PERSPECTIVES OF PASSIVE AND ACTIVE

# MAGNETIC RESONANCE IN ASTRONOMY

**presented by Stanislav Sýkora at**

*XXII NMR Valtice meeting of Eastern European NMR Discussion Groups*

**100 000 000 Tesla ⇒ $^{1}$H Larmor ~ 4e$^{15}$ Hz (~ 70 nm, X rays)**

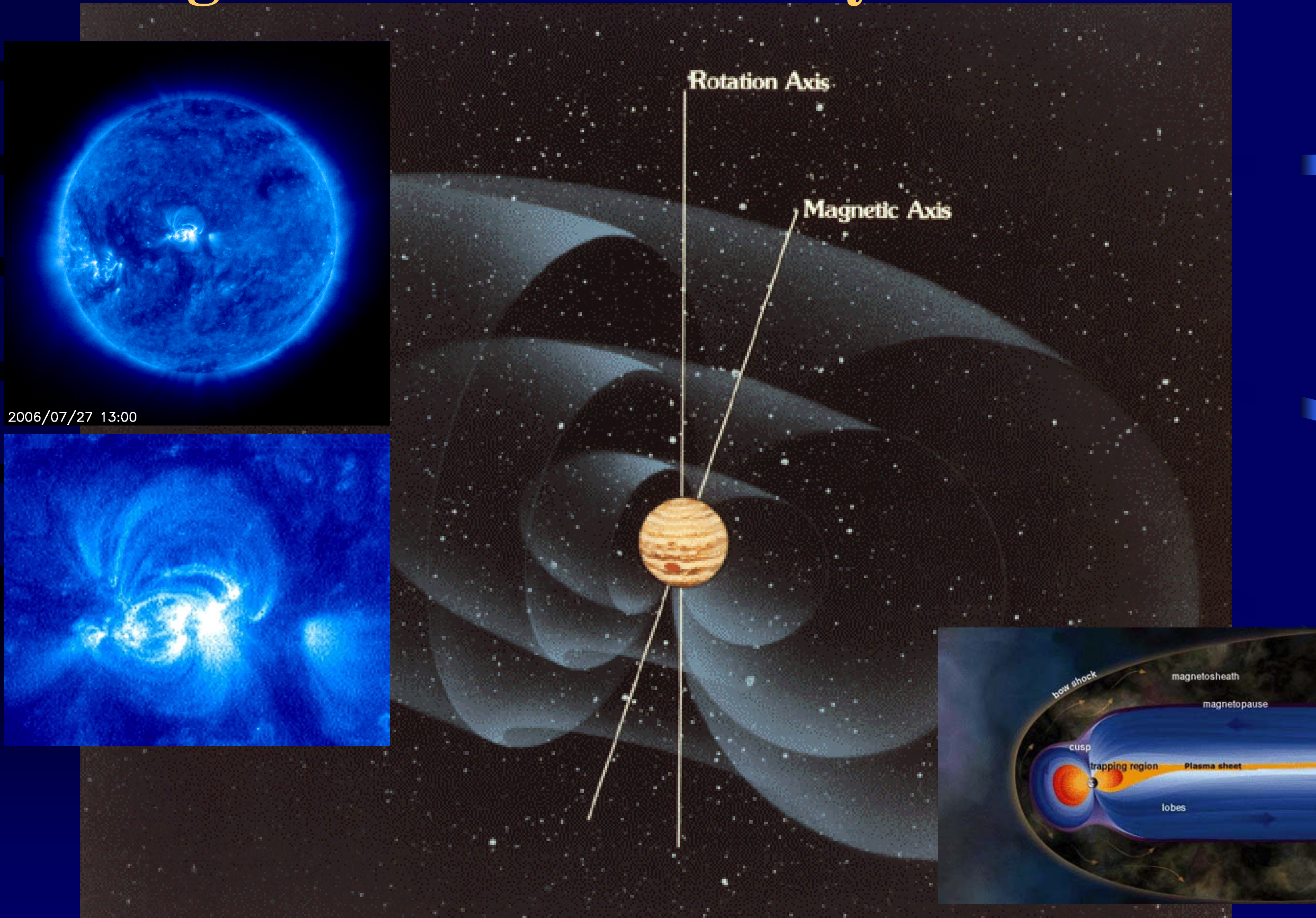
# Magnetic fields in the Universe

| Object | Field | Proton freq. | Electron freq. |
|---|---|---|---|
| INTER-GALACTIC SPACE | 1 nT | 0.043 Hz | 28 Hz |
| SOLAR WIND at Earth | 5 nT | 0.22 Hz | 140 Hz |
| INTER-STELLAR CLOUDS | 0.1 μT | 4.3 Hz | 2.8 kHz |
| EARTH SURFACE | 50 μT | 2.1 kHz | 1.4 MHz |
| SOLAR SURFACE | 0.5 mT | 21 kHz | 14 MHz |
| MASSIVE STARS | 10 mT | 430 kHz | 280 MHz |
| SUNSPOTS | 0.1 T | 4.3 MHz | 2.8 GHz |
| JUPITER SURFACE | 0.1 T | 4.3 MHz | 2.8 GHz |
| MAGNETIC STARS | 1.2 T | 51 MHz | 34 GHz |
| OLD NEUTRON STARS | Between white dwarfs and pulsars | | |
| PULSARS | 100 MT | 4.3e15 Hz | 2.8e18 Hz |
| MAGNETARS | 100 GT !!! | 4.3e18 Hz | 2.8e21 Hz |

# Magnetic fields of Solar System bodies

**Sun**: plasma vortices with **local magnetic fields** up to **200 mT**
**Mercury**: very, very faint global field
**Venus**: no magnetic field at all
**Earth**: **global field of 0.06 mT**, 1 satellite
**Mars**: no global field, **local magnetic lumps**, 2 satellites
**Jupiter**: **strong global field of 100 mT**, faint dust rings, 63 satellites
**Saturn**: **global field of 3.7 mT**, strong rings, 46 satellites
**Uranus**: **global field of 0.07 mT**, thin dark rings, 27 satellites
**Neptune**: **global field of 0.04 mT**, broken arc rings, 13 satellites
**Pluto**: ???

