# The Radio Transient Sky

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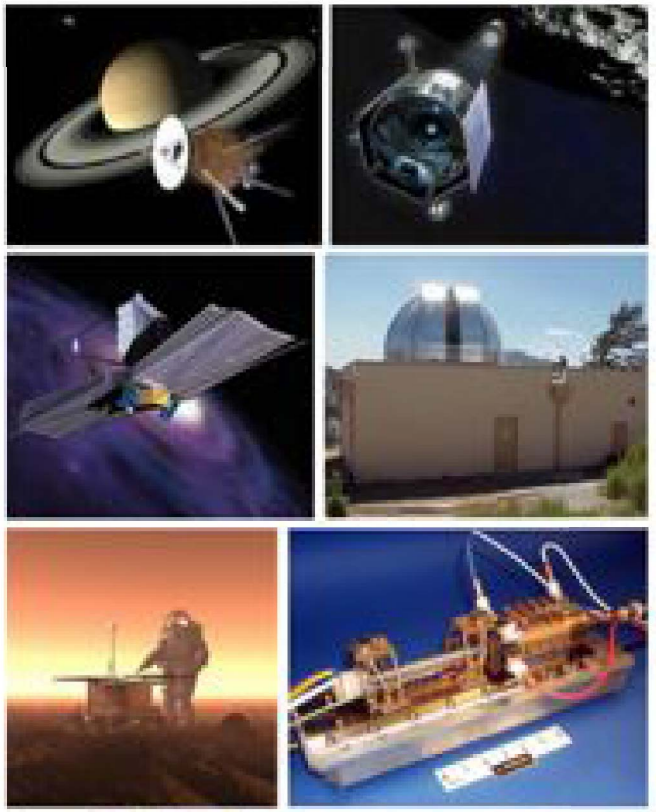
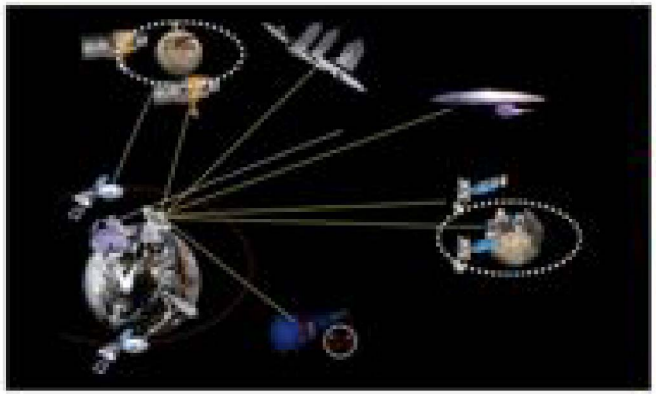
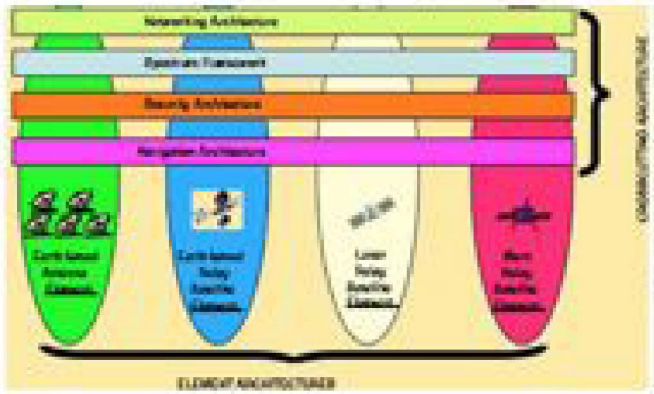




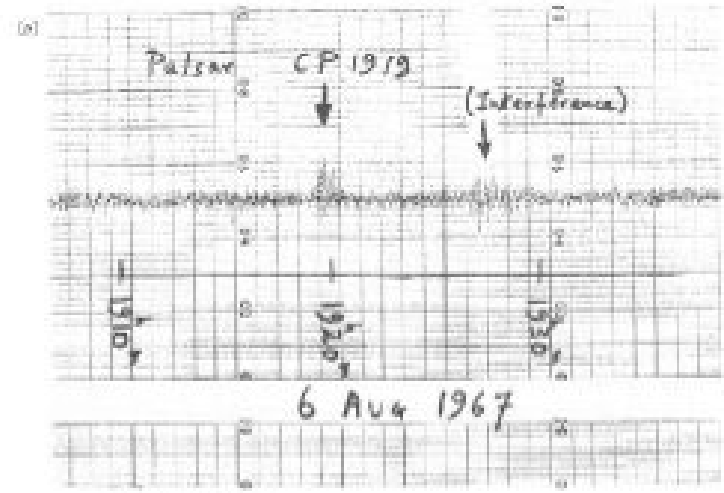


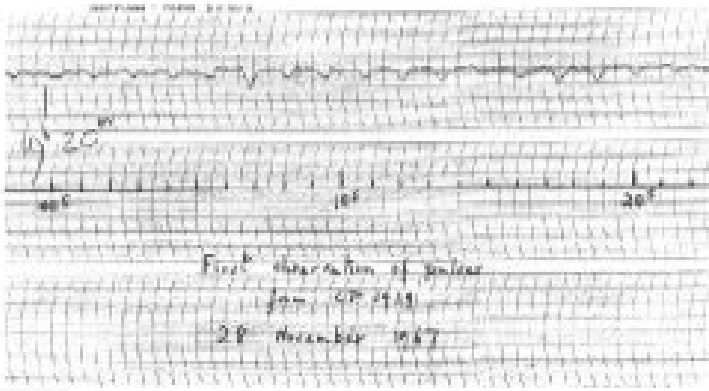
# Discovery of Neutron Stars

Jet Propulsion Laboratory
California Institute of Technology

- **Baade & Zwicky (1934) introduce concept of neutron star.**
  - **Unobservable because the Universe is thermal**
- **Observed (1967)**

