Science and System Requirements of the Imaging Survey

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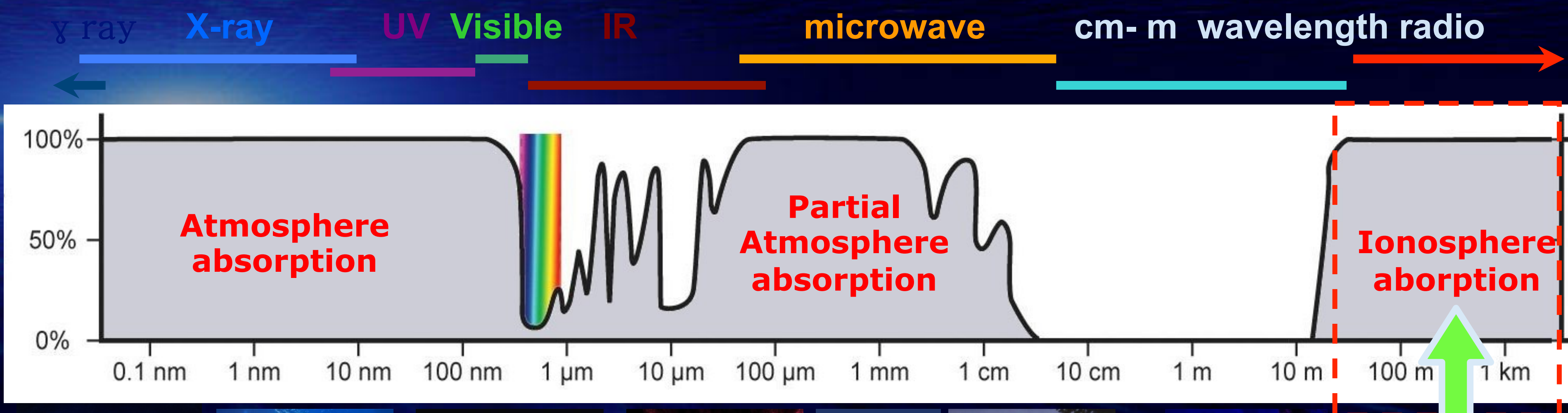
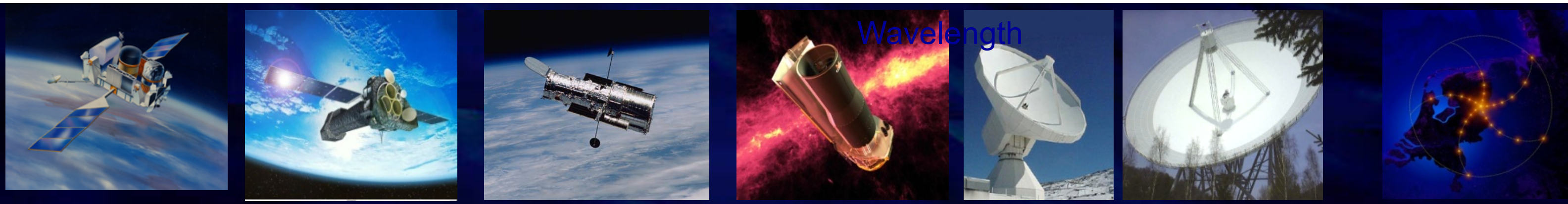
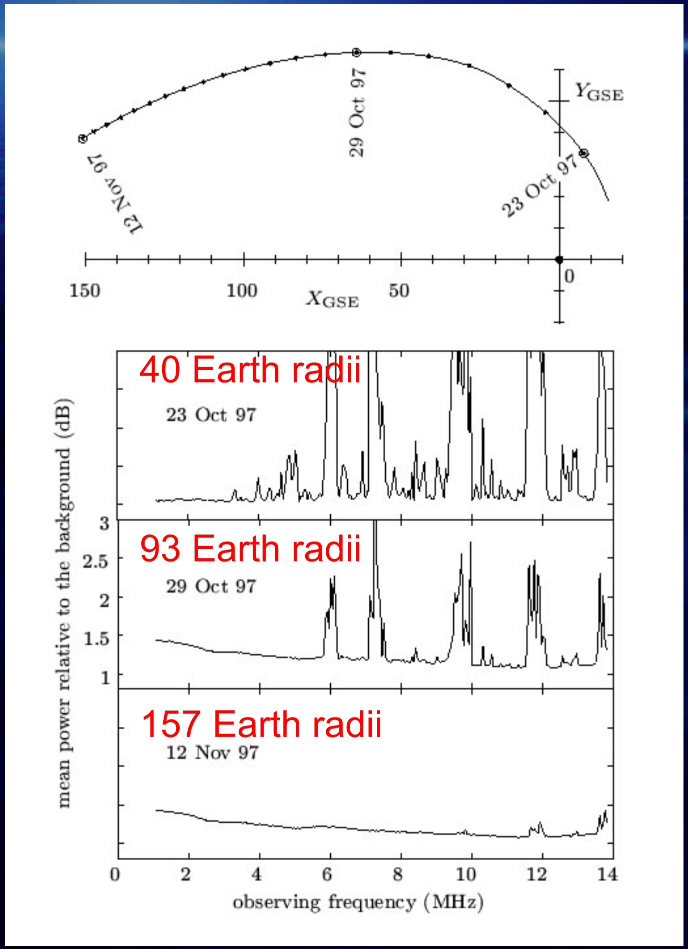
Why ULWA (radio!) in Space?





Terra incognita of cosmic electro-magnetic emission

Terrestrial interference



WAVES instrument on WIND

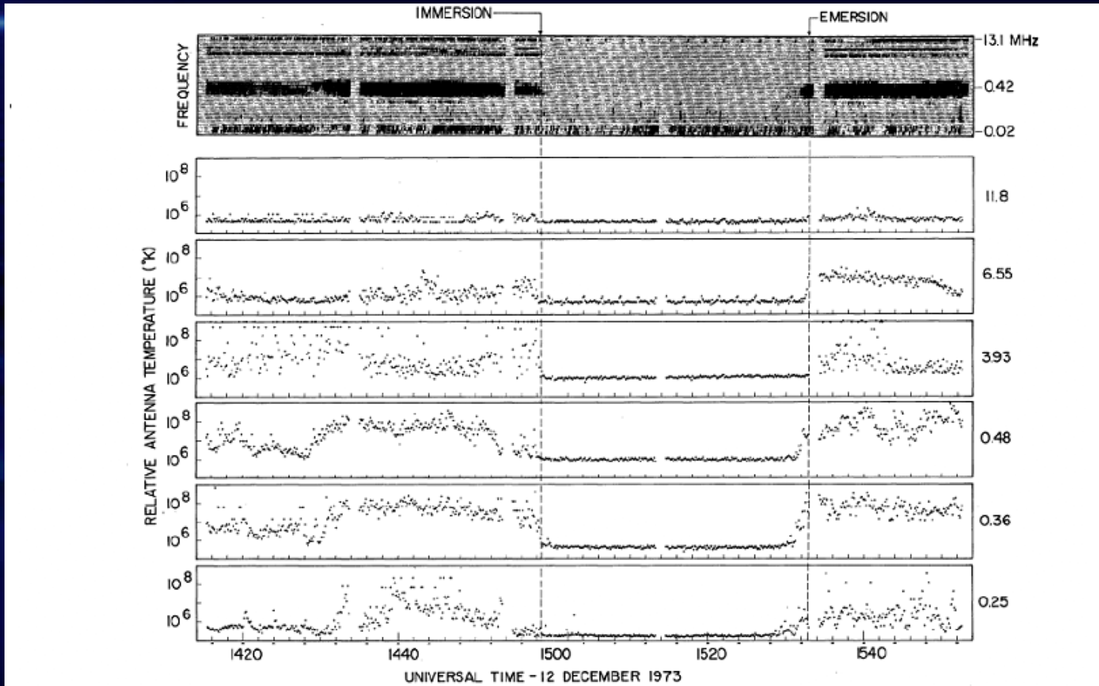


Fig. 5. Example of a lunar occultation of the Earth as observed with the upper-V burst receiver. The top frame is a computer-generated dynamic spectrum; the other plots display intensity vs. time variations at frequencies where terrestrial noise levels are often observed. The 80-s data gaps which occur every 20 m are at times when in-flight calibrations occur. The short noise pulses observed every 144 s at the highest frequencies during the occultation period are due to weak interference from the Ryle-Vonberg receiver local oscillator on occasions when both that receiver and the burst receiver are tuned to the same frequency

