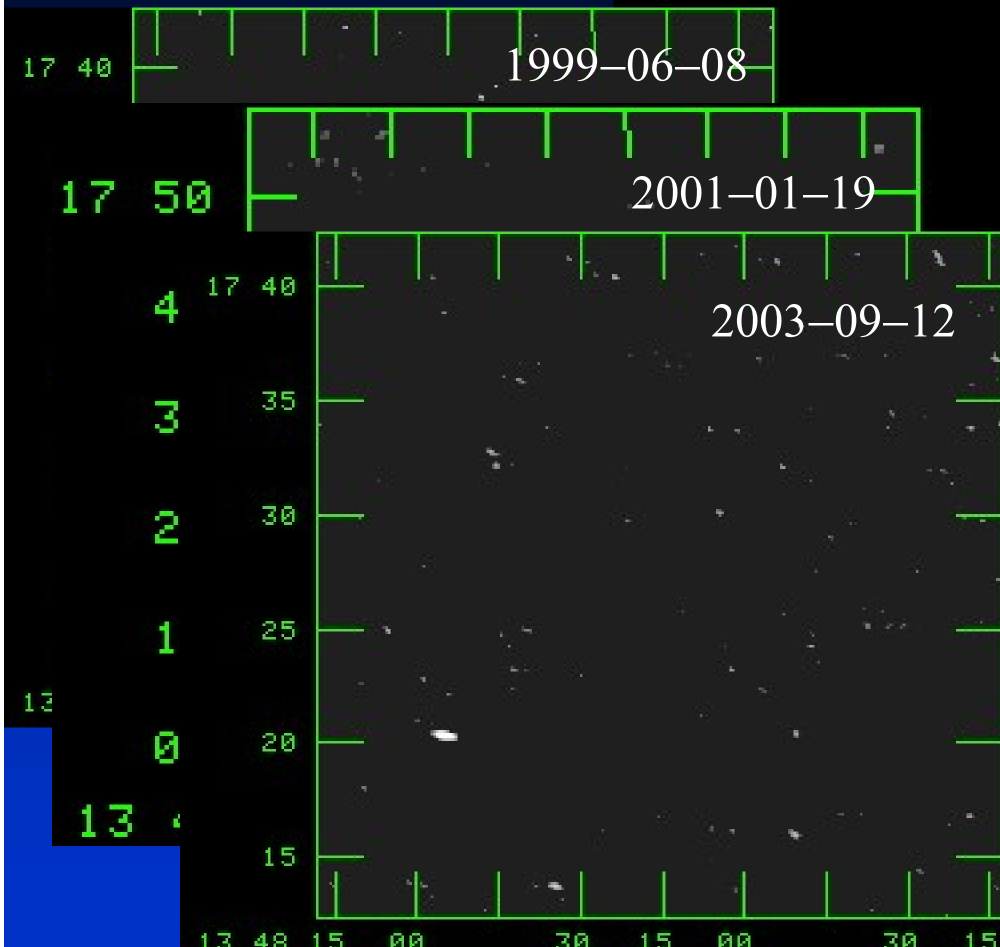
- "A Search for Extra-Solar Jovian Planets by Radio Techniques" (Yantis, Sullivan, & Erickson 1977)
- Soon after recognition that Saturn also an intense radio source (Earth, Jupiter, and Saturn)

Extrasolar Planet Predicted Radio Emission



[Lazio, Farrell et al. 2004]