  - **In telescope designed to exploit time domain, but …**
  - **Serendipitously**
  - **Could differentiate celestial and terrestrial interfering signals (RFI)**



Jocelyn Bell, 1967

# Who Cares About the Radio Transient Sky?

Jet Propulsion Laboratory
California Institute of Technology

**Transient radio sources are necessarily compact**

- **Markers of explosive or dynamic events**
- **Probe fundamental physics and astrophysics**

**Radio signals modified by intervening media and are powerful probes of those media**

- **Dispersion**
- **Scattering**
- **Faraday rotation**

"Radio Astronomy in the LSST Era"
(Charlottesville, VA; 2013 May)

# Radio Transients

## Coherent ("Fast")

- Generated by particles radiating in phase
  - $L \propto N^2$
- Tend to be at lower frequencies
  - Radiating volume $\propto \lambda^3$
- Propagation effects generally important
  - De-dispersion required
- W < 1 s

## Incoherent ("Slow")

- Generated by independent particles
  - $L \propto N$
- Tend to be at higher frequencies
- Propagation effects generally unimportant
  - De-dispersion not required
- W > 1 s

# Radio Transients

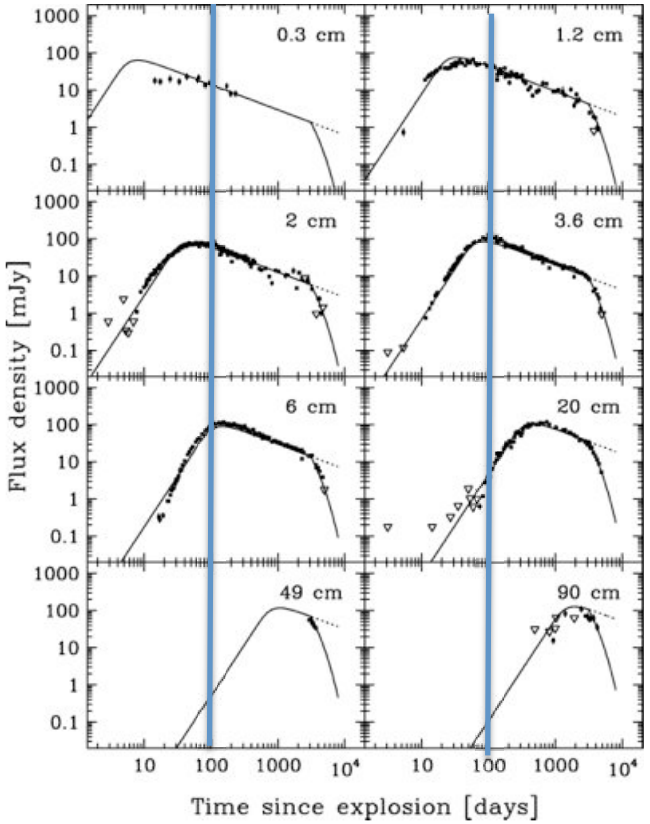
| | Coherent | Incoherent |
|---|---|---|
| Extragalactic | | |
| Galactic | | |

# Radio Transients

| Class | Object | Timescale | $\Delta t_{opt}$ |
|---|---|---|---|
| Extragalactic incoherent | SNe, GRBs, TDEs | Tens of minutes-years | Lags by minutes-months |
| | AGN | Tens of minutes-years | Lags by days-months |
| | GW counterparts? | Tens of minutes? | Lags? |
| Extragalactic coherent | Fast radio bursts? | Sub-second | unknown |
| | GW counterparts? | Sub-second | unknown |
| Galactic coherent | Masers (circumstellar, interstellar) | Tens of minutes | N/A |
| | Neutron stars | Sub-second | Simultaneous, if present |
| | Sub-stellar objects | Sub-second to hours | unknown |
| Galactic incoherent | Novae, stellar flares | Minutes-hours | Lags by minutes |
| Unknown | “Hyman bursters” | Minutes | unknown |
| Propagation effects | Affects pulsars, extragalactic sources | Minutes-days (pulsars)<br>Years (AGN) | N/A |

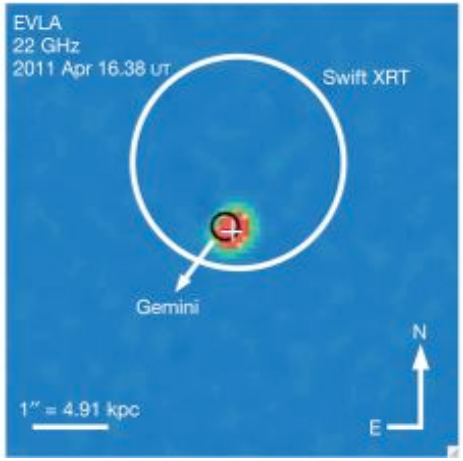
# "Slow" Radio Transients

- **Explosive Events**
  - **E.g., expanding synchrotron fireball, radio emission from blast wave impacting surrounding medium and accelerating particles**
    - ✦ **Radio supernovae, gamma-ray bursts, …**
    - ✦ **"Clean" environments likely to be faint? (BH-BH merger?)**




(Radio supernovae, Weiler et al.)