RAE-2 occultation of Earth

Available Maps

30 MHz @ 10 deg (Cane 1978)

10 MHz 5 deg map Cane & Erickson 2001

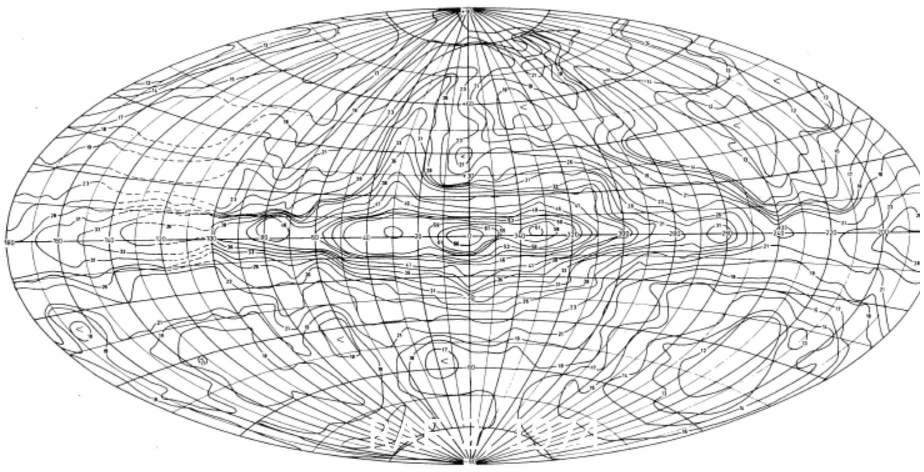
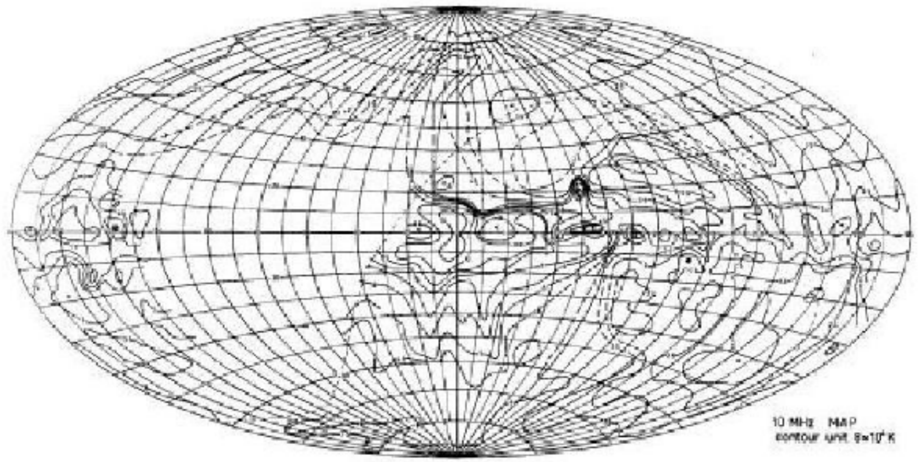
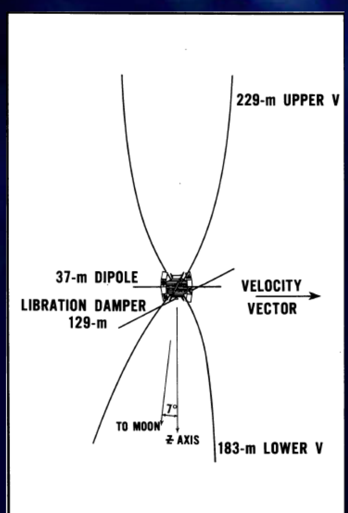


Fig. 1. Contour map of 30 MHz brightness temperatures plotted on a Hammer equal-area projection in galactic coordinates. The contour unit is 1000 K.



RAE-2, 1974



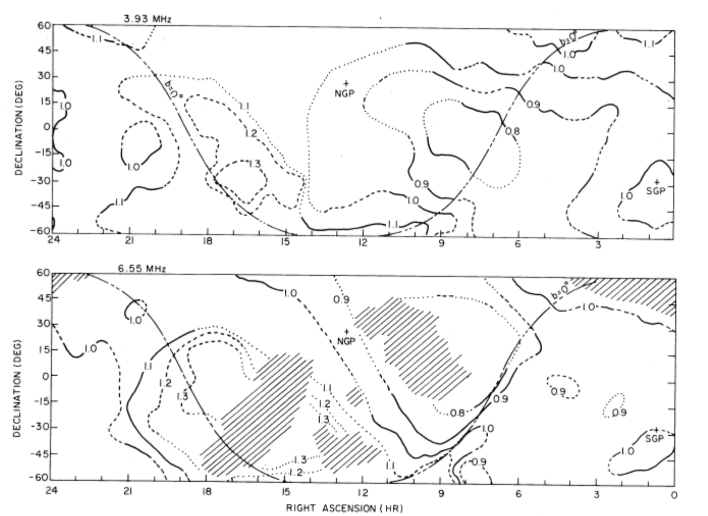
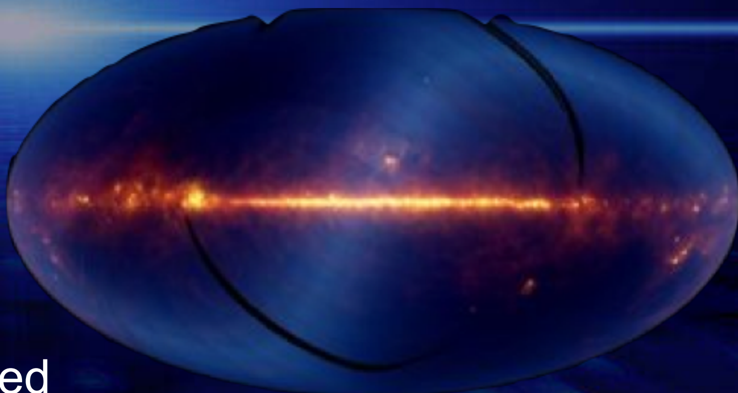


FIG. 4. RAE-1 background maps in units of the average brightness over the sky at 3.93 and 6.55 MHz in celestial coordinates. Coding of the contour lines and a first order correction for side lobes are discussed in the text.

