Magnetic Resonance in Astronomy
Feasibility Considerations

presented by **Stanislav Sýkora** at the
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and available at www.ebyte.it/stan/Talk_MRA_GIDRM_2006.html

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

An astrophysicist's word about <u>really</u> strong fields

Physics in Ultra-Strong Magnetic Fields

by **Robert C. Duncan** Dept. of Astronomy and McDonald Observatory, University of Texas at Austin

Abstract: In magnetic fields stronger than $B_Q \equiv 2\pi m_e^2 c^3/he$ = **4400 MT**, an electron's Landau excitation energy exceeds its rest energy. I review the physics of this strange regime and some of its implications for the crusts and magnetospheres of neutron stars.

In particular, I describe how ultra-strong fields

- **render the vacuum birefringent** and capable of distorting images ("magnetic lensing")
- **change the mass (self-energy) of electrons** ($m_e(B)$ has a shallow minimum)
- cause **photons** to **rapidly split and merge** with each other
- **distort atoms** into long, thin cylinders **and molecules** into strong, polymer-like chains
- enhance the pair density in thermal pair-photon gases
- strongly **suppress photon-electron scattering**, and
- **drive the vacuum itself unstable**, at extremely large B (in the region $1e^{45} – 1e^{49}$ Tesla)

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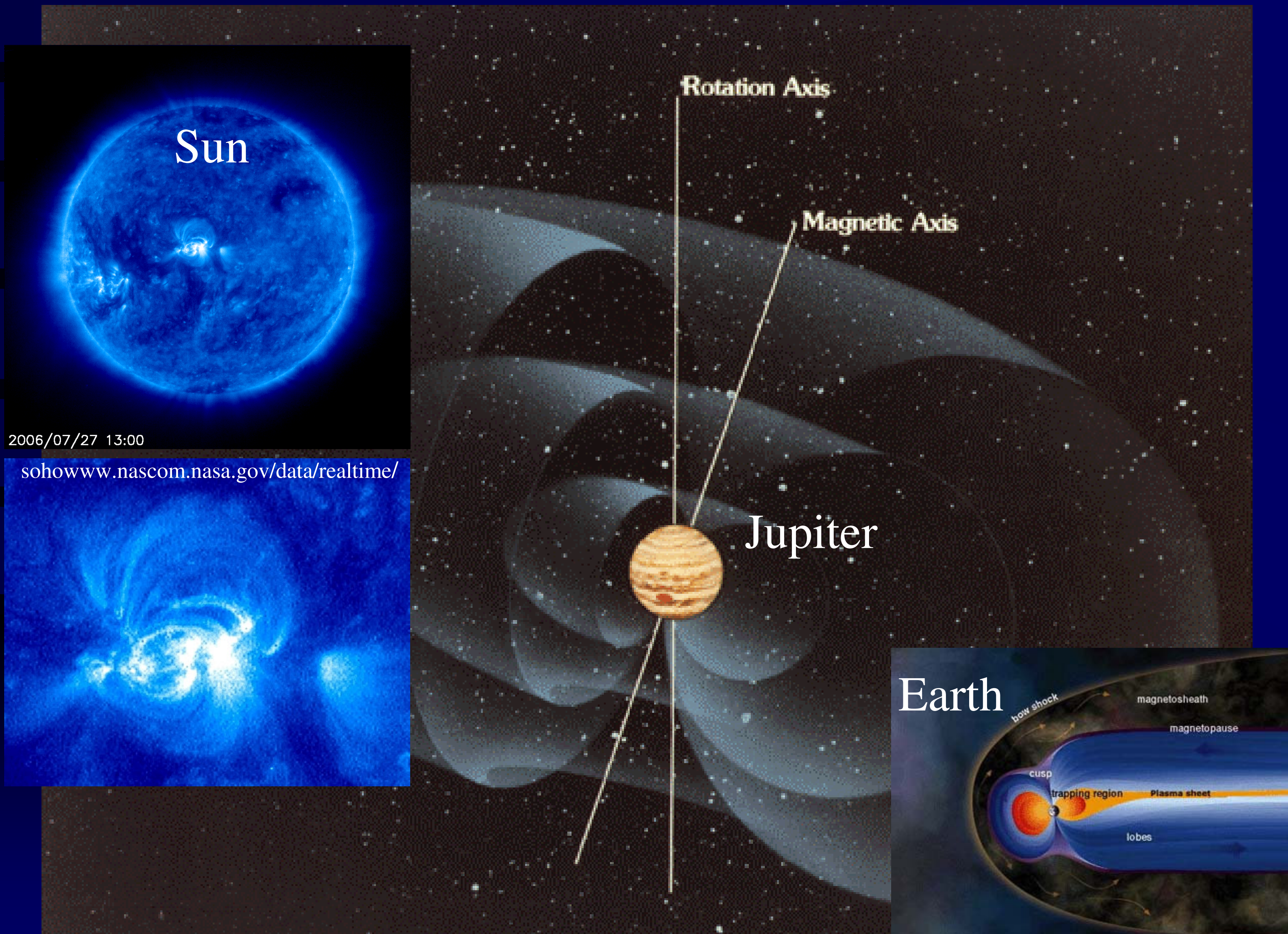
Authorized PDF can be downloaded from: www.ebyte.it/stan/blog.html (Jan.2, 2006)