- **Relativistic Jets**
  - **Magnetically collimated relativistic plasma**
    - **X-ray binaries, AGN, tidal disruption events**

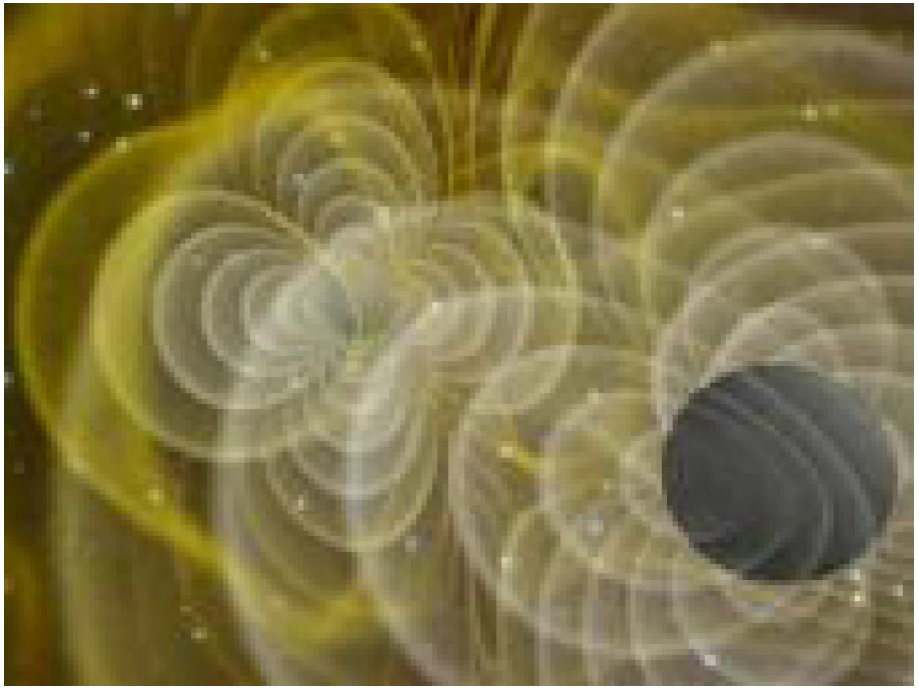



(Jet from tidally disrupted star, Zauderer et al.)

# GW Astronomy and the Time Domain

$$L_0 = 2.03 \times 10^5 \, c^2 \, M_\odot \, s^{-1}$$

- Generation of GWs requires large masses, high velocities, or both
- Potential sources include
  - ✧ Mergers
    NS-NS, NS-BH, BH-BH
  - ✧ Supernovae (asymmetric)
  - ✧ Rapidly rotating asymmetric neutron stars
  - ✧ Cosmic strings
  - ✧ …



# Gravitational Wave Events

## Why electromagnetic?

**More complete under-standing of GW candidate**

- **Nature of progenitor**
- **Environment**
- **…**
- **Confirmation**

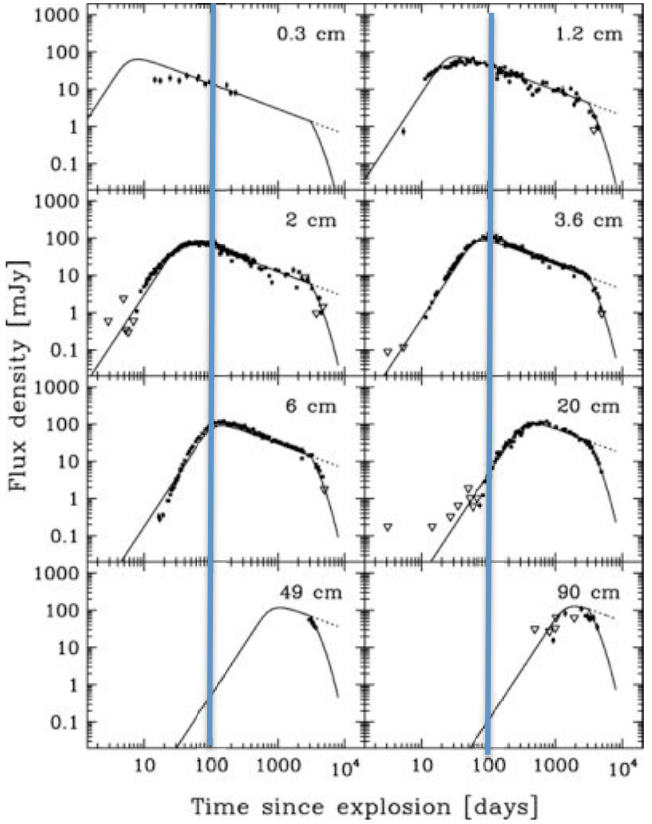
## Why radio wavelengths?

- **Non-thermal (high-energy) particle emission**
- **Precision astrometry**
- **Unaffected by dust obscuration**
- **Observe during daytime**
- **Low false positive rate?**
- **Time delays due to propagation through interstellar & intergalactic media**

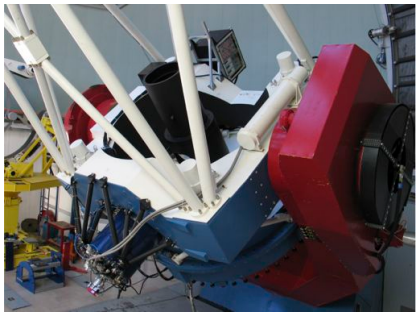
  $\tau \propto \lambda^2$, **“leisurely” slews based on trigger**

# "Slow" Radio Transients
## The Broader Context

- Optically thick expanding photosphere
- Shorter wavelengths brighten earlier
- Slow radio transients most likely to be productive as followup of shorter wavelength observations




(Radio supernovae, Weiler et al.)