3.93 MHz

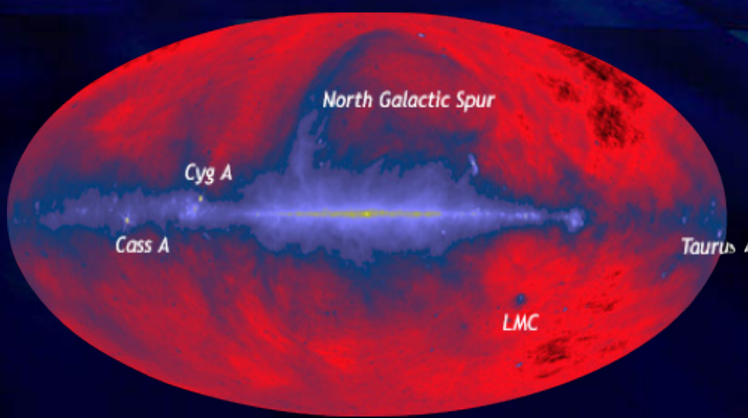
6.55 MHz

Milky Way in all "colours"

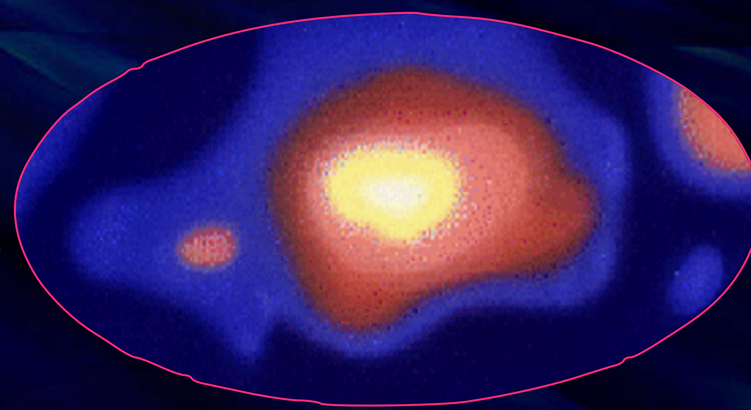


Infra-red

cm wavelengths



75 cm



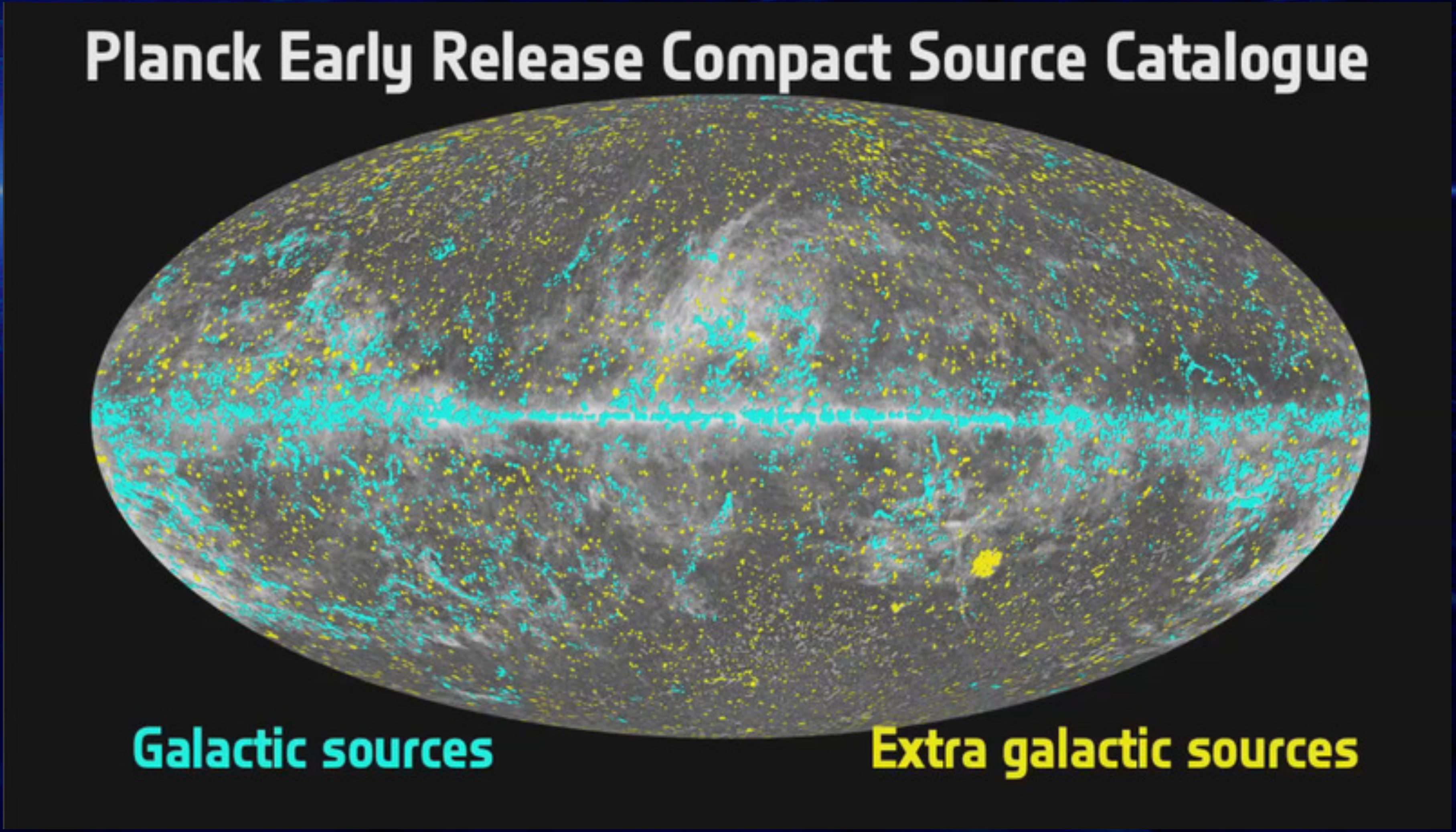
hypothetic decameters

DSL objectives

- ***Prime:*** pioneering studies in the hitherto unexplored window of the cosmic EM spectrum
  - Full sky continuum survey of discrete sources:
    - Ultra-steep spectrum extragalactic sources
    - Pulsars?
    - Transients (galactic and extragalactic)
  - Full sky map of (galactic) continuum diffuse emission
  - Search for signatures of Dark Ages
  - Recombination radio lines (of "macro-atoms")?
  - Search for "exo-Jupiters"
  - Solar-terrestrial physics
  - Radio-showers from high-energy particles (and neutrinos) interacting with Moon

- **Above all**, a lesson of science history:
  - Discovery of the unknown unknowns