Magnetic fields of Solar System bodies

Sun:	plasma vortices with **local fields up to 200 mT**
Mercury:	very, very faint global field
Venus:	no magnetic field at all
Earth:	**global field of 0.05 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:	**significant global field**, strong rings, 46 satellites
Uranus:	**significant global field**, thin dark rings, 27 satellites
Neptune:	**significant global field**, broken arc rings, 13 satellites
~~**Pluto**~~:	??? no data - and no longer a planet - ;-(

Magnetic fields of Solar System bodies



www.nasm.si.edu/ceps/etp/jupiter/jupmag.html

nmp.jpl.nasa.gov/st5/SCIENCE/magnetosphere2.html

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 …

? What's wrong ?

**With all those magnetic fields
and magnetic particles all around,
WHY don't astronomers EVER
mention**

Magnetic Resonance ?

**I don't know,
but maybe we can change that !**

Excitation & Detection

Present laboratory detection methods:

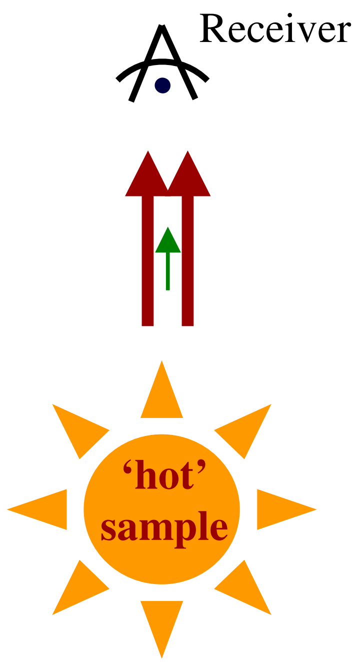
- **Magnetic induction** (the most common method)
- **SQUIDS** (superconducting quantum-interference devices)
- **Magnetic force** (mechanical detection)

These are all ruled out since

- **we are far away from the ‘sample’ and/or**
- **the ‘samples’ are far too big**

Back to *real* spectroscopy

Passive emission

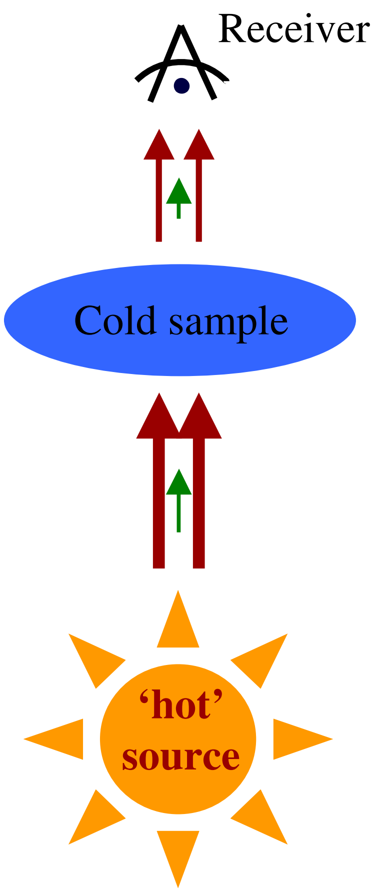


We must separate the desired signal (→) from the bulk (→)

We need:

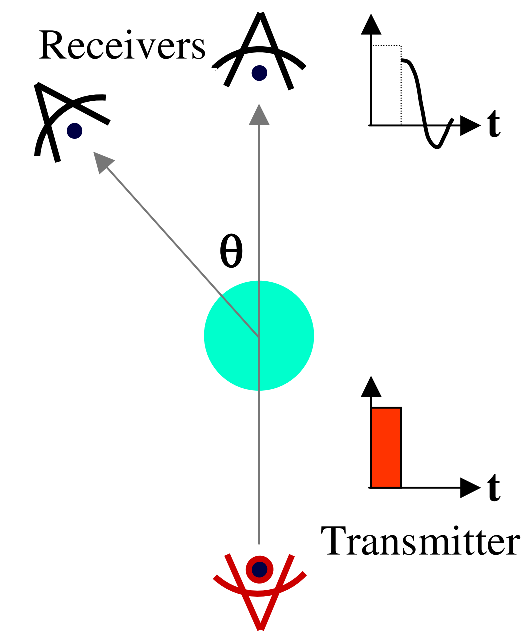
- Special signal features
- Sophisticated receiver

Passive absorbtion



Dtto

Active absorbtion
Scattering (Dispersion)
Fluorescence



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

MRA objects of interest
in passive spectroscopy

Natural sources of possible MR signals observable with a radiotelescope (array) or optical or X-ray telescopes (depending upon Larmor frequency):

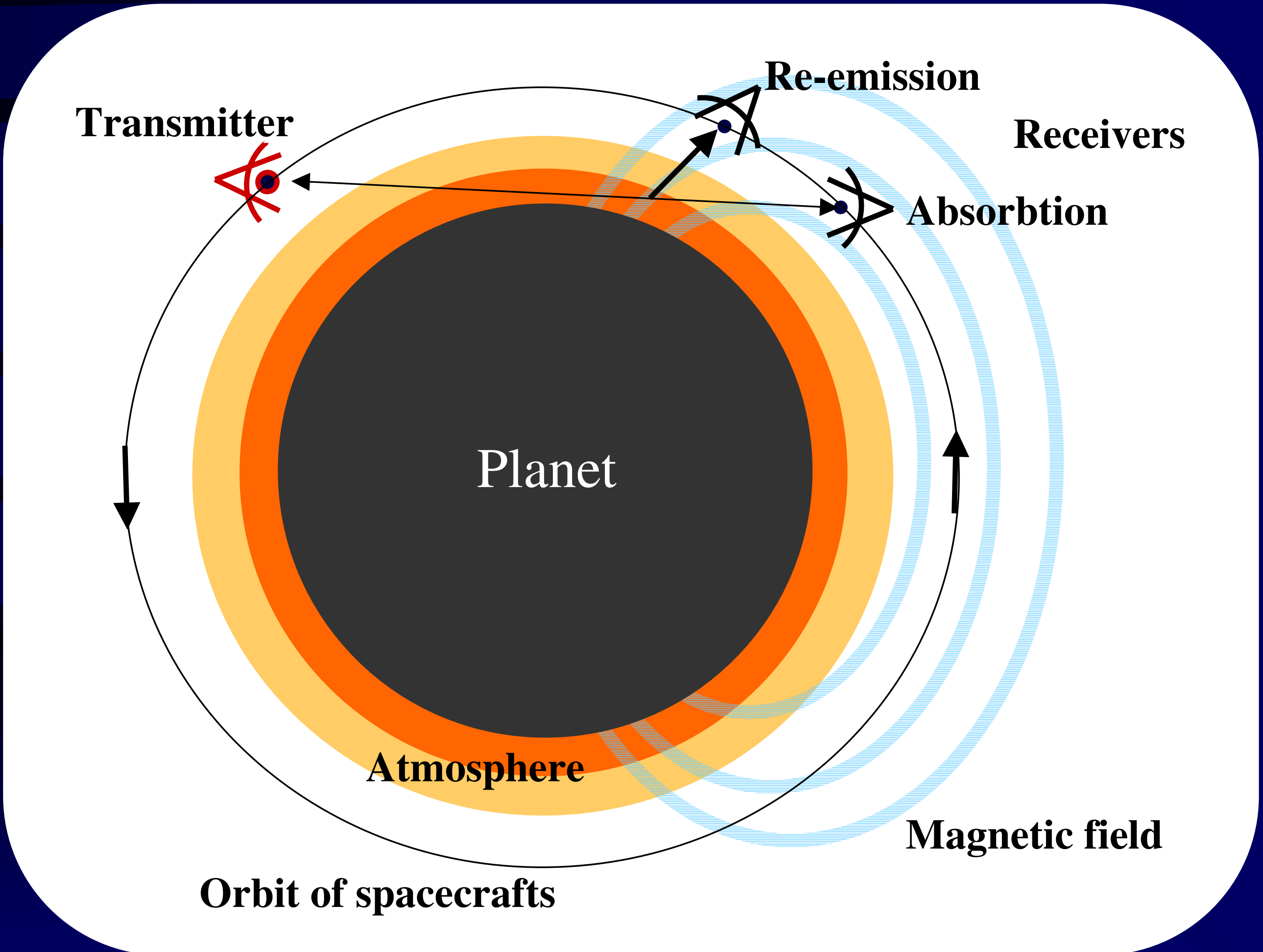
- **Sunspots** (^{1}H: 1-10 MHz, electrons: 1-7 GHz; possibly neutrons and muons)
- **Jupiter** (2-5 MHz ^{1}H, 1.5-3GHz electrons)
- **Dwarf stars** (any frequency from 1 MHz to hard X-rays might happen)
- **Pulsars** (^{1}H: soft X-rays, electrons: hard X-rays, other: from IR - UV - X)
- **Magnetars** (^{1}H: hard X-rays, electrons: γ-rays)