Very Large Array Studies

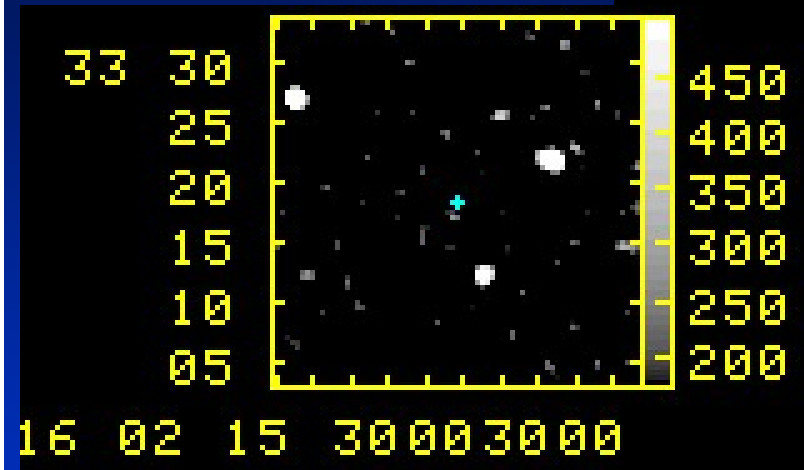


τ Boo at 74 MHz

- The radiometric laws indicate τ Boo is a good candidate ("bursts" ~ 0.1 Jy near 50 MHz).
- 27 radio antennas, each of 25-m diameter, used as interferometer.
  - Resolution of a 10- to 36-km antenna
  - Sensitivity of a 130-m dish
- VLA can observe at 74 MHz with sub-Jansky sensitivity.