# Magnetic fields of Solar System bodies



# Magnetic particles to reckon with

| Particle | Spin | γ [MHz/T] |
|---|---|---|
| Electron | 1/2 | -28024.953 |
| Muon | 1/2 | -135.539 |
| $^{3}$H Triton | 1/2 | +45.415 |
| $^{1}$H Proton | 1/2 | +42.577 |
| $^{3}$He Helion | 1/2 | -32.434 |
| Neutron | 1/2 | -29.165 |
| $^{2}$D Deuteron | 1 | +6.536 |

… and all other magnetic nuclides …

# ???

**With all those magnetic fields,
and with magnetic particles all around,why
don't we ever hear about**

**Magnetic Resonance ?**

# Excitation & Detection

**Present laboratory methods:**

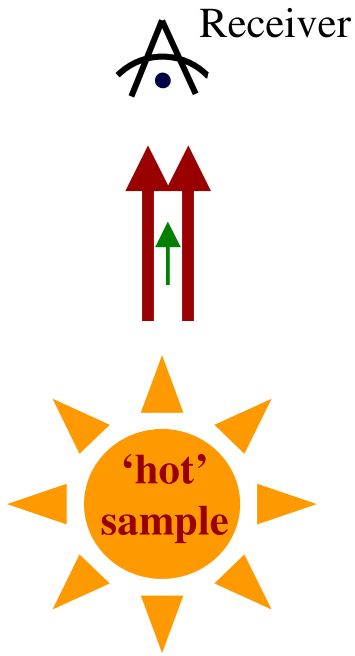
- **Magnetic induction** (the most common method)
- **SQUIDS** (superconducting quantum-interference devices)
- **Magnetic force** (mechanical detection)

**These are all ruled out**

**since we are far away from the sample and the ‘samples’ are too big**

# Back to *real* spectroscopy

## Passive emission

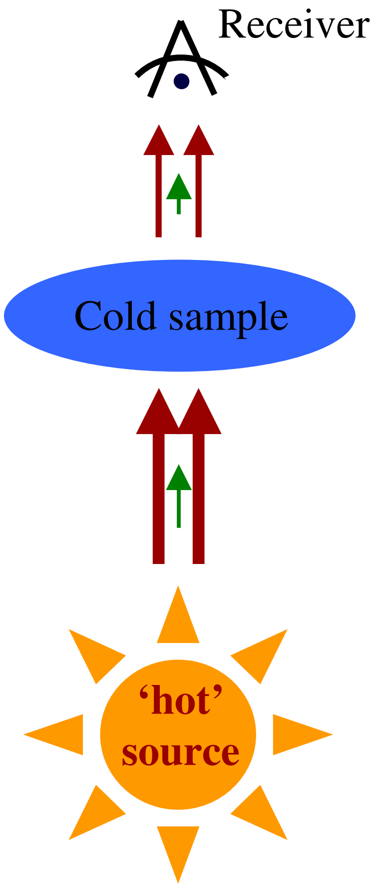



We must separate the desired signal (→) from the bulk (→)

**We need:**

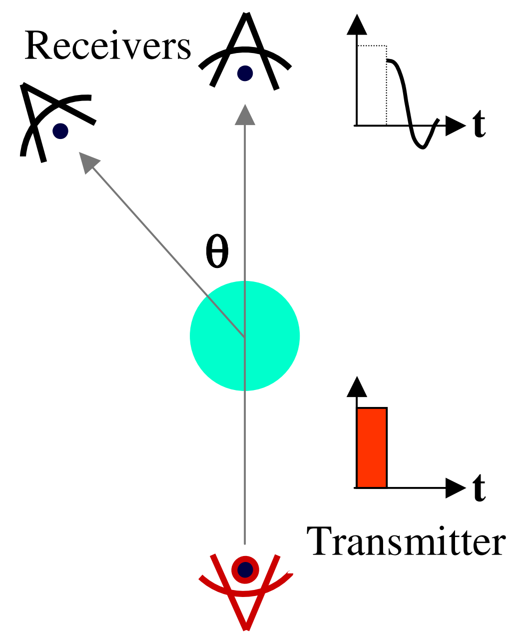
- Special signal features
- Sophisticated receiver

## Passive absorbtion




Dtto

## Active absorbtion
## Stimulated emission
## Fluorescence




Here we have also θ and t to play with, but we need more hardware

# Historic mystery

**It appears that nobody has ever tried**
**a plain spectroscopic arrangement to detect MR signals**.

I have found no paper of that type.
Not even a negative report,
**nor an analysis why it should or should not work**!

**I have no explanation of why this is so, except human laziness**
("*coils and cavities work, so why bother*")

# Detecting & Distinguishing spin radiation

There are lots of of interesting objects to look at.

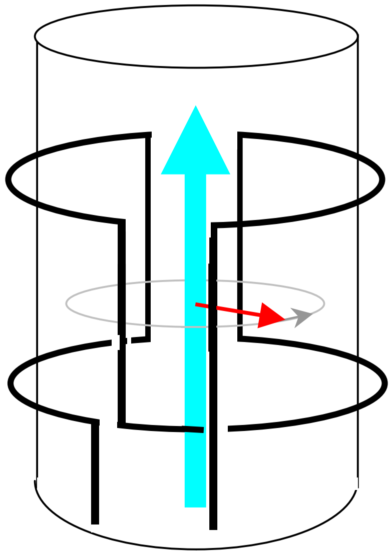
**But how can we detect spin radiation**
**and discard everything else**