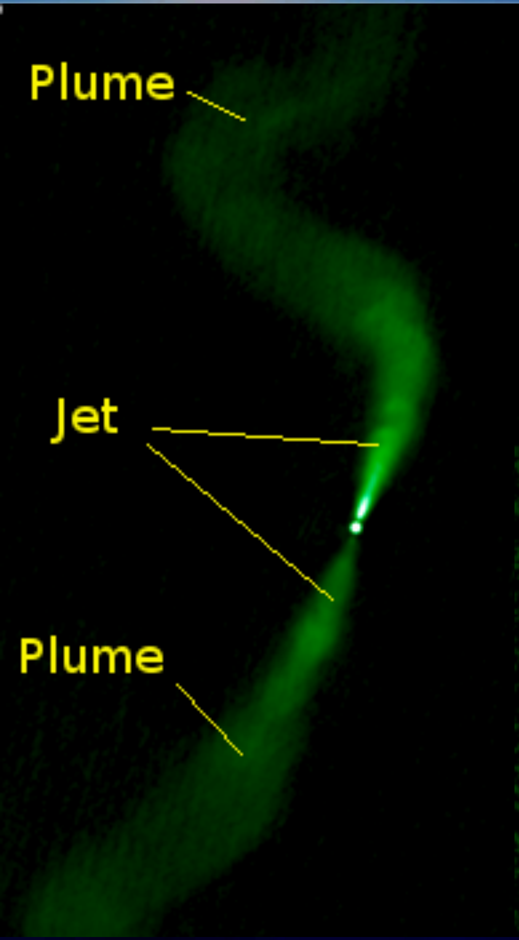
Survey of discrete continuum



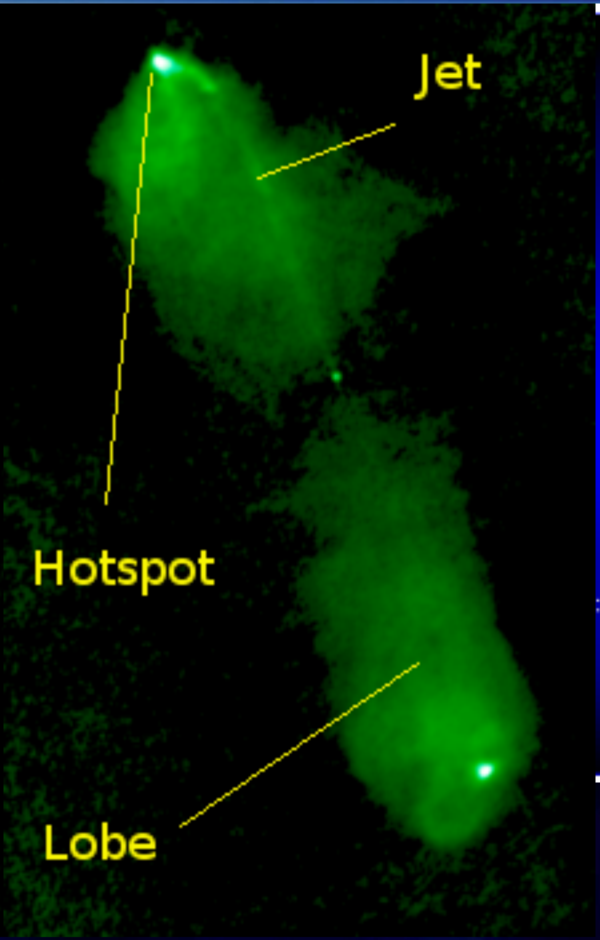
- Classification/statistics (*log*N-*log*S) of sources at frequencies <10 MHz
- Their spectral properties (synchrotron selfabsorption, evolution)

Extragalactic Sources

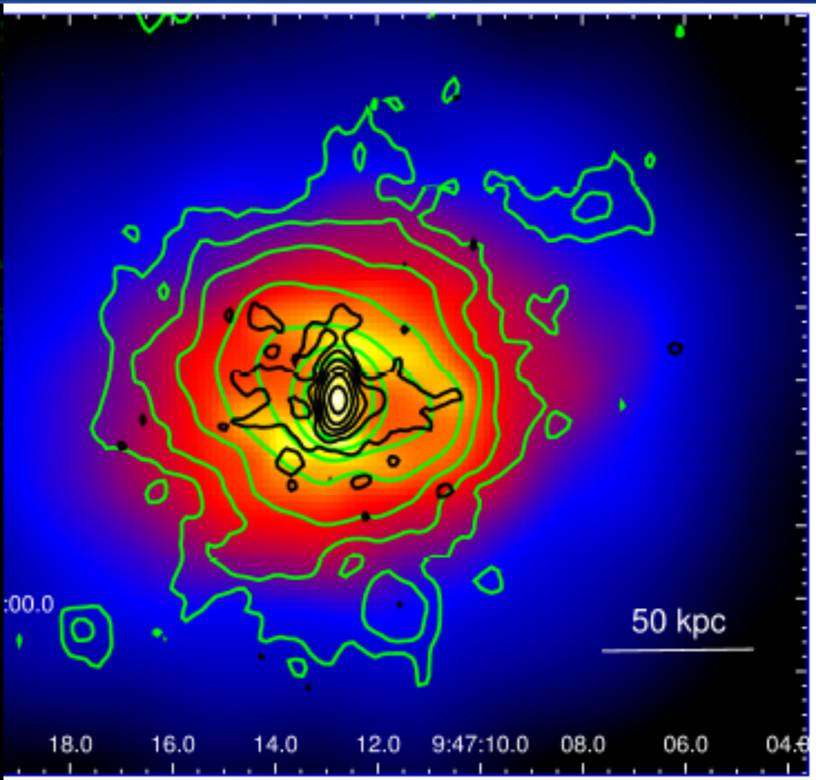
3C31 (FR I)



3C 98 (FRII)

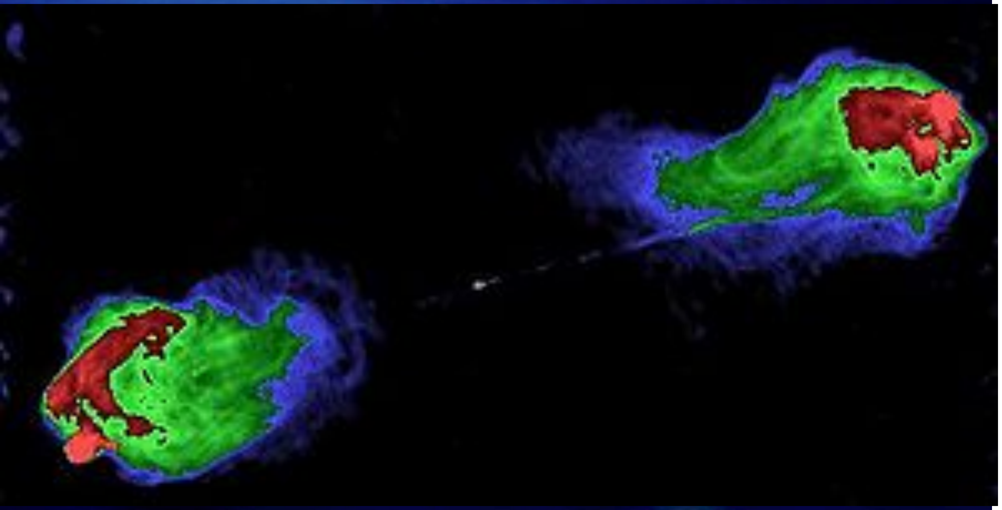


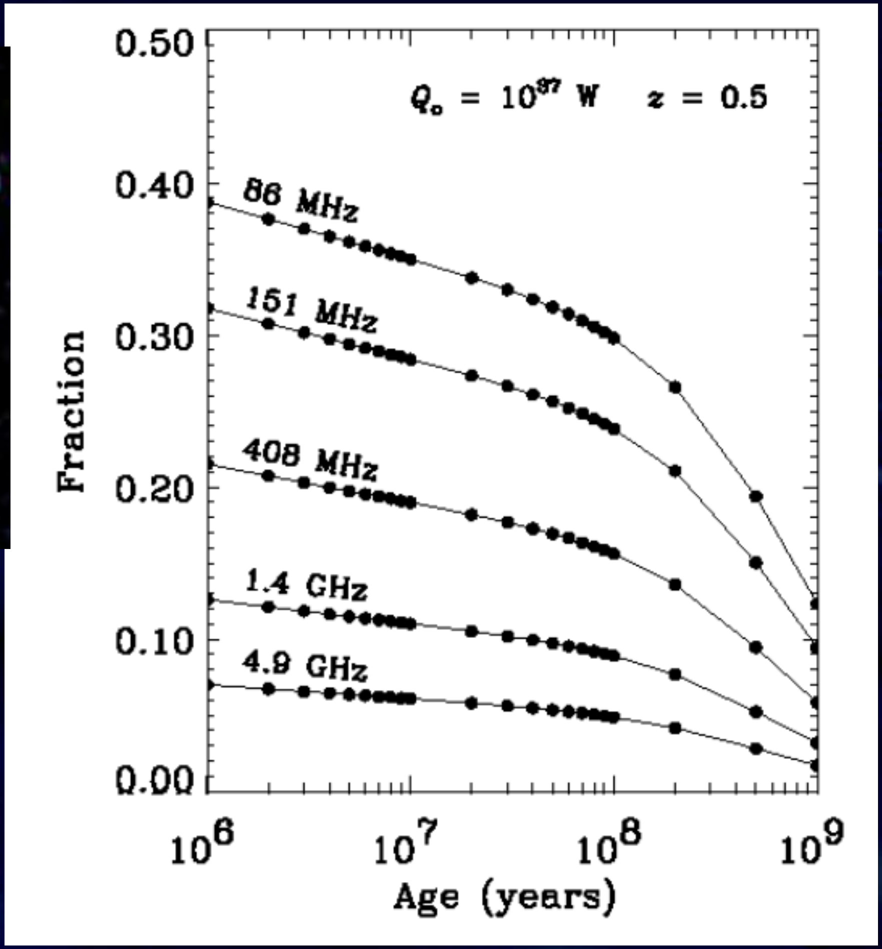
Cluster halo (Gitti et al. 2014)