  1 Jy = 10^{-26} W/m^2/Hz

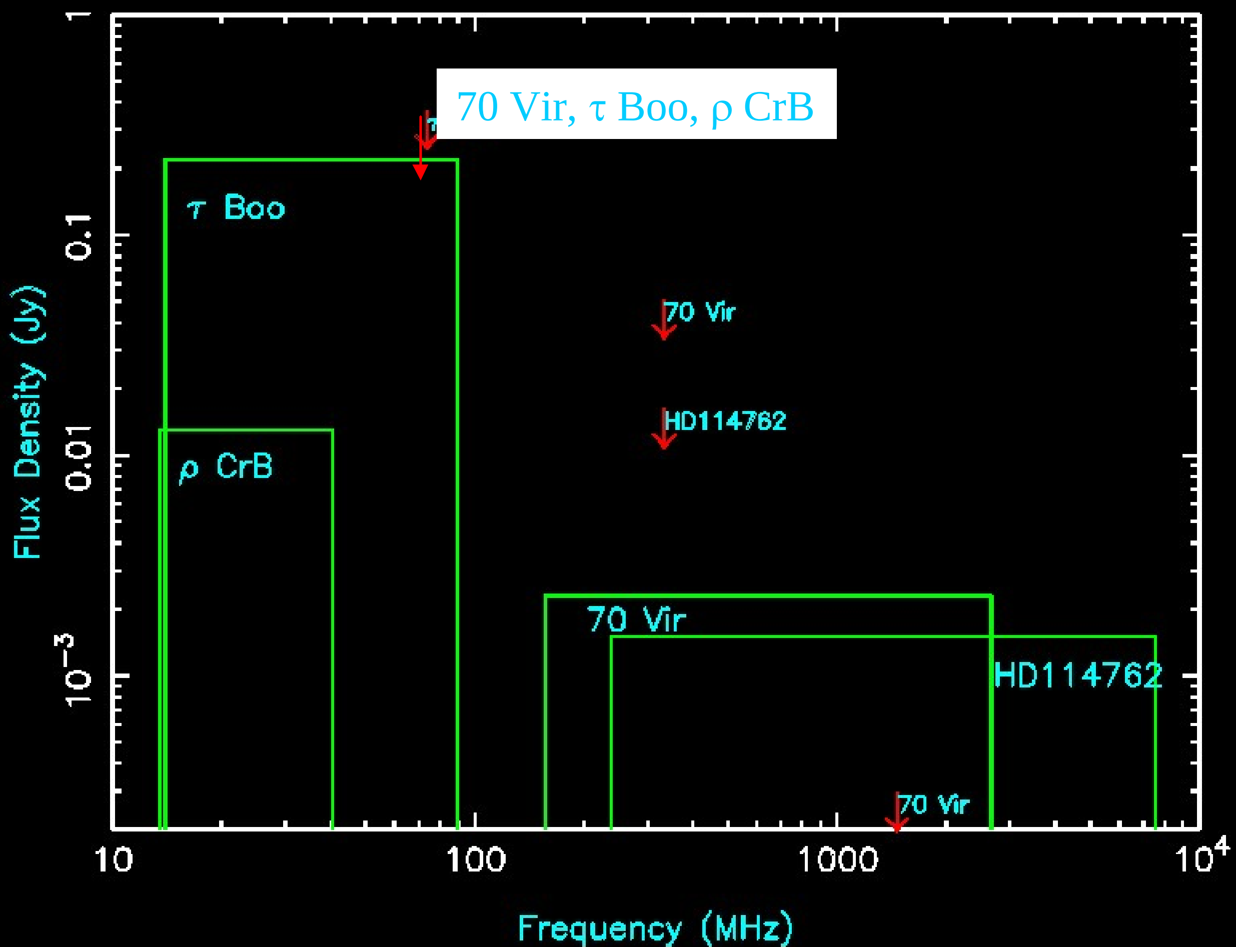
VLA Studies II



ρ CrB at 74 MHz

- A variety of other planets have been observed by our group and by Bastian et al.
- Comparable sensitivities at 74 MHz, better at higher frequencies.
- No detections yet…