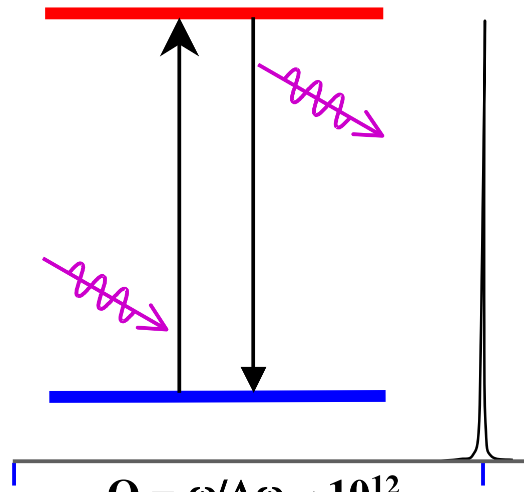
**???**

**<u>This</u>** is he most crucial question
(not the cost of a spacecraft)

# Theoretical ambivalence:

## we have no coherent explanation of the MR phenomenon






**CLASSICAL**

Technical aspects,
Bloch equations,
etc

**HYBRID**

Density matrix,
Coherences,
etc

**QUANTUM**

Sharp Spectral lines,
Coupled spin systems,
etc

**For "explanations",**
**we use what suits us best in any given situation**

# Properties of spin radiation

## Properties which are sure

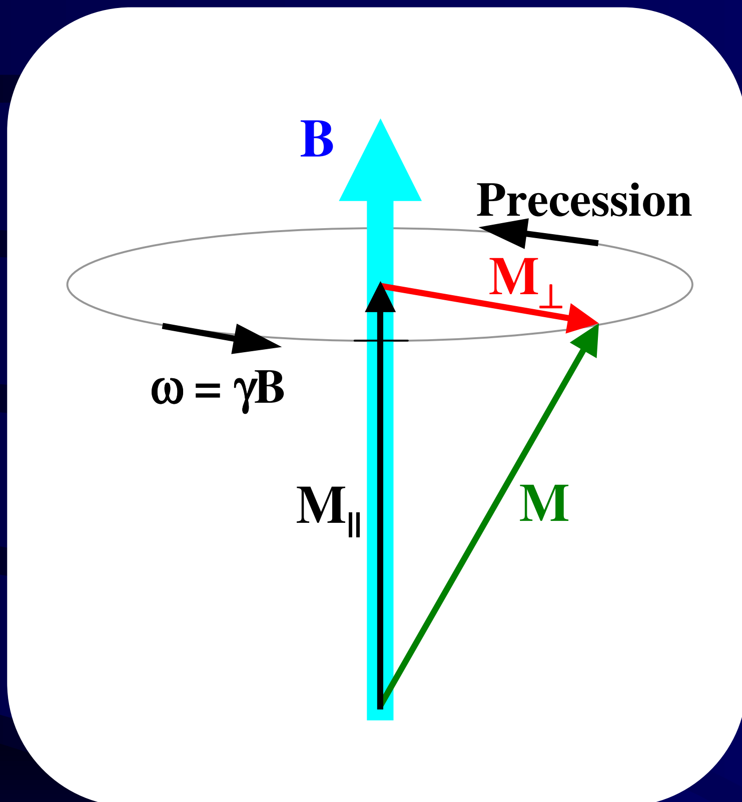
- **Linear frequency(field) dependence**
- **Narrow frequency bands** depending on field homogeneity
- **Re-emission dying out with $T_1$**, possibly quite slowly
- **Particle composition fingerprints** according to $\gamma$-values

## Educated guesses

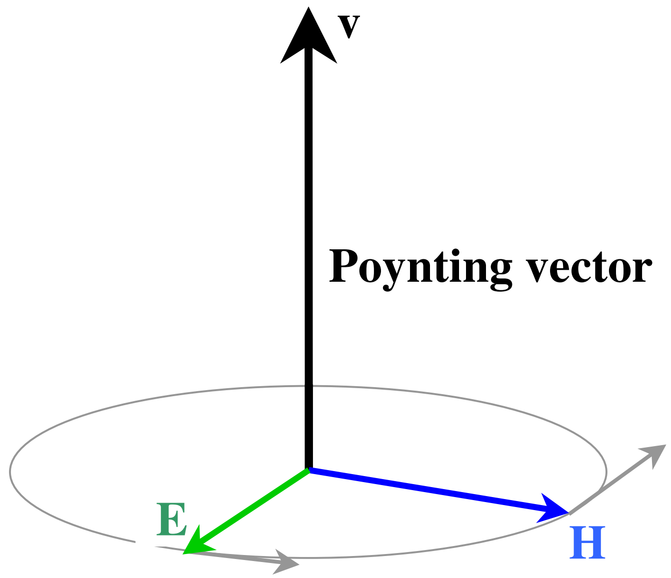
(until real experiments get carried out)

- **Perfect chirality** (circular polarization)
- **Extreme directionality** (alignment along the magnetic field)

# Chirality of spin radiation



# Directionality of emitted spin radiation




$\nabla \times \mathbf{E} = -\mu \, \partial \mathbf{H} / \partial t$

$\nabla \times \mathbf{H} = +\varepsilon \, \partial \mathbf{E} / \partial t$

$\nabla . \mathbf{E} = 0$

$\nabla . \mathbf{H} = 0$

$\mathbf{P} = \mathbf{E} \times \mathbf{H}$

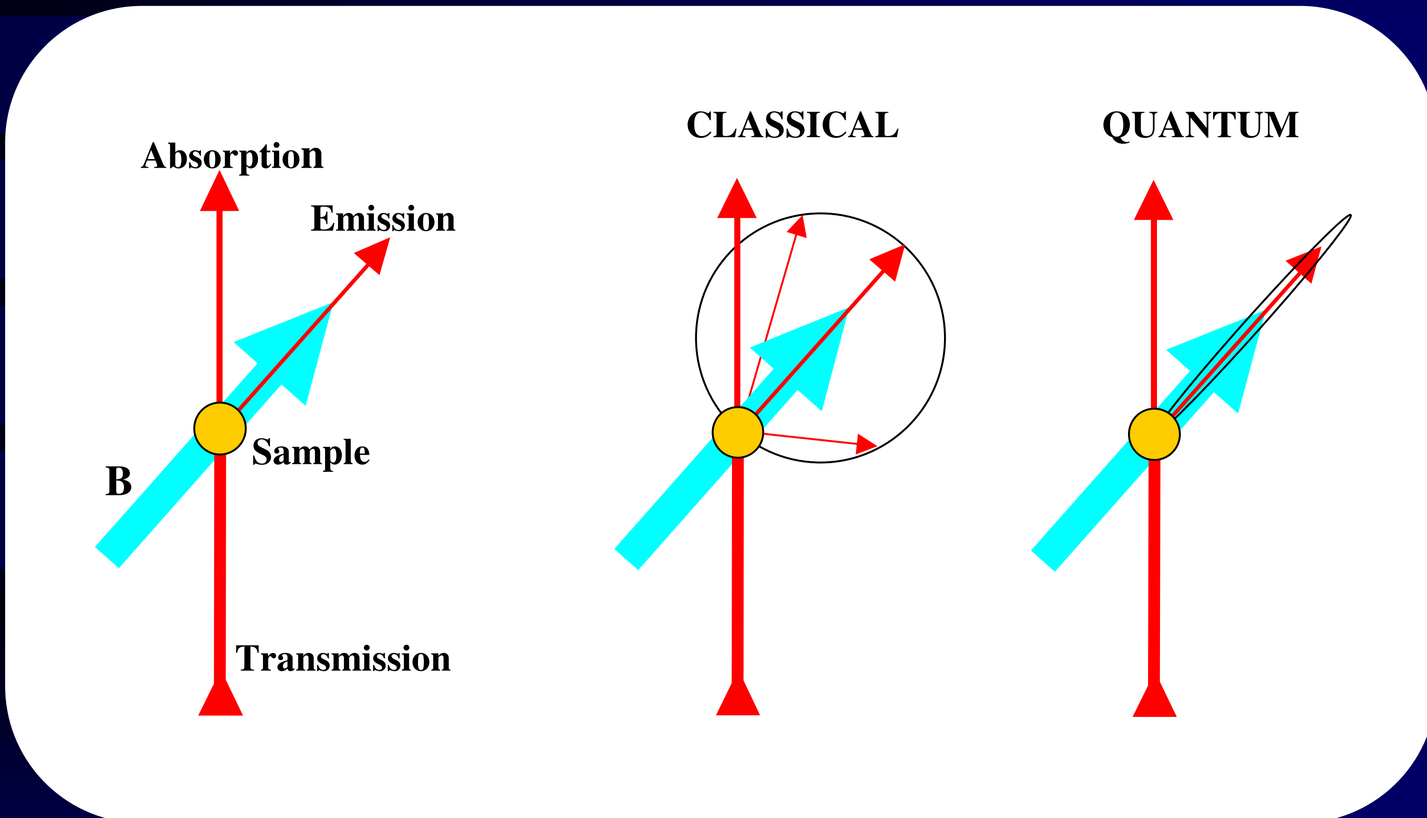
**Elmag radiation:**

$\mathbf{E} \perp \mathbf{H}$, $\mathbf{E} \perp \mathbf{v}$, $\mathbf{H} \perp \mathbf{v}$