MRA objects of interest
in active spectroscopy

So far limited to the Solar System

- **Sub-planetary** on Earth:
  Techniques: Two fixed radiostations or one fixed and one mobile station
  Objects: Sections of troposhere, atmosphere, oceans, seas, lakes, icecaps
  Looking at: Water protons (2000-2500 Hz) and radicals (1.3 –1.6 MHz)
  (oxygen, ozone, nitroxides, thunderstorm systems chemistry)
- **Planetary**:
  Techniques: Flyby with two or more spacecrafts (grazing),
  One station fixed on a satellite, one space-faring
  Objects: Atmospheres of the Earth and Jovian planets
  Looking at: Earth : see above
  Jupiter: ^{1}H (ca 2-5 MHz) – H_2, hydrocardons, …
  ^{3}He (ca 2-6 MHz)
  Radicals (1.3 – 4 GHz): Jovian thunderstorms chemistry

Examples of active MRA arrangements



Detecting & Distinguishing MR signals

We have seen that there are lots of candidate objects for MRA and a lot of interesting things to look at

But how can we detect MR signals and discard everything else ???

This is really the most crucial question

(not the cost of a spacecraft)

Historic mystery #1

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*")

Historic mystery #2

There is a growing awareness of the fact that

we have no coherent explanation of the MR phenomenon:

1. **To detect signals, we use induction and there is no quantum theory of that, just 19th century physics. No radiation enters/exits the coil volume. Quantum description would require quantum electrodynamics and the exchange of *virtual* photons (photon creation and annihilation operators).** ***No theoretician ever tried to carry it through.***

2. **To explain why resonance lines are so sharp and why NMR and ESR look the way they do, we can't avoid quantum physics. We say that there are sharp energy level and that photons get absorbed and/or emitted only at very specific frequencies corresponding to energy level differences.** ***No experimentalist ever tried to actually carry out such an experiment.***

? Don't you think that this is strange ?