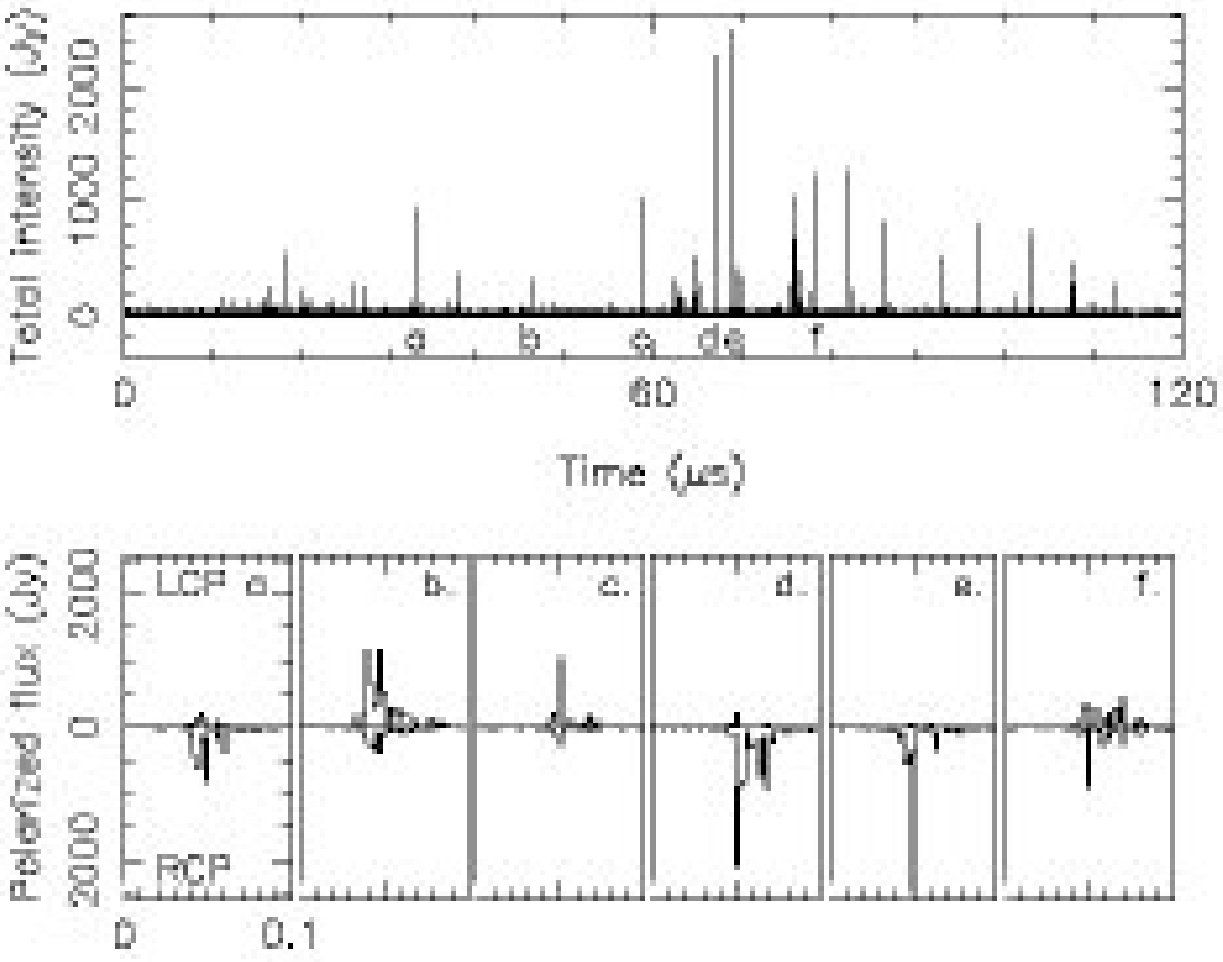


# Radio Transient Phase Space

- Considerable phase space to explore!

| | Coherent | Incoherent |
|---|---|---|
| **Extra-galactic** | Fast Radio Bursts(?) | Supernovae<br>Tidal disruption events<br>Intrinsic AGN variability<br>… |
| **Galactic** | Magnetized neutron stars (pulsars, RRATs)<br>Brown dwarfs<br>(Extrasolar planets?)<br>Cosmic ray-generated pulses<br>… | Novae<br>Flare stars<br>Microquasars (X-ray binaries)<br>… |

# Giant Pulses from Radio Pulsars




- On ~ 2 ns
- Off ~ 10 min
- $T_B > 10^{30}$ K

  Brightest objects in the Universe
- Probe of
  - pulsar emission mechanism
  - scattering environment?

➢ **Arecibo can detect a Crab-like pulsar to 1.4 Mpc**

Crab pulsar (Hankins et al. 2003)

# Pulses and Media

- Refractive index of plasma is frequency dependent
- Arrival time of pulse is frequency dependent