$|\mathbf{v}| = c$

$|\mathbf{E}|/|\mathbf{H}| = Z_0$ (377 Ω)

# Directionality of emitted MR radiation: ?! theoretical doubts !?



# Directionality of spin radiation: Stan's CONGECTURES

**In emission**, the outgoing radiation matches the frequency, is **totally** circularly polarized and propagates **strictly** in the direction of the magnetic field (<u>single-spin description</u>)

**In absorption**, the incoming radiation must match the frequency and have a correct circularly polarized **component** aligned with the field (<u>ensemble description</u>)

# Passive spin radiation detection.

## Exploit:

**(A) Narrow width of resonance lines:**

Frequency scans over particular spectral widths.

**(B) Multinuclear patterns:**

Search for expected combinations

**(C) Chirality (circular polarization) $C^+$, $C^-$:**

Alternate the chirality of the receiver,

or use two receivers with opposite chiralities.

Measure the differential signals $S(C^+,t_i)$, $S(C^-,t_i)$

**(D) Long correlation times ($T_2$) of spin signals:**

Measure correlations $\langle S(C^+,t_i)S(C^+,t_k)\rangle$, $t_k - t_i = \tau$.

**(E) Directionality of the radiation.**

Frequencies flash out in narrow beams.

# Active spin radiation detection.

## Exploit also:

**(F) Chirality of transmitter $C^+$, $C^-$:**

**When the chirality is wrong, there is no absorption.**

**Again, measure differential signals.**

# In stimulated spin radiation detection.

## Exploit also:

**(G) Combined Tx-Rx chirality:**

**Of the 4 combinations, only 1 gives signal.**

**Use synchronized Tx-Rx chirality sequences.**

**(H) Slowly-decaying ($T_2$) responses (FID's):**

**Use pulsed, chiral transmitters and receivers .**

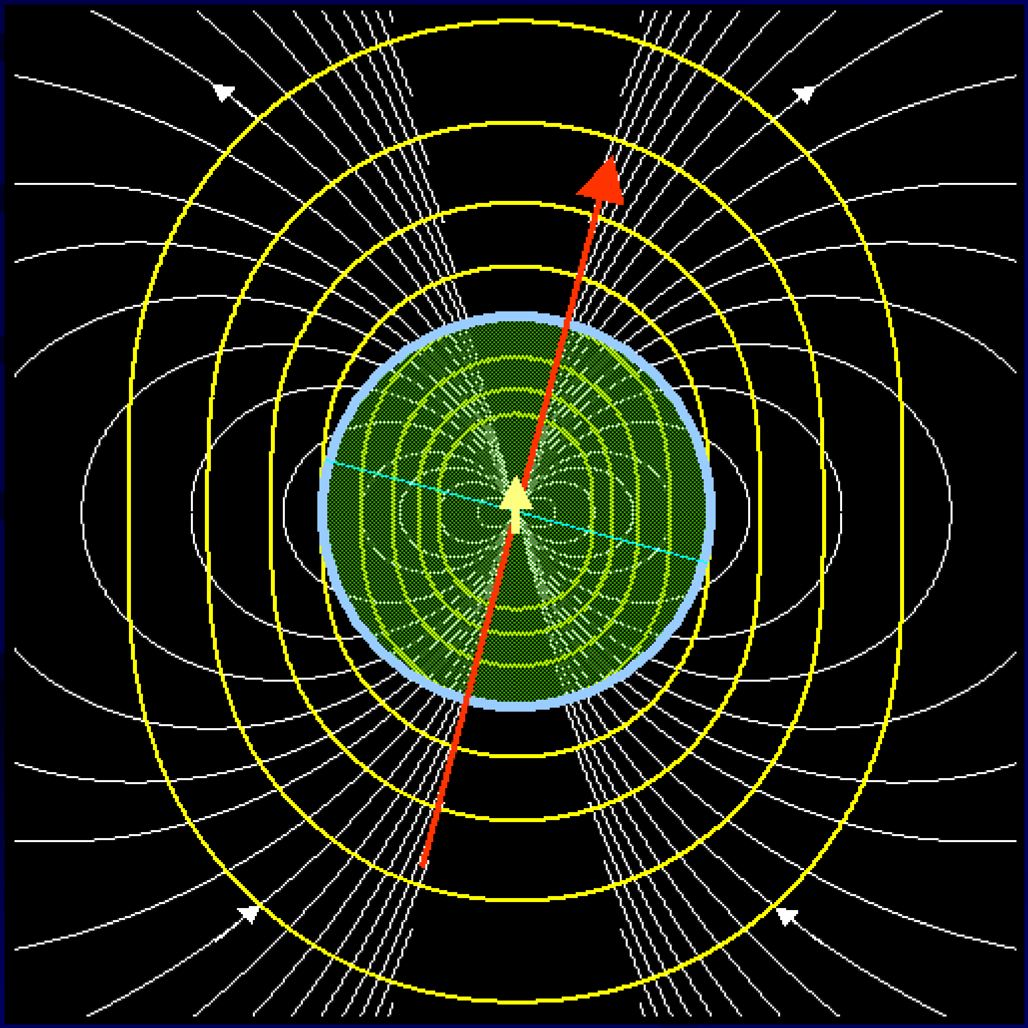
**Develop spin-specific measurement sequences.**