VLA Studies

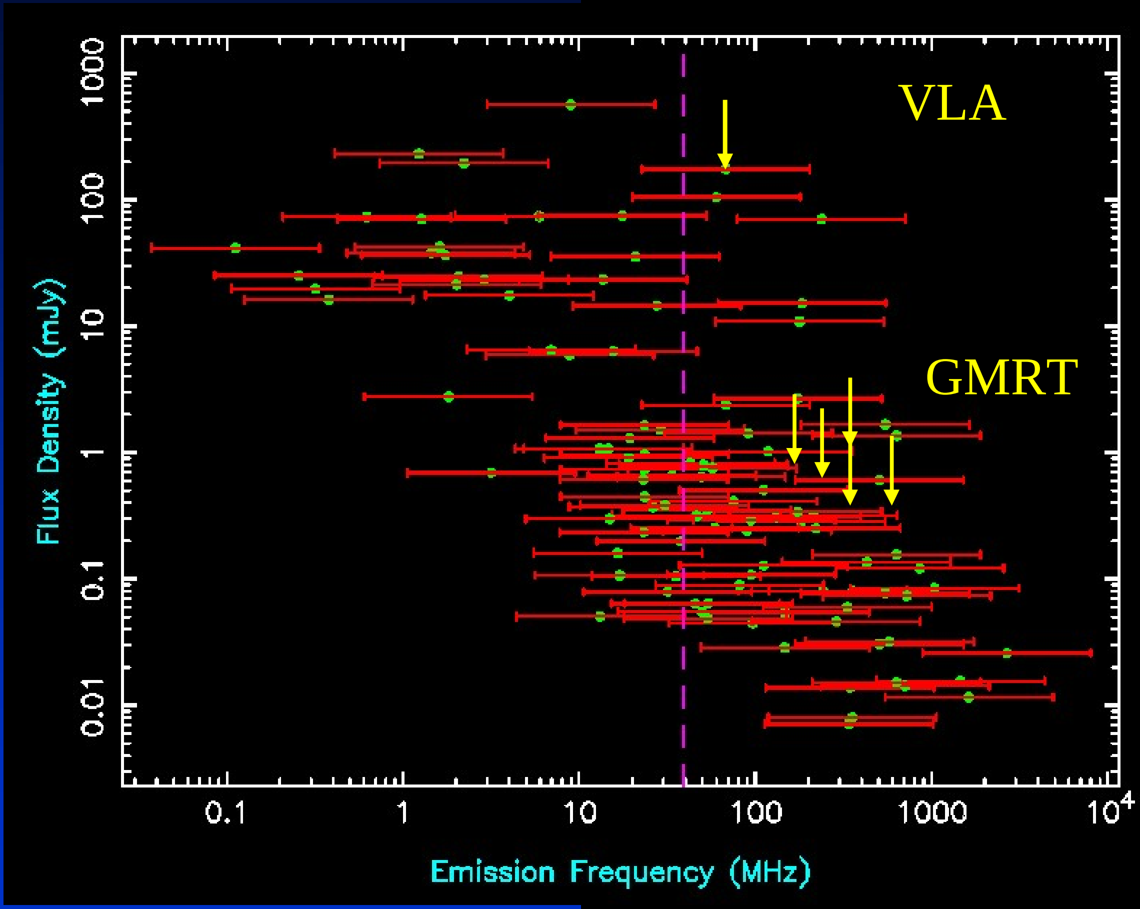


Additional limits

HD 104985	0.22 Jy
HD 108874	0.33
GJ 903	…
Gl 876	…
υ And	~ 0.4

(Bastian et al. 2000; Farrell, Lazio, et al. 2003; Lazio, Farrell, et al. 2004)