Properties of MR radiation

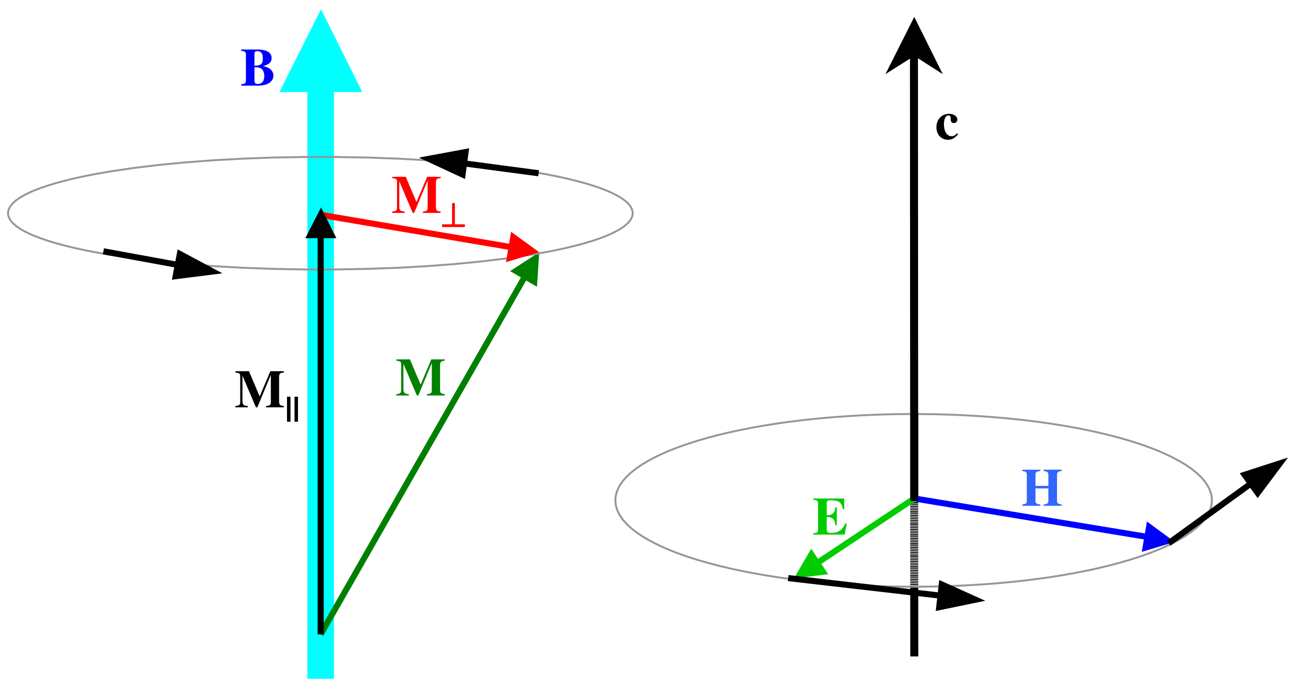
Distinguishing properties of which we are sure:

- **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 γ-values**

Educated guesses (until real experiments get carried out):

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

Chirality of MR radiation



γ < 0 … clockwise rotation of M around the magnetic field B.
Emitted waves are circularly polarized

Exploiting Circular Polarization

- **<u>Use circularly polarized receivers</u>:**
  incoming radiation must be circularly polarized (CP)
- **<u>Use circularly polarized transmitters</u>:**
  excitation is possible only with correct CP sign.

Differential methods (CPD):

Detect the difference signal $S = S(CP^+) - S(CP^-)$

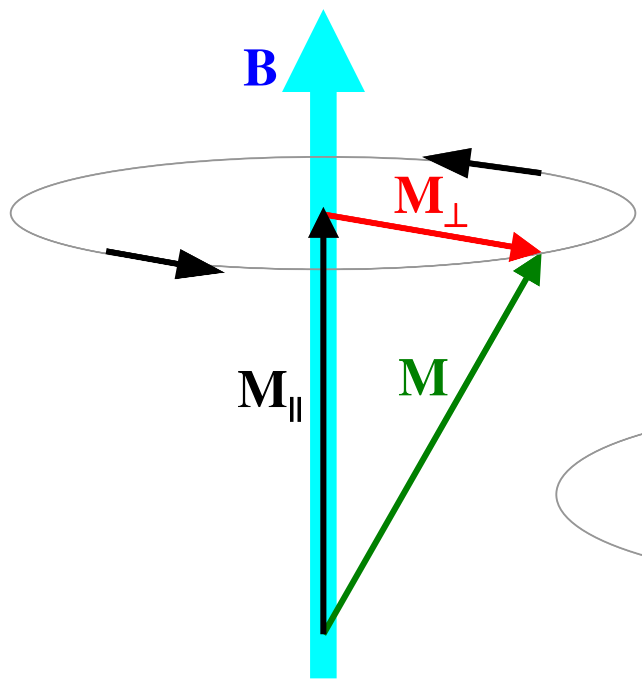
Passive circular-polarization alternation (PCPA):