**Hadamard-type methods with variable timing.**

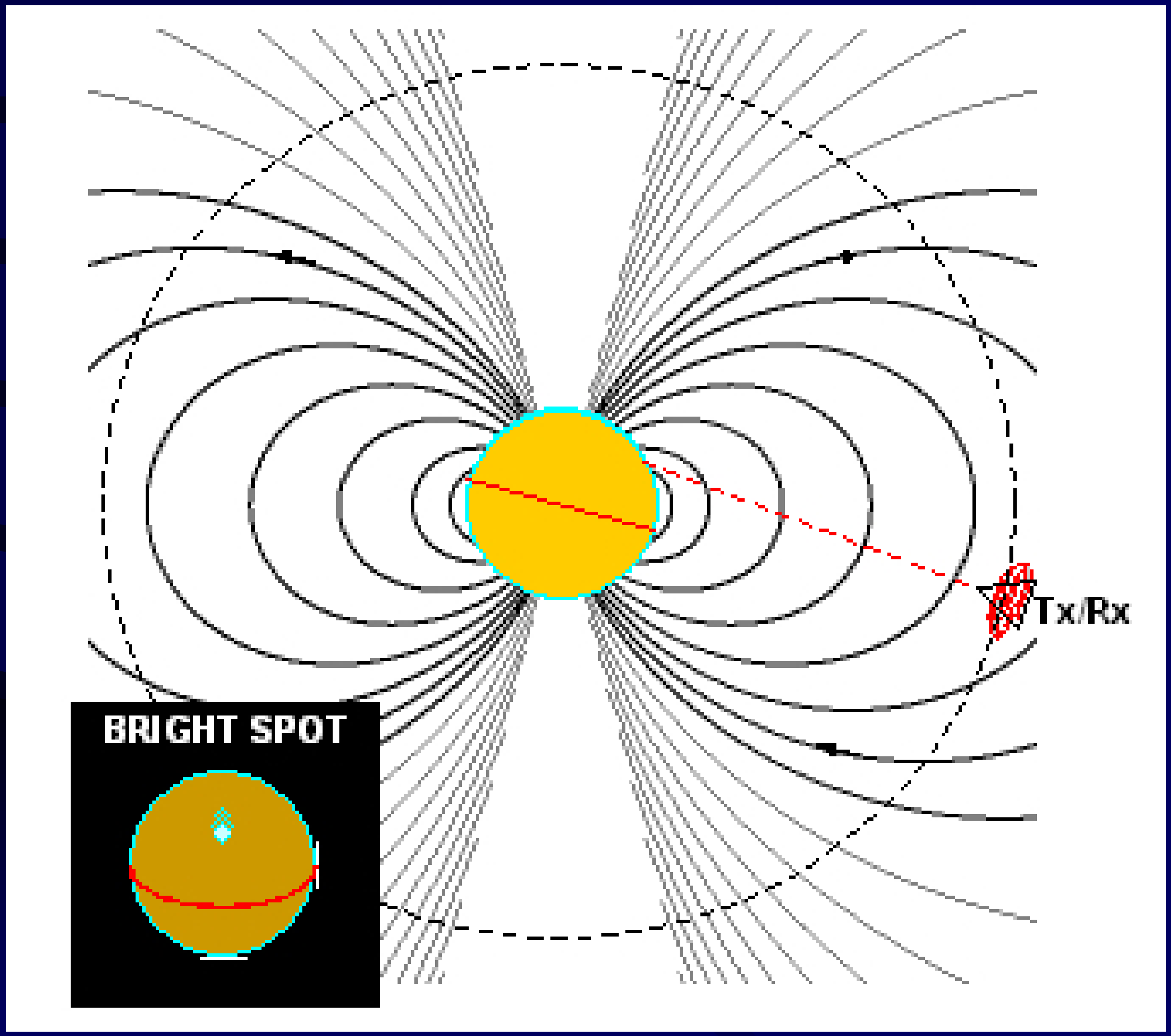
**Methods to overcome/exploit time-of-propagation phenomena**