Extrasolar Planet Radio Emission

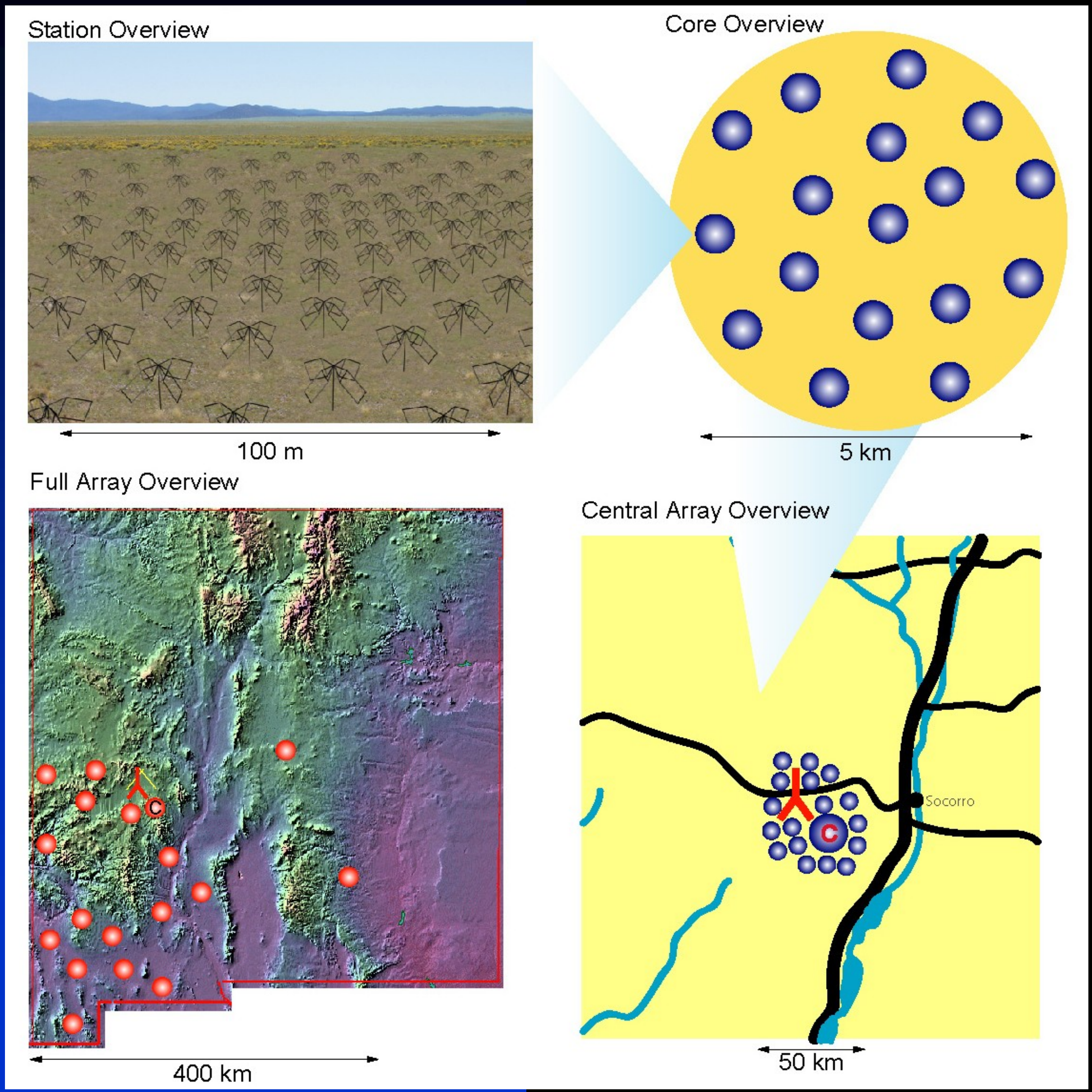


Why no detections yet?

- Variability
- Stellar wind flux
- Radiometric Bode's law does not apply outside of solar system.
- Telescope sensitivity
- …

[Lazio, Farrell et al. 2004]

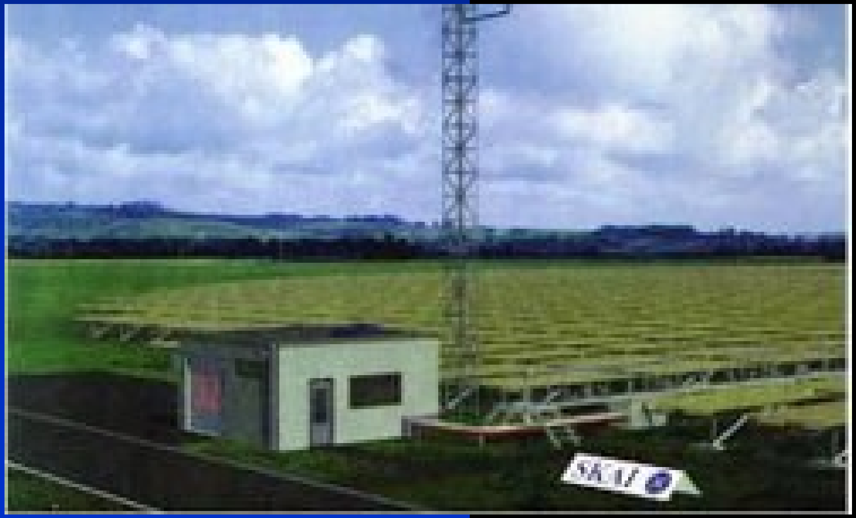
Long Wavelength Array (LWA)



- Returning to roots of radio astronomy
- Several technological issues solved from previous generation of instruments
- Frequency range: 10–80 MHz
- Initial operation in 2008
- Southwest Consortium (NRL, UNM, UT:ARL, LANL)