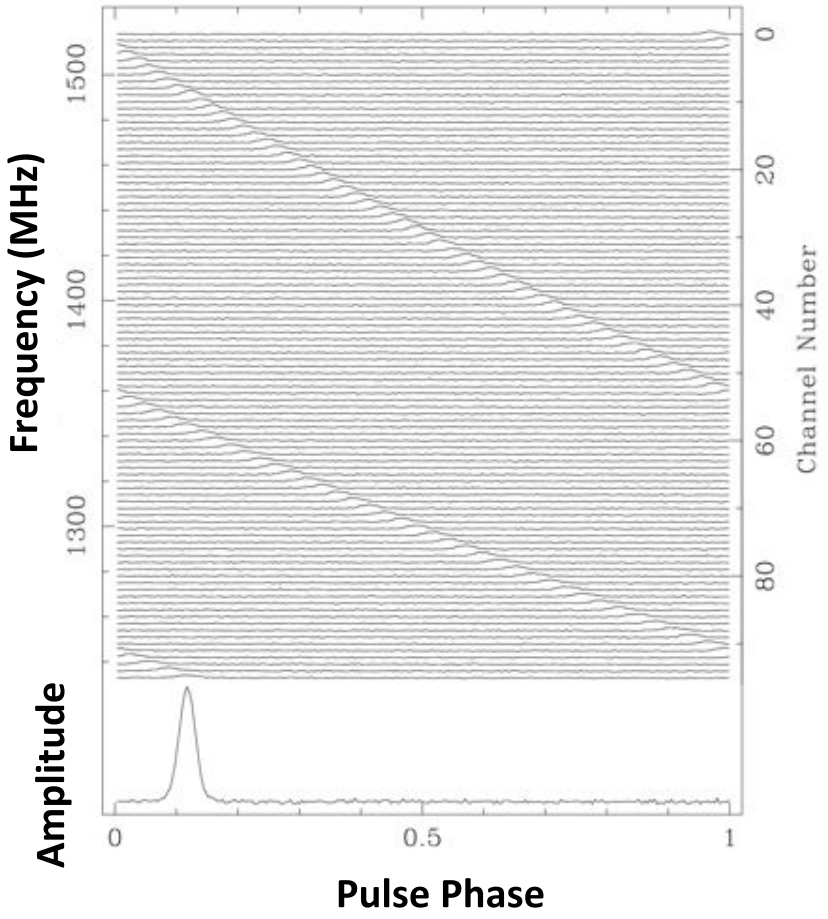
$$t = \mathrm{DC} * \mathrm{DM}/\nu^2$$

$$\mathrm{DM} = \int n_e(z)\, dz$$

  - Lower frequencies arrive later

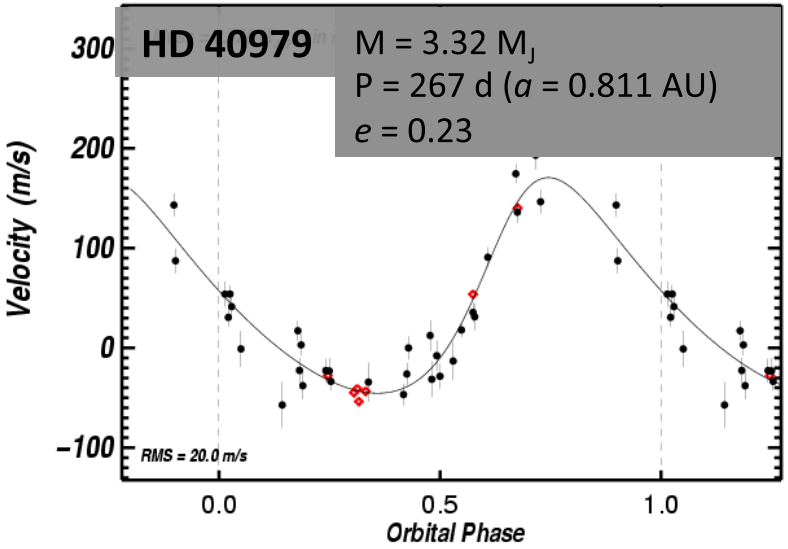
➢ Arrival time differences between different frequencies are a direct probe of an intervening medium

  ➢ If a radio pulse can be produced by an object at intergalactic distances, direct measure of intergalactic medium (IGM)




Lorimer & Kramer

# Extrasolar Planetary Radio Emission



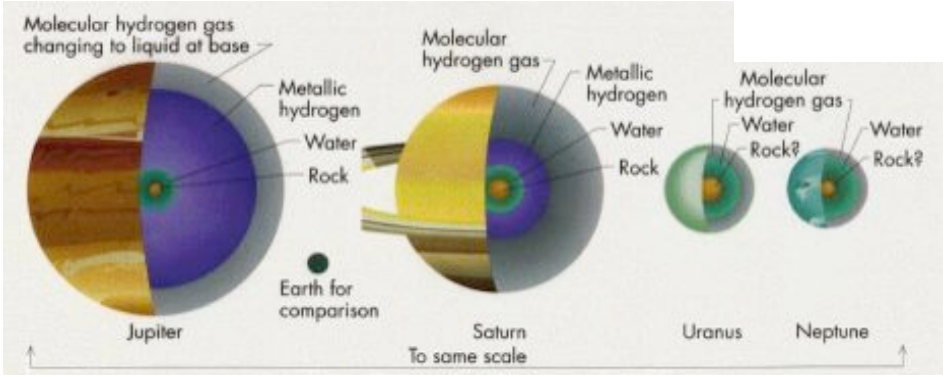

## Discovery of extrasolar planets!

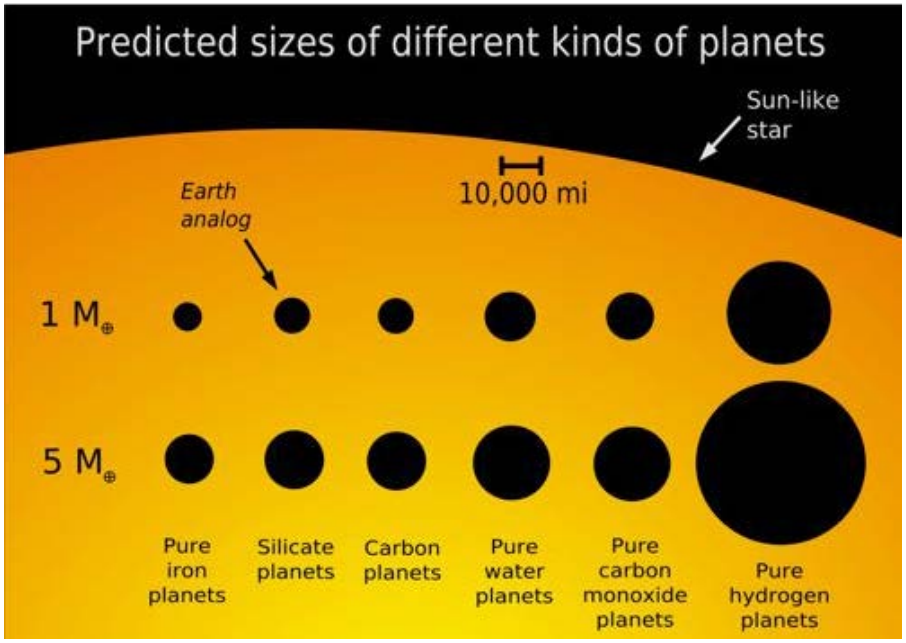
- ~ $10^3$ extrasolar planets
- Indirect detection via optical signature
- Direct detection via their shadow

## Detecting ⇒ characterizing

- What are their properties?
- Can we detect planets at other wavelengths?
  - ✓ IR thermal emission detected
  - ? Magnetospheric radio (viz. Jupiter)
- Implications for habitability?