**Etc, etc.**

# Dipolar field of a magnetic planet

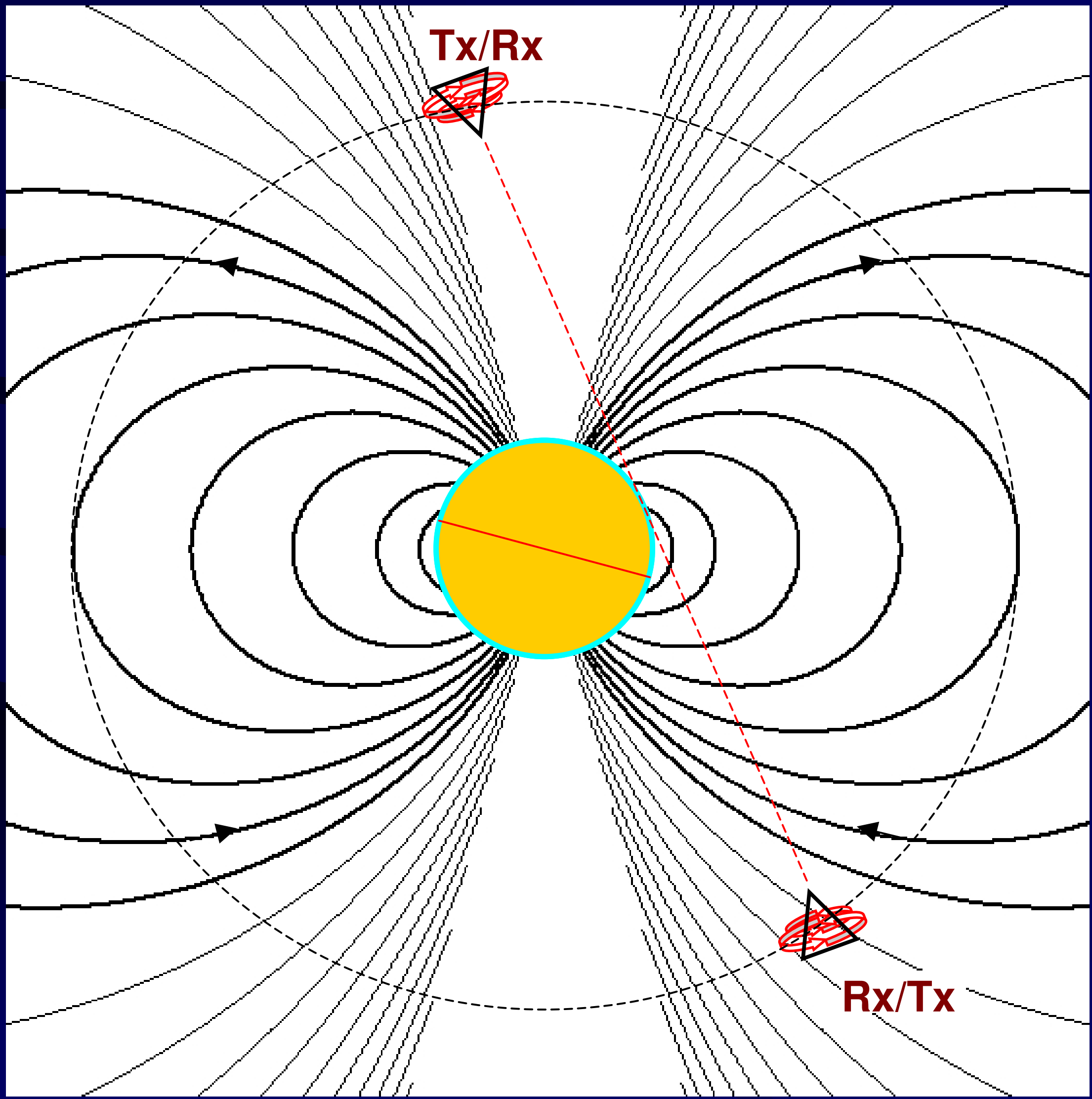


# Active MRA with a single spacecraft



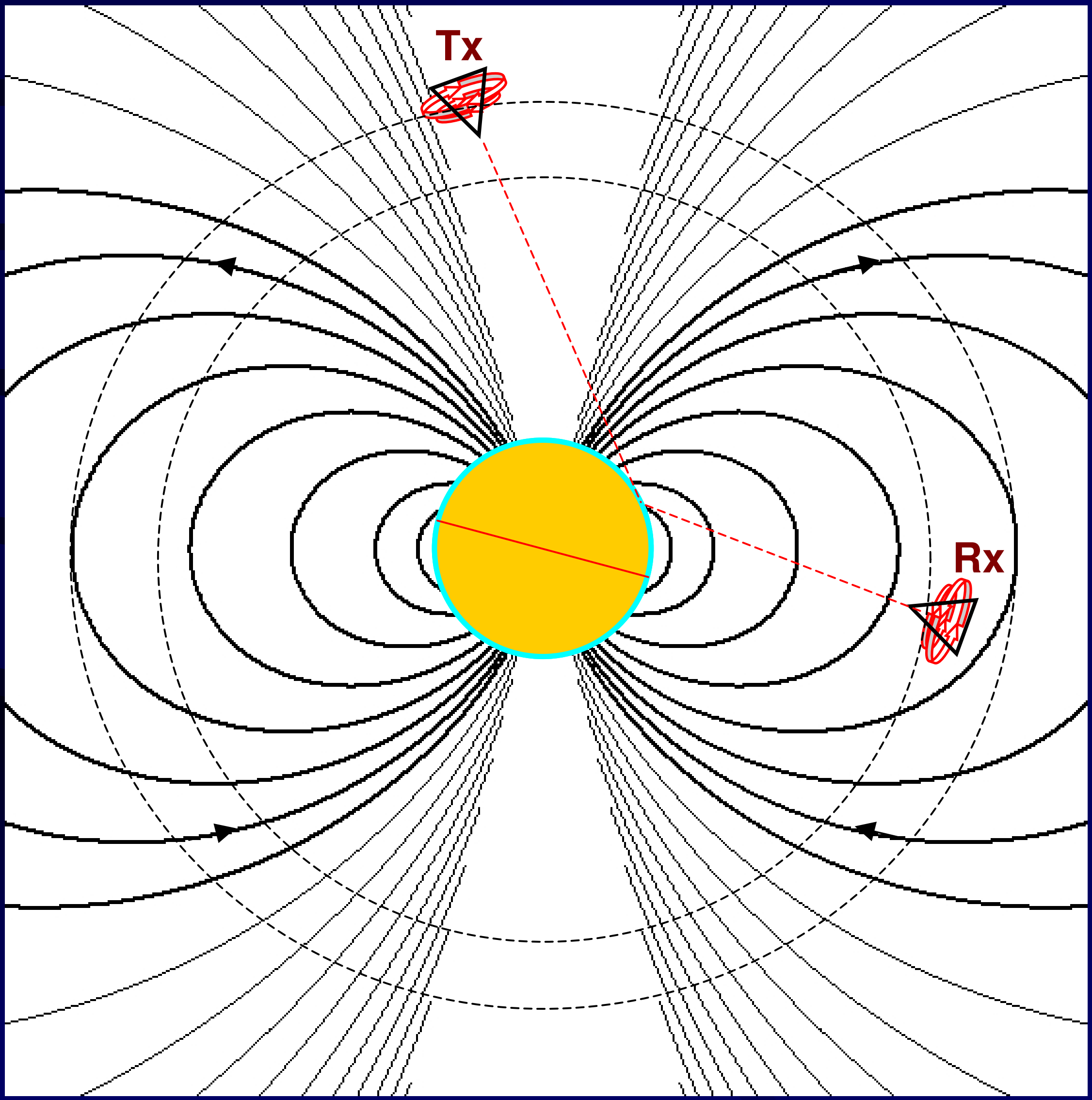
# Active MRA with two spacecrafts

## absorption-mode platent grazing

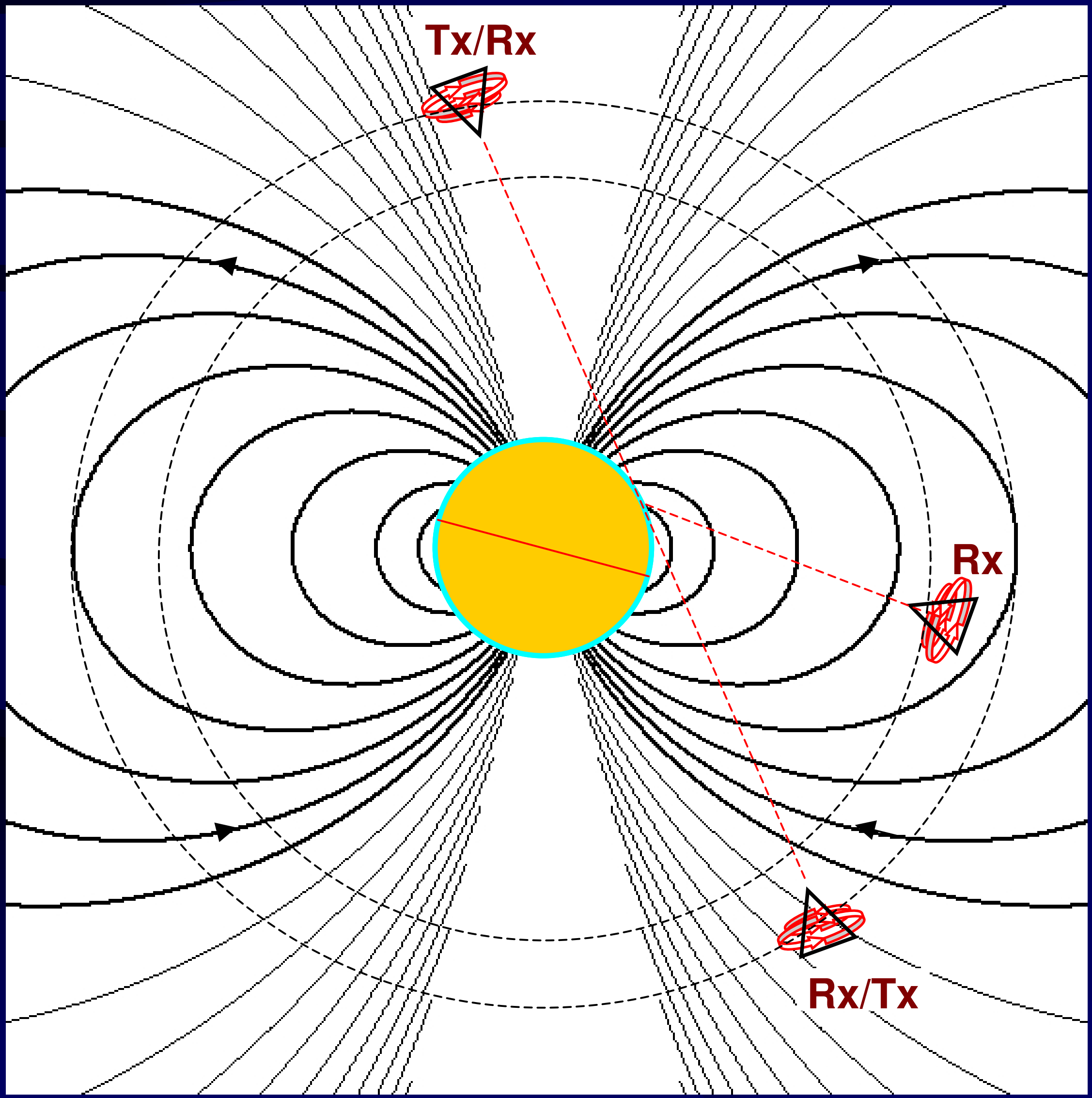


# Active MRA with two spacecrafts

## stimulated emission mode

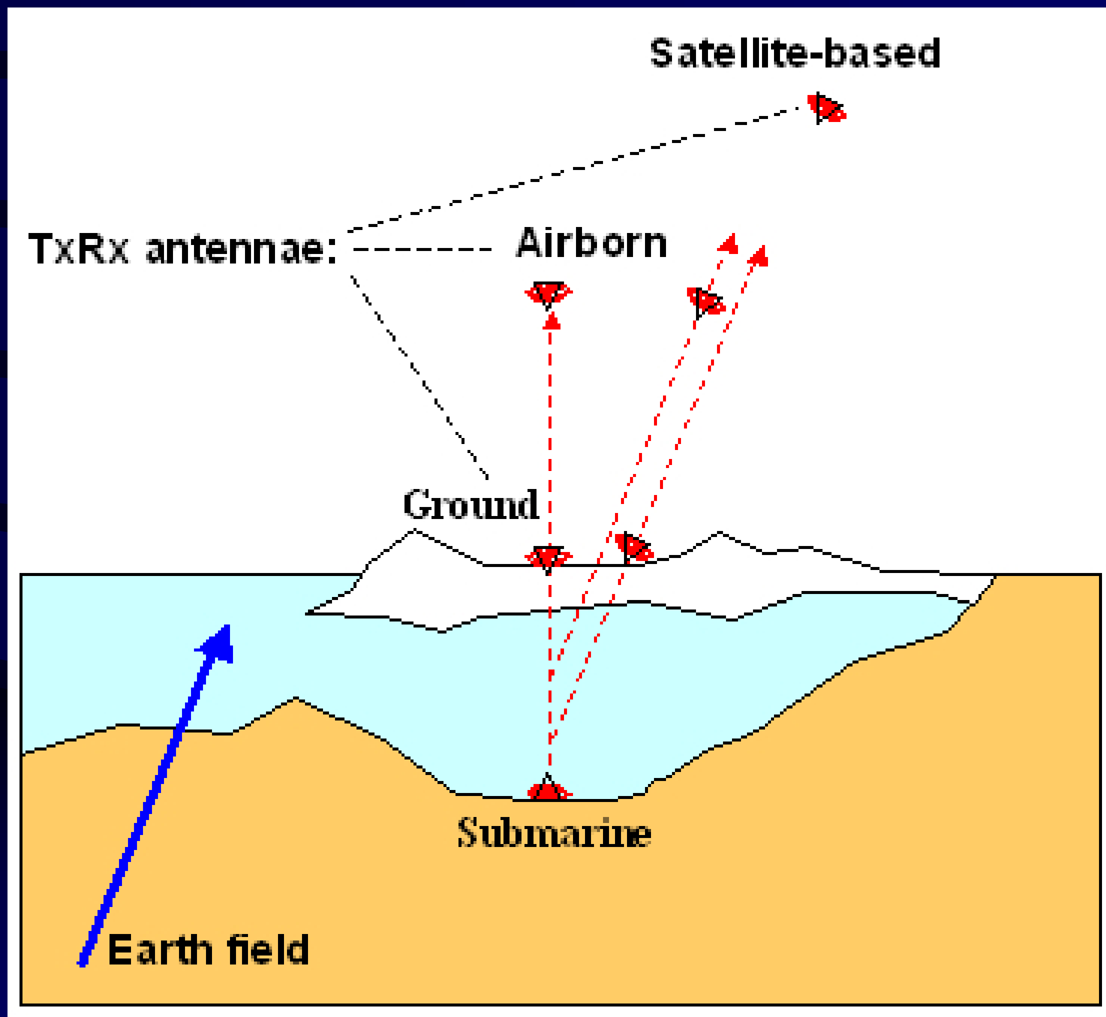


# Active MRA with three spacecrafts



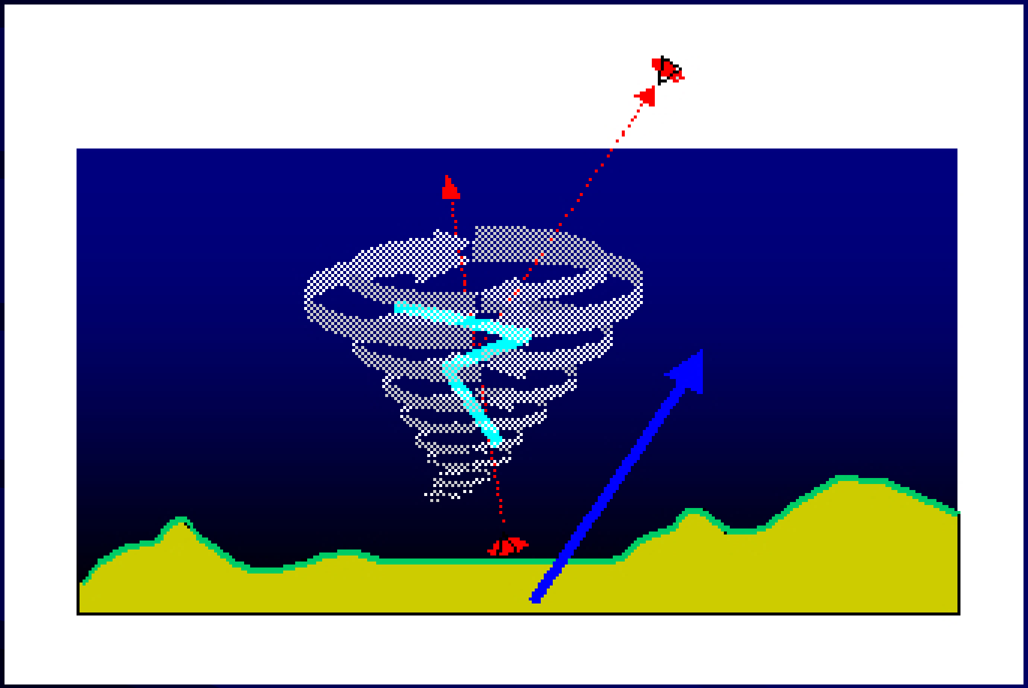
# Subplanetary, active MRA

## atmospheric phenomena ($^{1}H$, $e^{-}$)



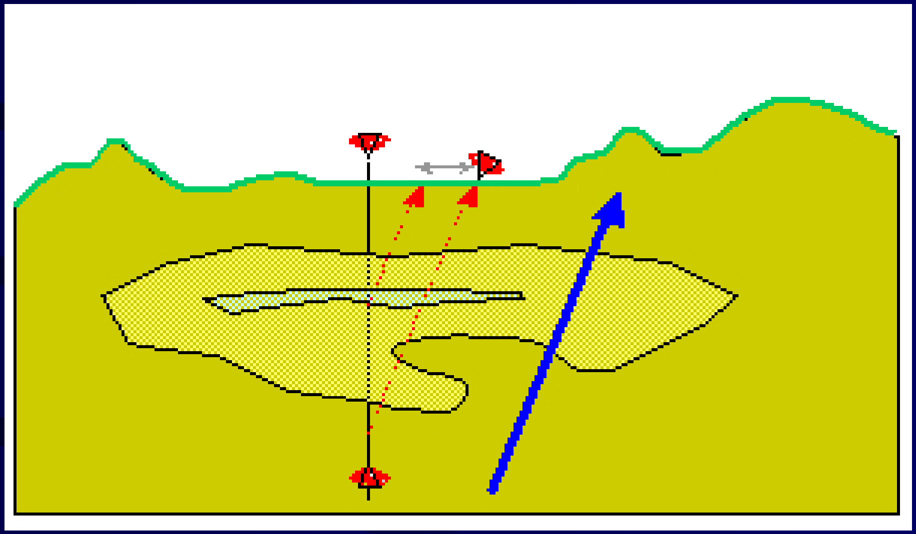