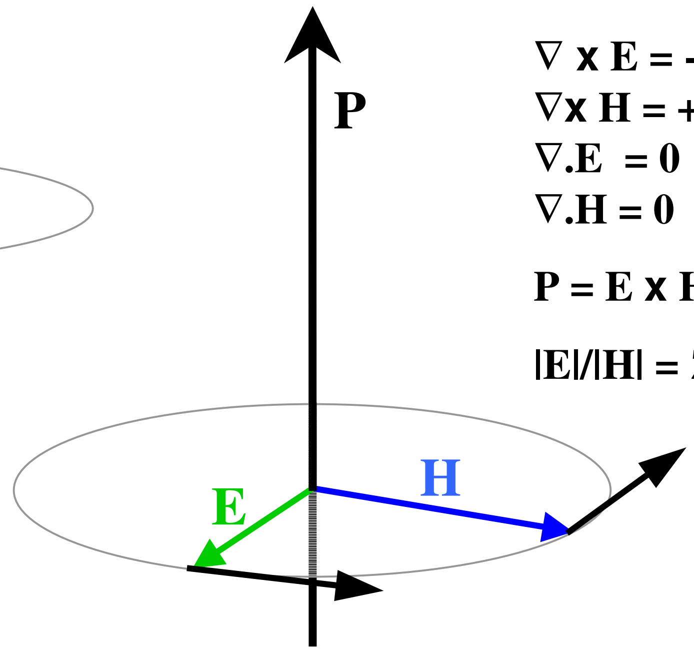
Switch between CP^+ and CP^- at a known rate

Active circular-polarization alternation (ACPA):

Switch both the transmitter and the receiver between CP^+ and CP^- using suitable sequences