http://lwa.nrl.navy.mil/

Square Kilometer Array

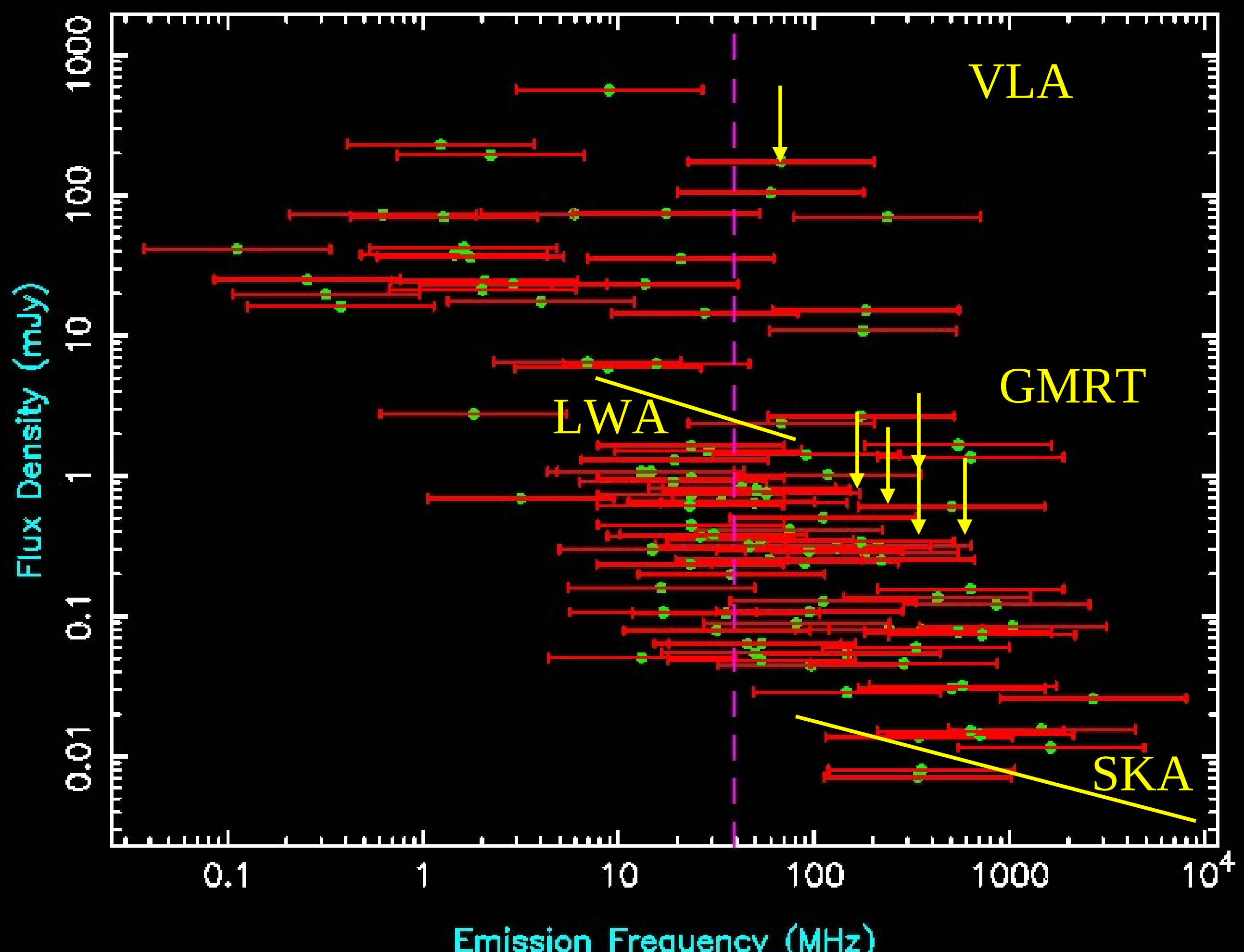


- Next generation radio telescope
- ~ 100x as sensitive as the Very Large Array
- Frequency range: 0.1–25 GHz
- Site and design studies on-going

  (Decision points in 2006 to 2008)

http://www.skatelescope.org/

Predicted Radio Emission



[Lazio, Farrell et al. 2004]