# Subplanetary, active MRA

## atmospheric phenomena ($^1H$, $e^-$)



# Subplanetary, active MRA

## subsurface prospecting (oil, gas, water)



## Yesterday, I was asked:

# ARE YOU SERIOUS ?

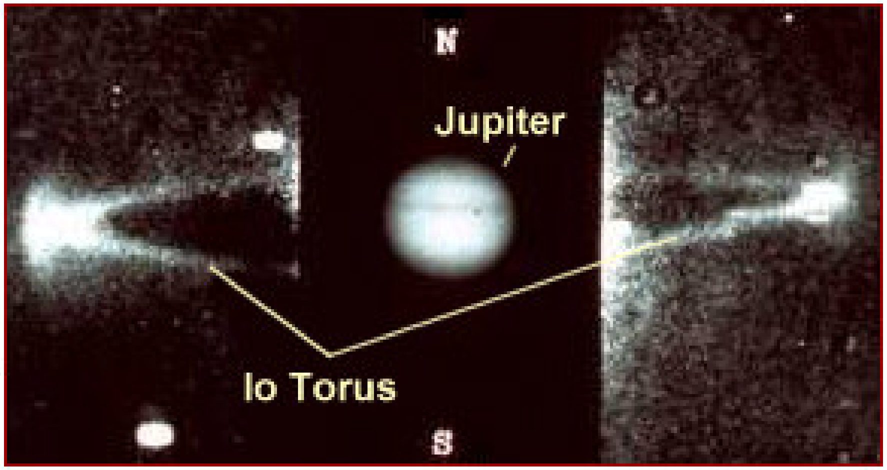
# Today, my answer is:
# HOW COULD I NOT BE ?!!

## Radio Storms on Jupiter

Science @NASA
NASA explores. Humanity benefits.
science.nasa.gov

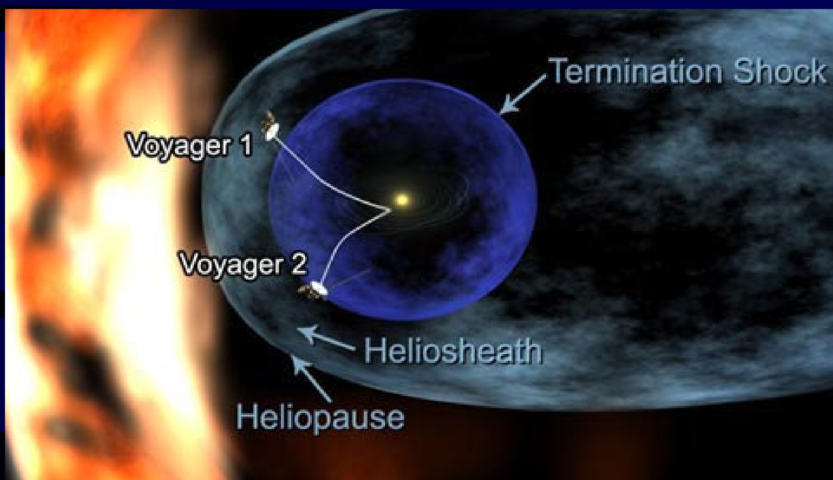
**Giant Jupiter is a source of odd radio noises. Now anyone can listen to them using a NASA-sponsored audio stream on the Internet.**

**Right**: The Io torus, photographed from Earth. [More]




Jupiter's Io-controlled radio emissions don't go in all directions. The radio laser beam has the shape of a wide hollow cone. If Earth is inside the cone, we hear nothing. If Earth is outside the cone, we also hear nothing. But if Earth is in the narrow edge of the cone, we can hear some strong radio bursts.

# Is sensitivity an issue ?




**Of course it is,**
**but consider Voyager:**

**20 W @ 100 a.u. ($1.5e^{10}$ km)**
**30 m receiver antenna,**

**and they keep talking to it !**

# Thank You All for your Patience,

…

# and the Organizers for their courage to let me talk

**The exploration of this topic will continue on my web site [www.ebyte.it](http://www.ebyte.it)**

**Acknowledgement: This research was funded by my wife**