Directionality of MR radiation





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

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

$\nabla . E = 0$

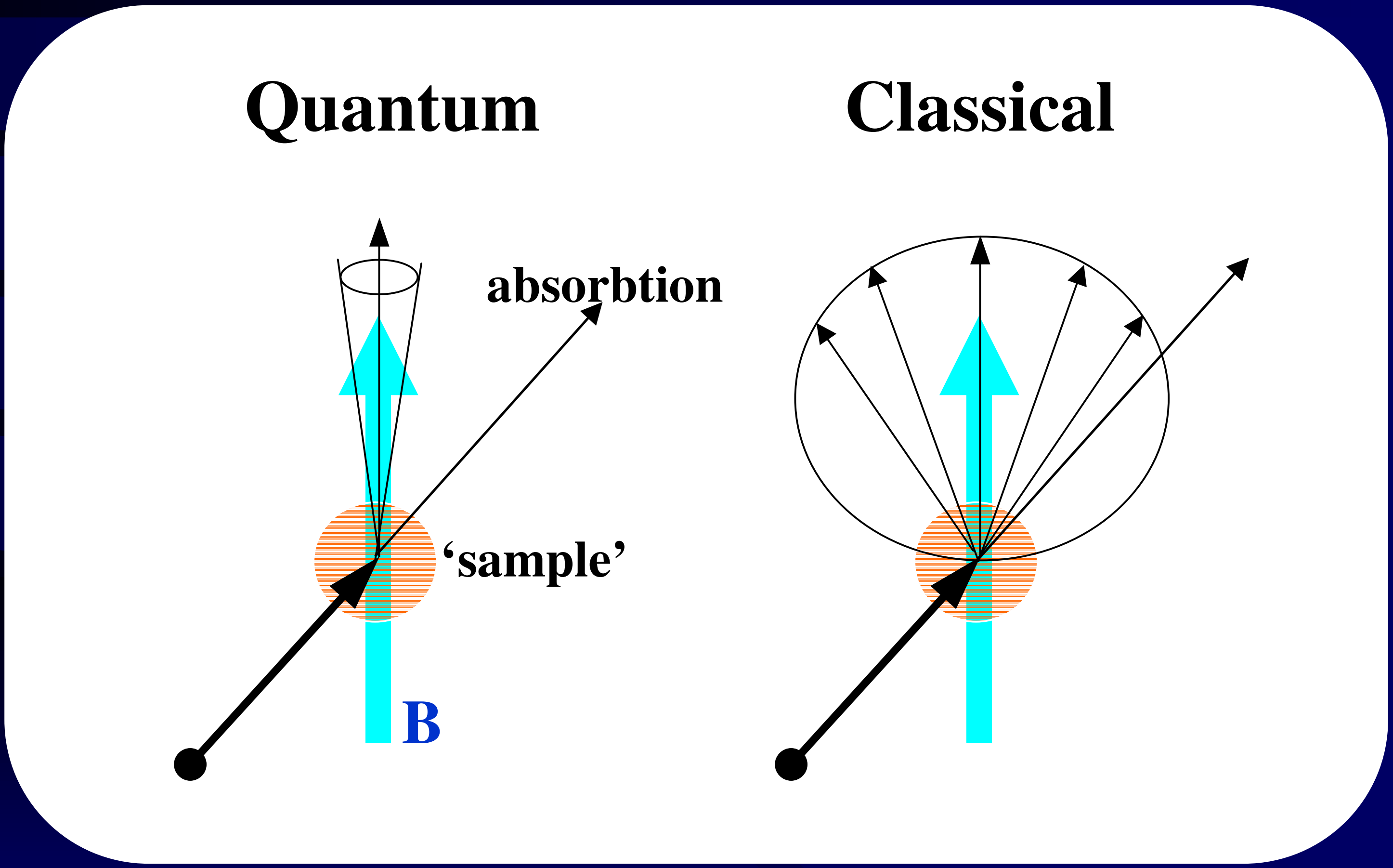
$\nabla . H = 0$

$P = E \times H$

$|E|/|H| = Z_0 = 377\ \Omega$

Poynting vector P is aligned along the magnetic field B

Directionality of (re)emitted MR radiation:
?!! theoretical doubts !!?



Time-delay problems when probing extensive objects

Signals from different areas arrive at diferent times and get all mixed together

This could be a great problem.

In active modes, help might come from:

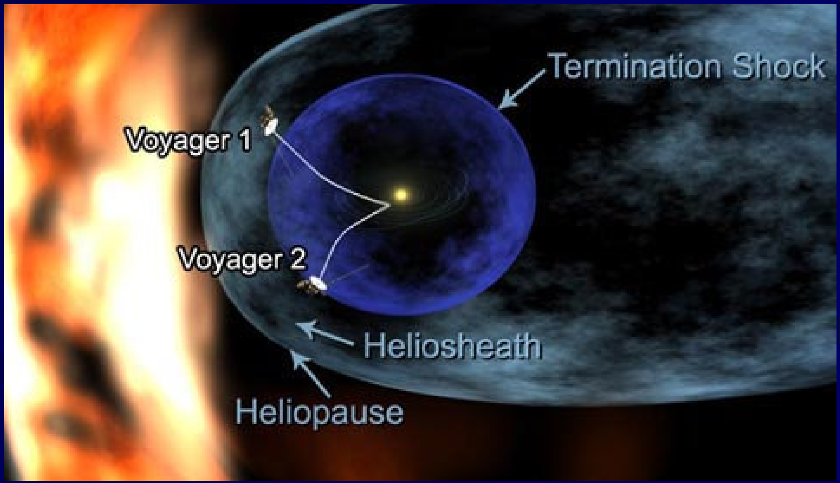
- **Strict directionality (if confirmed), combined with directional antennae (this might lead also to high resolution)**
- **Variable-delay pulse sequences of Hadamard type with extensive use of CP cycling**

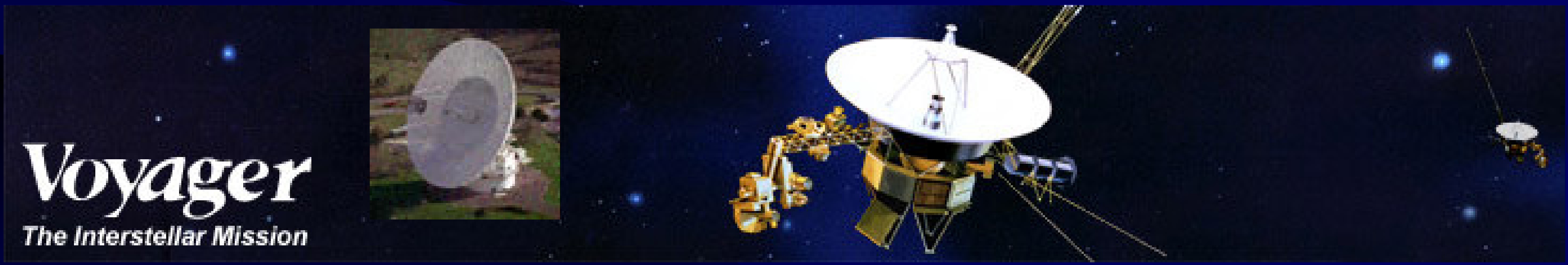
Is sensitivity an issue ?