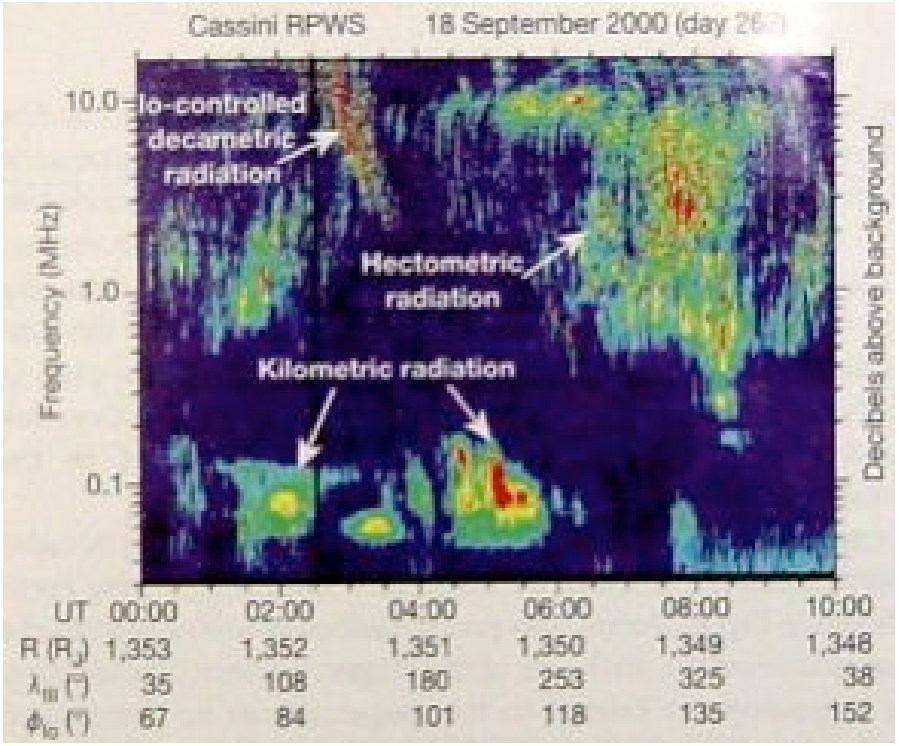
# (Extrasolar) Planetary Interiors

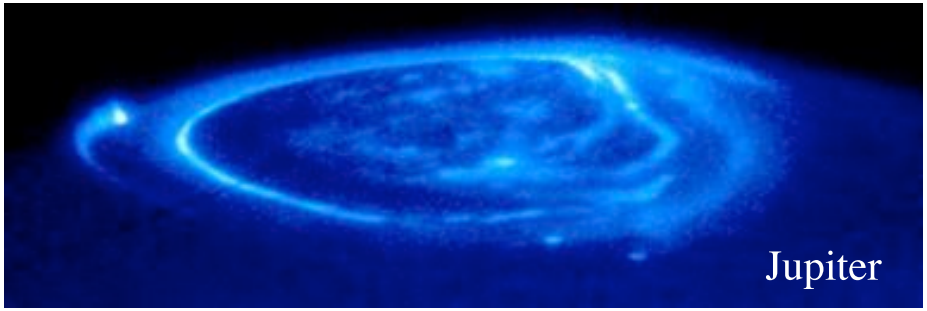



- **Magnetic field from conducting fluid in interior**
  - **Earth: liquid Fe core**
  - **Jupiter: metallic $H_2$**
  - **Saturn: metallic $H_2$**
  - **Uranus: salty $H_2O$ (brine)**
  - **Neptune: salty $H_2O$ (brine)**
- **Extrasolar planetary interiors?**
  - **Fe rich**
  - **Si rich (like Earth)**
  - **C rich**
  - **O ($H_2O$) rich**
  - **CO rich**
  - **H rich**

# Planetary Radio Emission (in the Solar System)

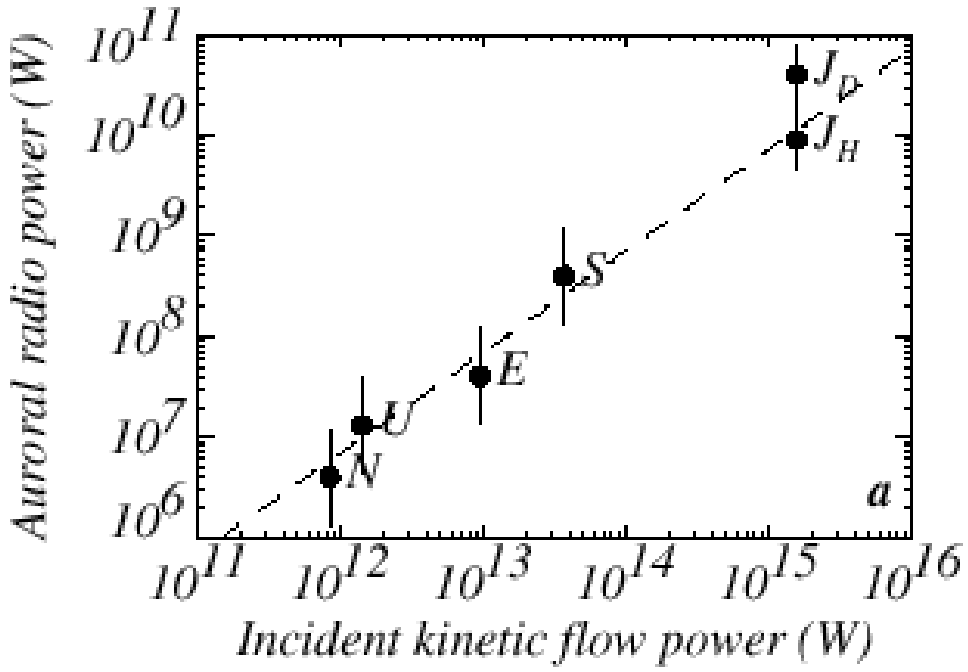



- Burke & Franklin (1955) discover Jovian radio emission.
- Late 1960s/70s: Earth's polar region recognized as radio source ($10^7$ W).
- *Voyagers*: Opens up field
- All gas giants have strong planetary magnetic fields and auroral/polar cyclotron emission.