Jets and Spectral Aging

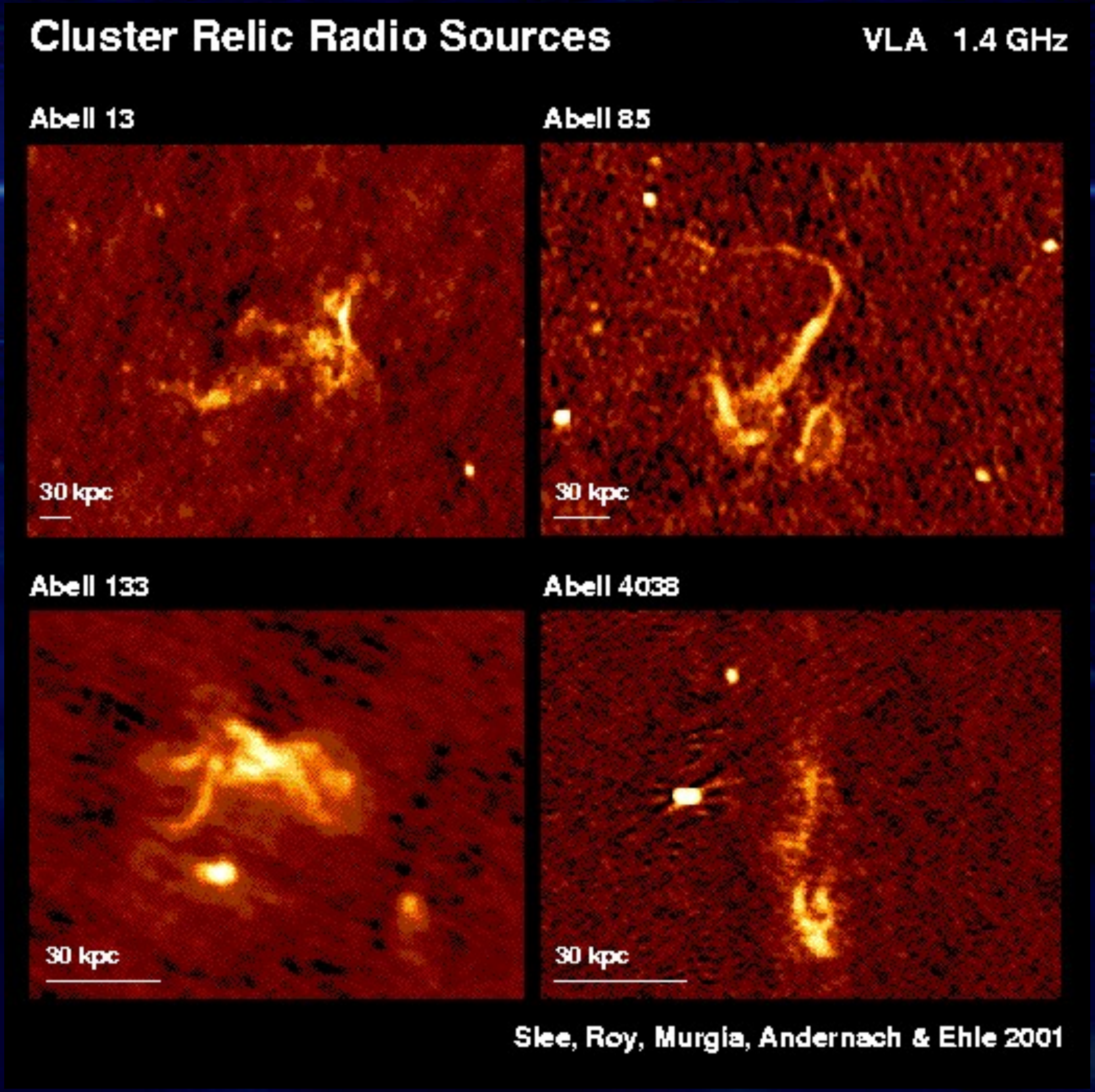
Blundell & Rawlings 2002



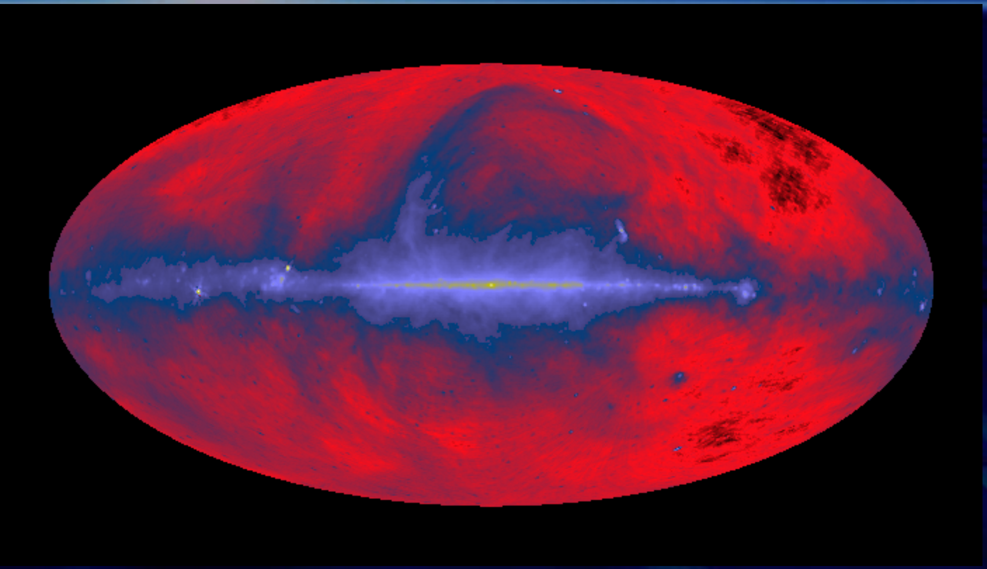


Fossil extragalactic radio sources

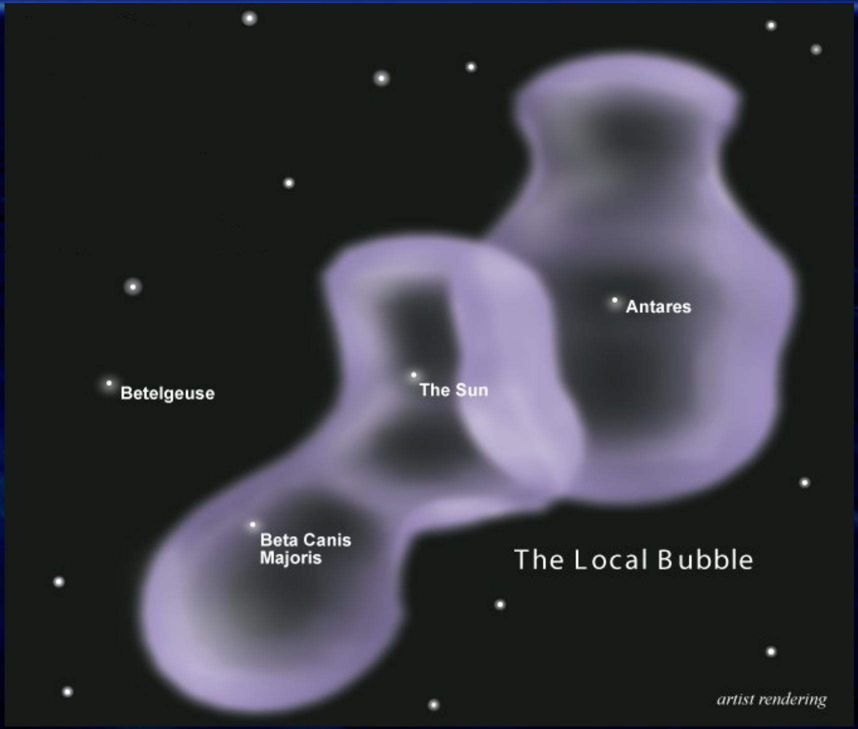
- When quasars die, they leave relic plasma.
- The plasma forms buoyant steep-spectrum bubbles.
- They may be revived and refreshed at outer shocks produced in large scale structure formation of the universe and cluster mergers (Ensslin et al. 1998; Ensslin & Brüggen 2002).
- ULWA is the most efficient domain for their studies