Yes, but consider Voyager:

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

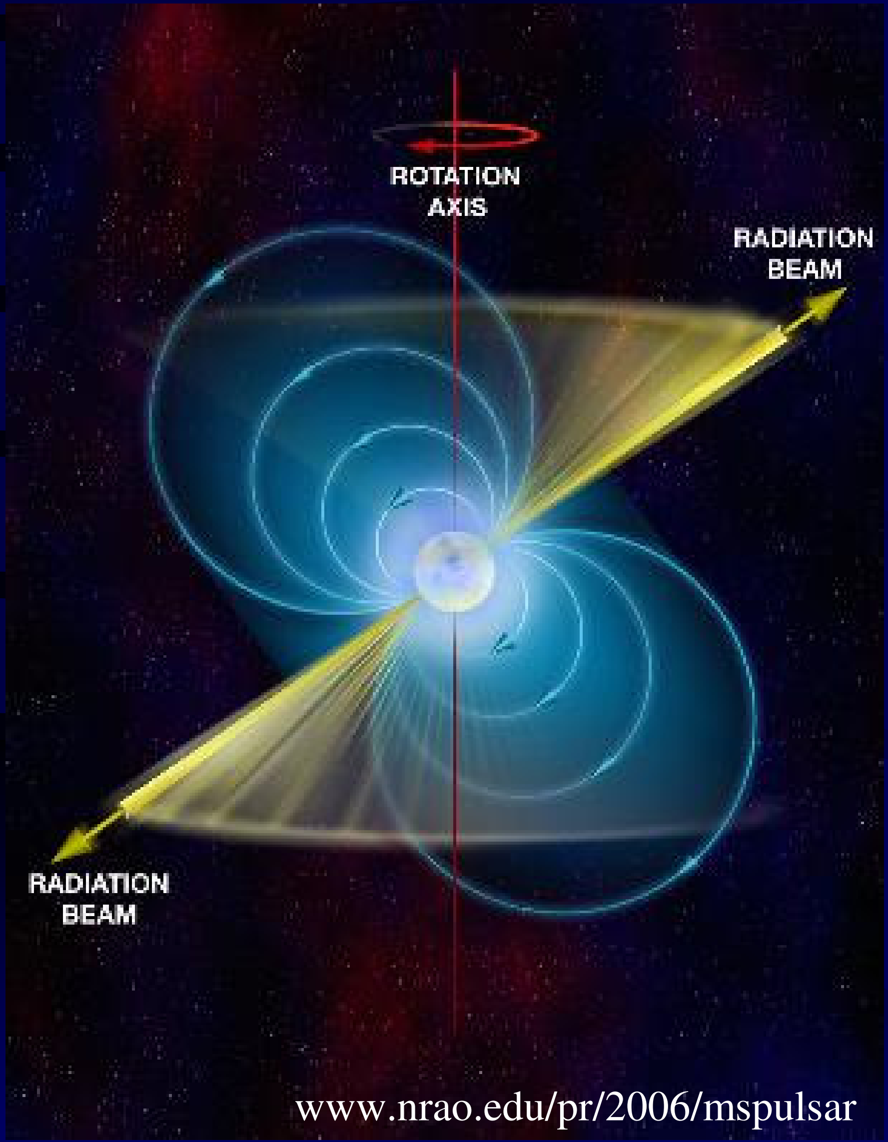
and they keep talking to it !!!





voyager.jpl.nasa.gov

Speculations about pulsars



www.nrao.edu/pr/2006/mspulsar

100 Mega Tesla !!!

and rotating very fast (716 Hz)

Or, maybe, not rotating at all ?

What do the spins do over there ???

I skip this for lack of time.

Follow www.ebyte.it/stan/blog.html

I will keep returning to the MRA topic as often as possible

Next steps

- Reconcile classical and quantum descriptions of MR phenomena
- Spectroscopic detection of MR radiation in laboratory
- Laboratory verification of the characteristics of MR radiation
- Earth-bound experiments with gated chiral antennae
- Re-examination of pulsar spectra with circularly polarized devices

-------------------------------- space-born: --

- MR analysis of Earth's atmosphere using the space station and an earth-bound station, both with gated chiral antennae
- MR analysis of Jovian atmosphere from a pair of spacecrafts equipped with gated chiral antennae
- Etc … …