Summary

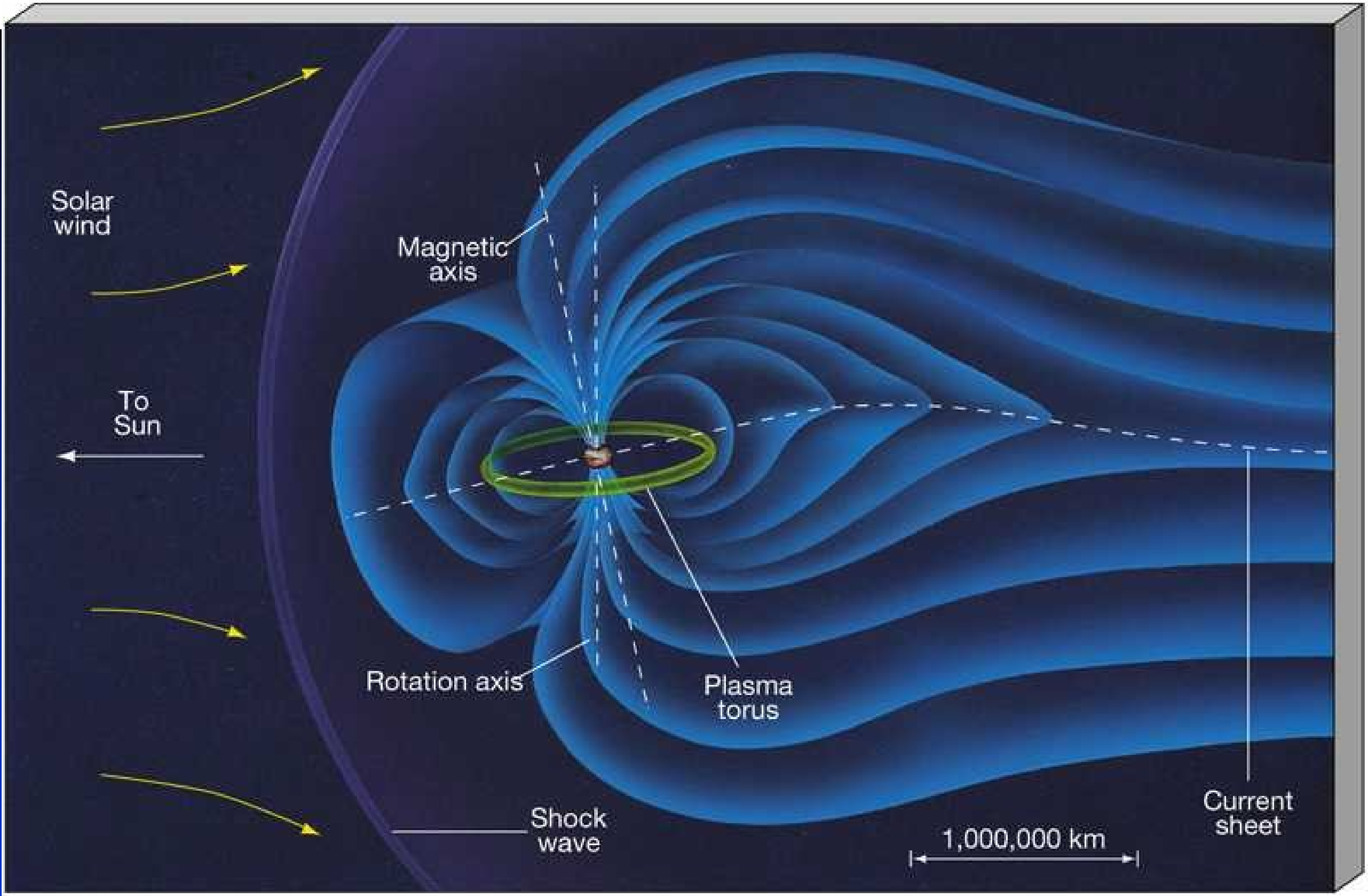
- Planetary magnetospheres both informative and sheltering
  - Rotation
  - Atmospheric loss
- “Magnetic planets” in our solar system emit in the radio ⇒ ***Radiometric Bode s Law***
- Current searches toward ~ 10 extrasolar planets have been negative.
  + Separate “star” from “planet” ⇒ orbital periodicity?
  - Upper limits on stellar wind or planet’s magnetic field
- Prediction from current census is that future generation radio telescopes look promising.
  - VLA and GMRT data (stellar variability may assist detection)

Research in radio astronomy at NRL is supported by the Office of Naval Research.

FINITO

Difficulties

- Emission weak – probably beyond current capabilities even with variability;
- Beaming increases the flux density, but decreases the probability of detection concomitantly;
- Difficult to disentangle detected emission from that of the star (periodicity is a key to resolving this ambiguity);
- For planets with relatively weak magnetic fields, the cutoff frequency ($f_c \sim 2.8\ B_{surf}$ MHz) might actually be below our own ionospheric cutoff frequency (~ 10 MHz);
- Background source confusion is a serious observational problem at long wavelengths (might only be able to observe systems far from galactic plane);
- EGPs very close to primary might exhibit different characteristics.


Solar wind
To Sun
Magnetic axis
Rotation axis
Plasma torus
Shock wave
1,000,000 km
Current sheet