Milky Way and Solar Neighborhood



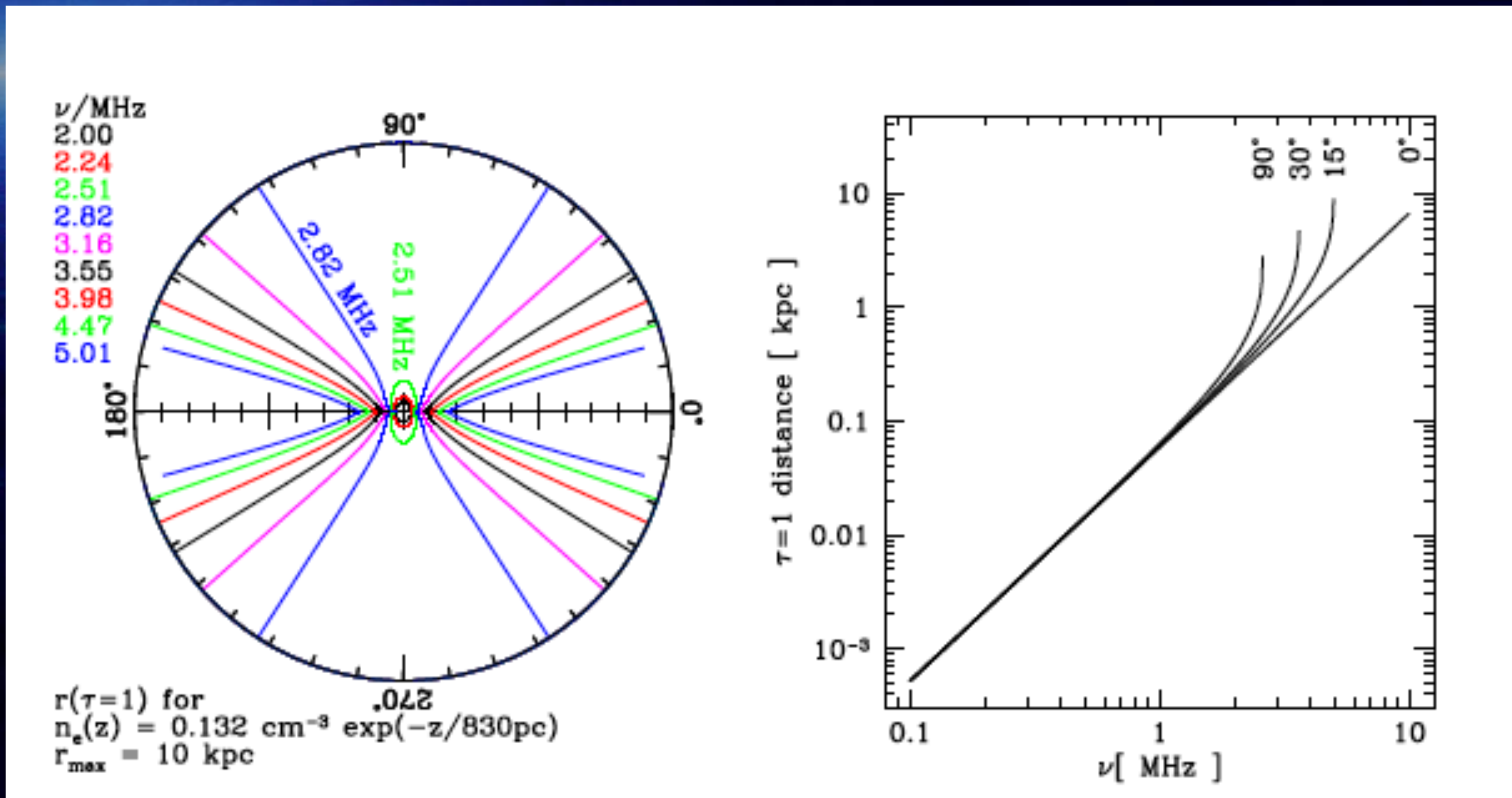
408MHz map



Local Bubble

ISM absorption

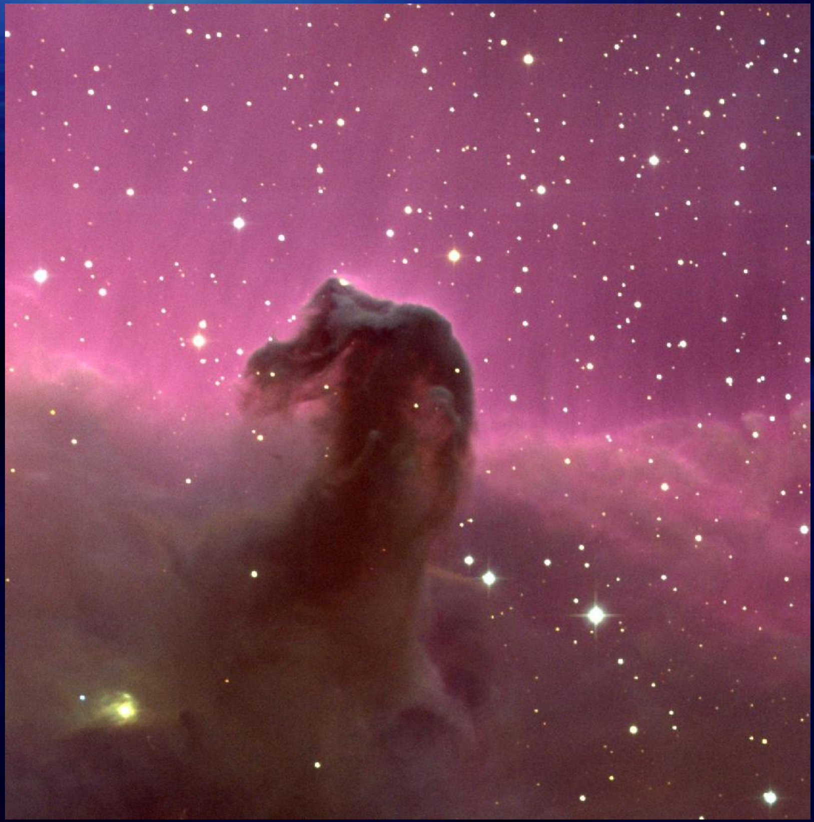
Jster & Falcke 2009



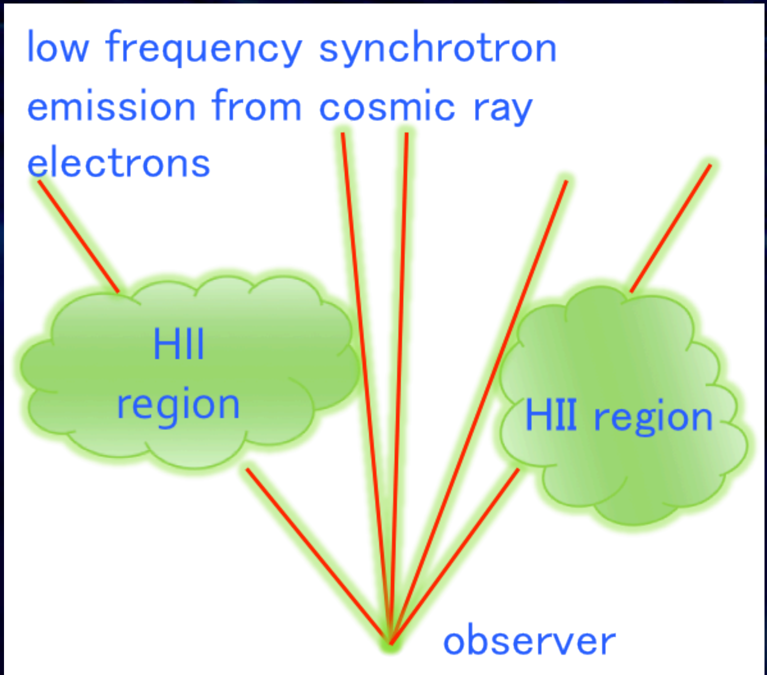
$$D(\tau = 1) \approx 100\,\mathrm{pc}\left(\frac{n_e}{0.132\,\mathrm{cm^{-3}}}\right)^{-2}\left(\frac{T_e}{7000\,\mathrm{K}}\right)^{3/2}\left(\frac{\nu}{1\,\mathrm{MHz}}\right)^{2}$$