  Jupiter: Strongest at $10^{12}$ W

# Radiometric Bode's Law

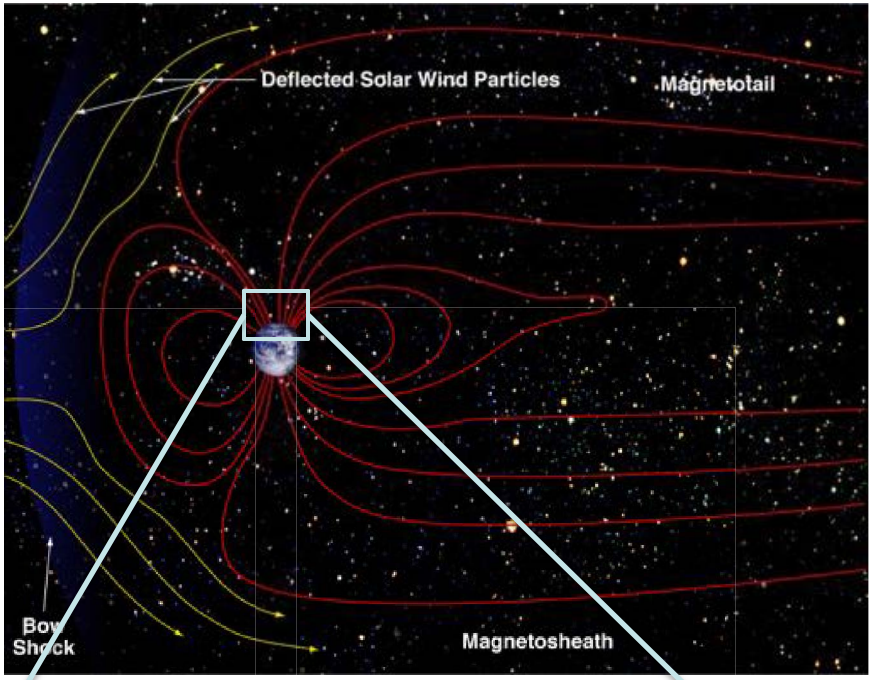


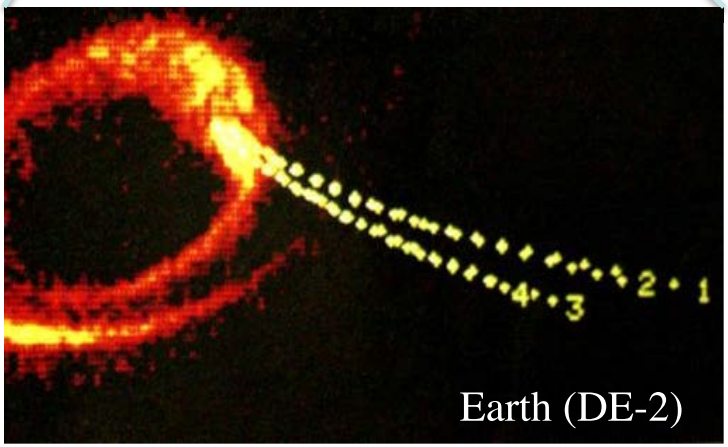

$P \sim 4 \times 10^{11}\ W\ \omega^{0.79}\ M^{1.33}\ d^{-1.60}$

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

- Zarka (1997), Farrell et al. (1999) extend to extrasolar planetary systems
- 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 "inflated" hot Jupiter
  - V, r ← solar values