Interstellar Medium and Origin of Cosmic Ray

With absorption by interstellar free electrons can probe WIM structure

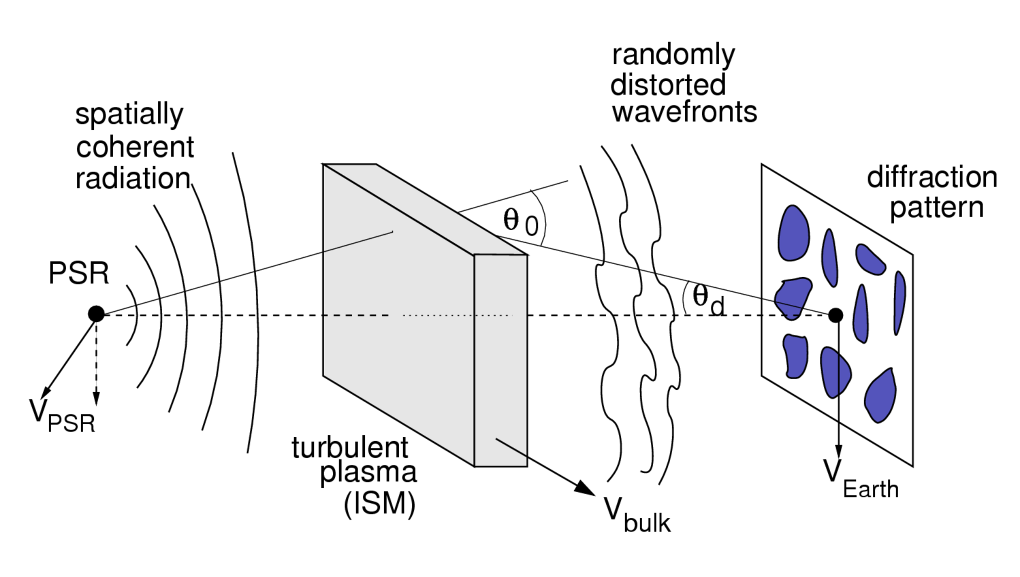


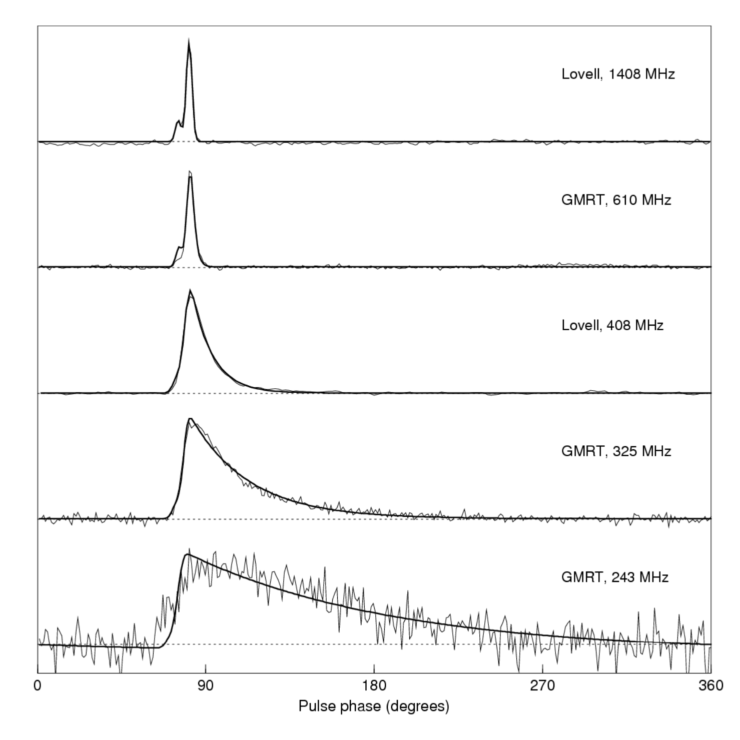
HII region is opaque to low frequency (a few MHz) synchrotron emission from cosmic ray electrons. So, observing the HII region enables determination of cosmic ray in that short l.o.s., helps address the quest on the origin of cosmic ray.