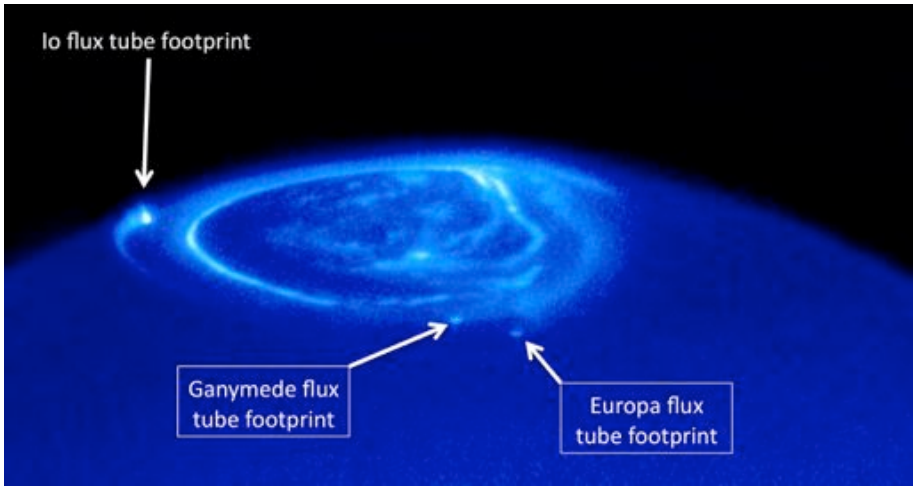
# Magnetospheric Emissions



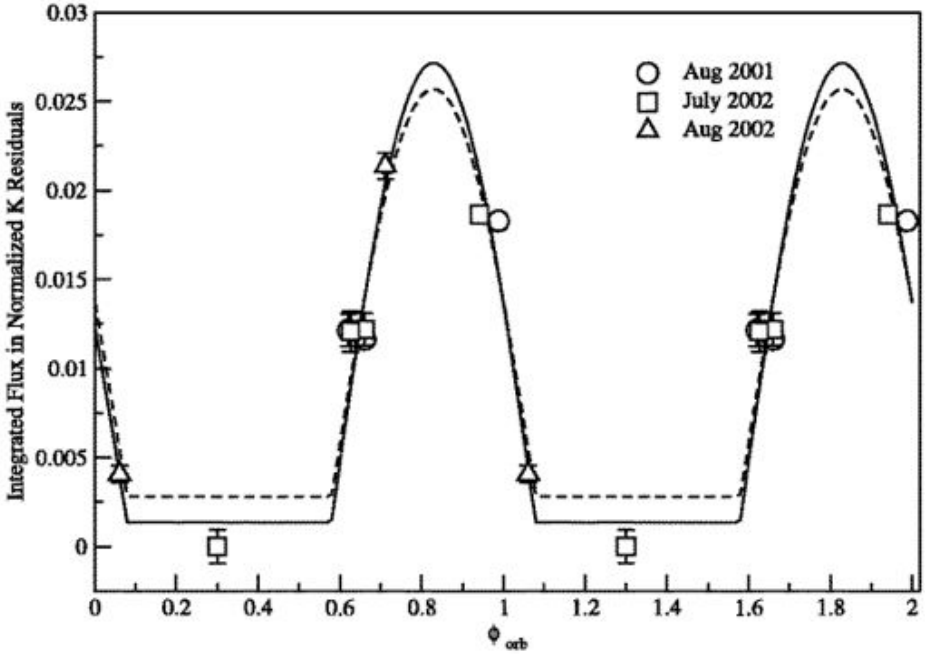




Stellar wind provides energy source to magnetosphere

- ~ 1% of input energy to auroral region emitted in UV
- ~ 1% of auroral input energy into electron cyclotron maser radio emission



# Extrasolar Planetary Magnetic Fields?

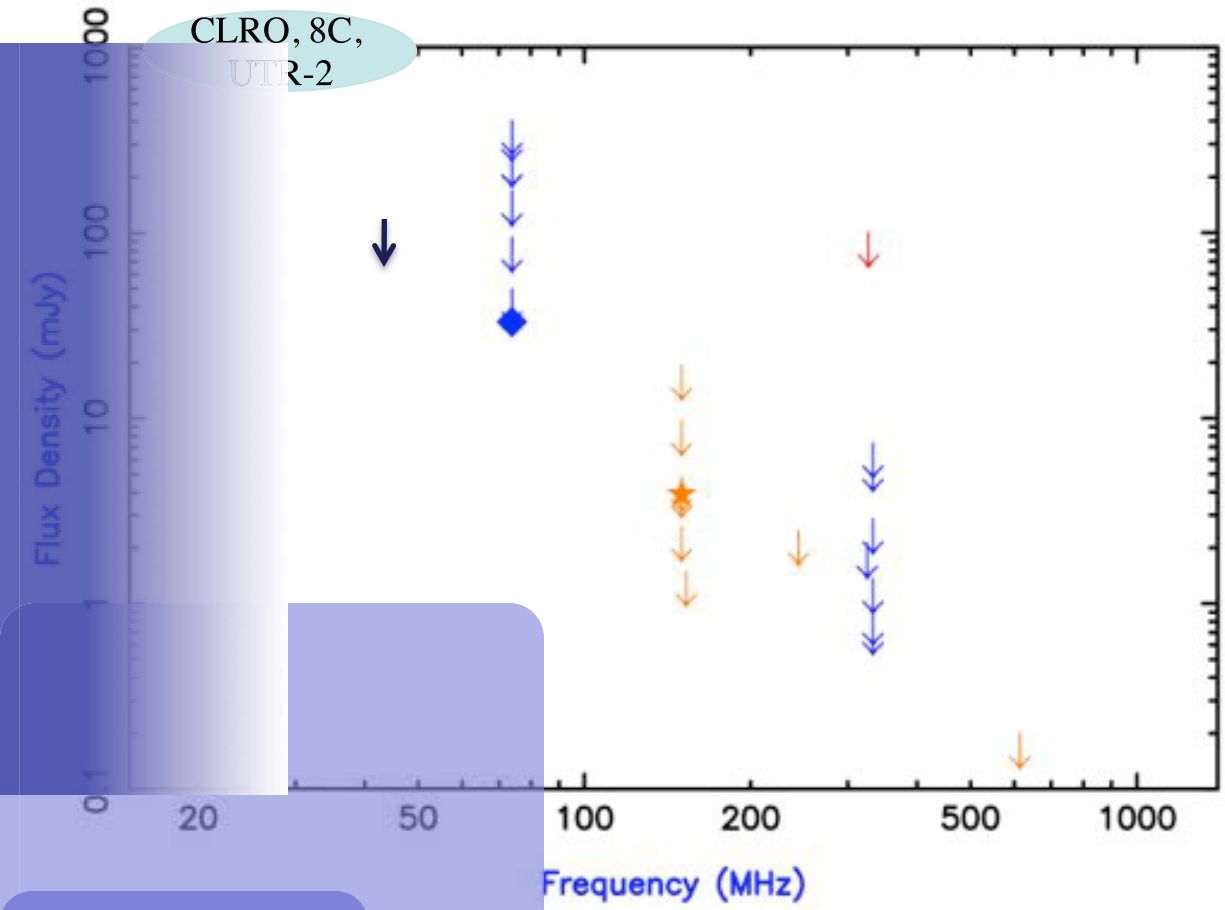



- **Observe Ca II H and K lines (393.3, 396.8 nm, Shkolnik et al. 2003, 2008)**
  - **HD 179949: 0.84 $M_J$ planet in 3.1 d orbit**
    - **Detect ~ 4% variations in "line strength"**
    - **No estimate of planetary magnetic field strength**
    - **Also observed τ Boo, υ And, 51 Peg, HD 209458**

➢ **But other approaches give wildly differing field strength estimates**

- **Inflated radii due to Ohmic dissipation?**
- **Auroral UV emission**

# Extrasolar Planetary Radio Emission Searches




- VLA
- GMRT
- GBT

# The Radio Transient Sky Summary

- Radio transient sky has been rich source of discovery
- Still significant unknowns associated with many source classes

**"Fast" radio transients (coherent emitters)**

May require followup at shorter wavelengths, considerable discovery space?

**"Slow" radio transients (incoherent emitters)**

Likely to be important part of followup for transients detected at shorter wavelengths

- Significant new infrastructure becoming available!

  See following talks ….