Pulsar—temporal braodening

Dispersion and Scattering





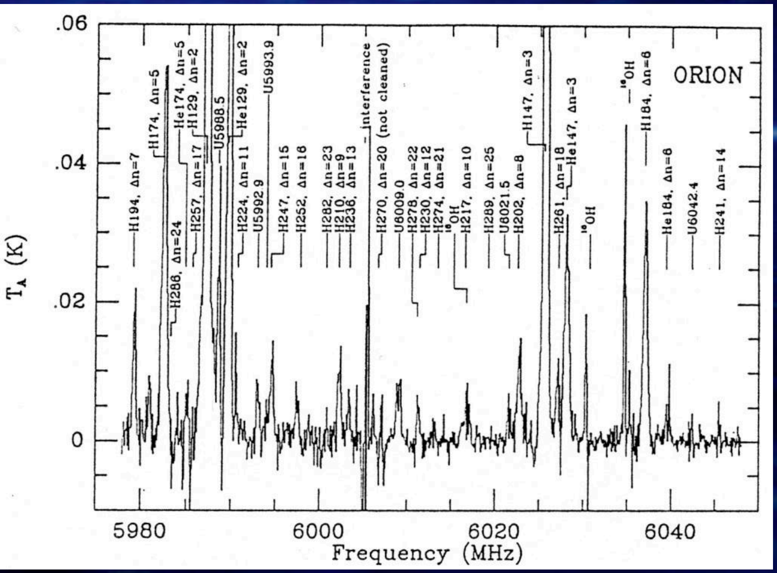
$$\mathrm{ISM}: \Delta t = 6\,\mathrm{yr}\,(\nu/\mathrm{MHz})^{-4.4}$$

$$\mathrm{IPM}: \Delta t = 0.1\,\mathrm{s}\,(\nu/\mathrm{MHz})^{-4.4}.$$

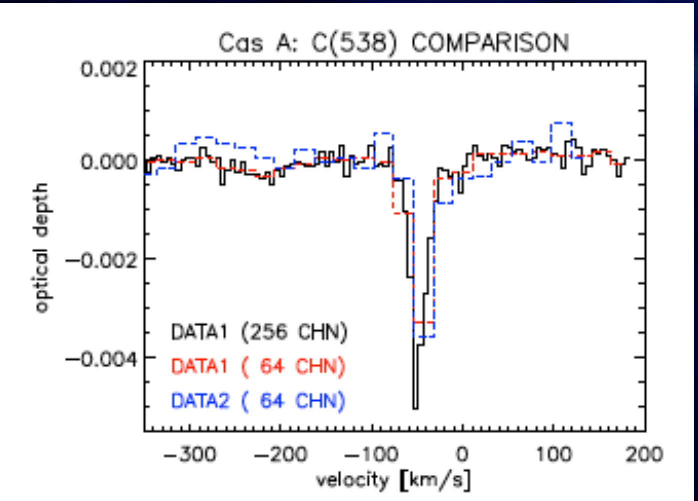
Maybe not optimal for this frequency?

Radio Recombination Lines

Bell et al. (2011)



Asgekar et al. (LOFAR)



- Konovalenko & Sodin (1980) C 631α @ 26.13 MHz toward Cas A (UTR-2)
- n ~ 100-1000 (C atom)
- optical depth ~ $10^{-4} - 10^{-5}$
- multiple-line folding may require special data processing or transmit raw data
- velocity widths: ~10km/s or less, require spectral resolution 10^5
- Probably difficult for this project

de-Polarization

Faraday rotation

$$\Delta\psi_{RMS} = 2.6 \times 10^{-13}\ \lambda^2\ \Delta N_e\ \lambda^2 a\ B_{\parallel} \sqrt{L/a}\ \text{rad},$$

Typically, a turbulent cell of 0.001pc already cause a 1 rad rotation at 1MHz: depolarization.

Circular polarized light may be preserved: convert the linear polarization to circular ones?

But may be it is still better to keep all polarizations, for possible reflection, etc., since this is a totally unexplored spectrum.

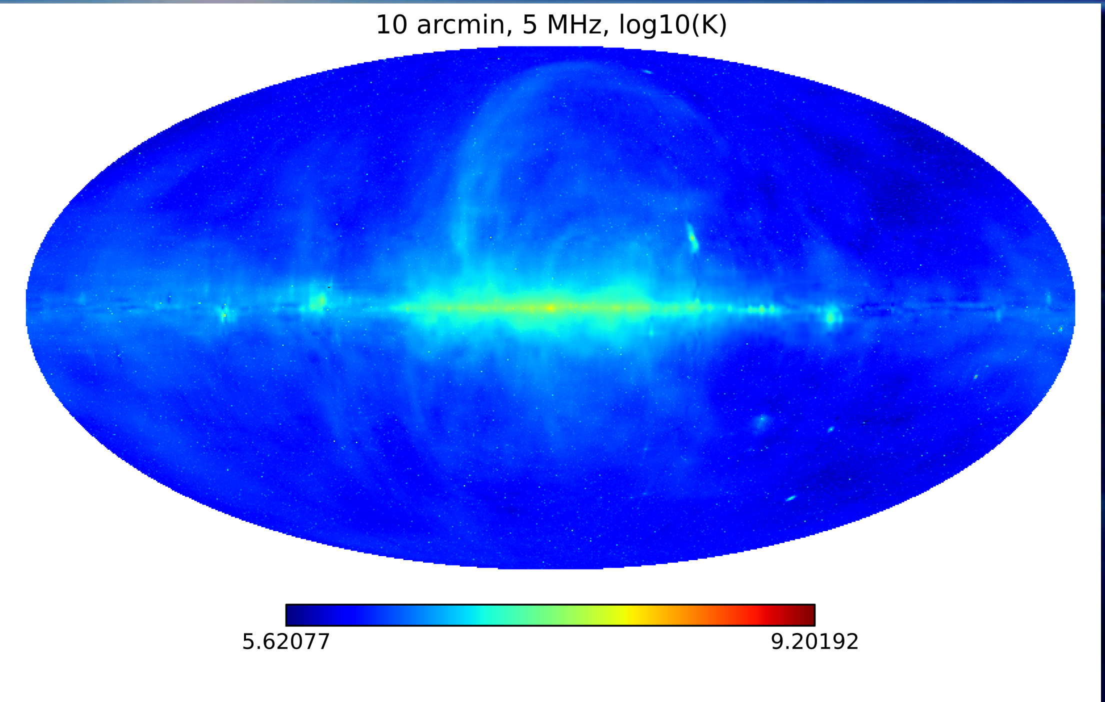
Also, desirable to have three instead of two pairs?

Frequency Range

Frequency Range	Space Advantage	Science
30-120 MHz	RFI and ionosphere refraction	EoR/dark age signal (spectrum)
10-30 MHz	RFI and strong ionosphere refraction	EoR/dark age, extragalactic source, Milky Way, ISM, transients
1-10 MHz	Ionosphere absorption	Milky Way, ISM, cosmic ray, transients,
<1 MHz	Ionosphere absorption	solar/planetary

Adjustable frequency/selected band data transmission

Angular Resolution



$$\theta = \frac{\lambda}{D_{max}}$$

Baselines of O(10km) with a few longer ones, maximum 50-100km

at 10MHz, this will give angular resolution about 10arcmin.

At 1MHz, can still achieve better than degree scale resolution

log distribution?

ISM scattering induce significant angular smearing

$$\vartheta_{\rm ISM} \approx \frac{30'}{(\nu/{\rm MHz})^{2.2}\sqrt{\sin b}},$$

Frequency and Time Resolution

- Most sources are continium source, frequency resolution unimportant, RFI mitigation, current spec.: frequency resolution 250
- radio recombination line – but maybe too difficult for this project
- EoR/CD 21cm spectrum: global signal not sharp
- time resolution: for the lunar array design, $\omega \sim 6e\text{-}4$, $\Delta u \sim u\, \omega\, \Delta t < 1$ require $\Delta t < 20ms$ for $u = 30000$ (10MHz, 100km baseline), for higher frequency or longer baseline this requirement is stronger
- This requires higher downlink data rate and/or on-satellite data storage and processing power

Sensitivity Estimates

flux Sensitivity

$$S_{rms} = \frac{2kT_{sys}}{A\eta_Q\sqrt{n_a(n_a-1)n_{pol}\Delta\nu t}}$$

Estimates on the worksheet:

At 10MHz, 3MHz bandwidth, 8760 hours integration time (1year, 24hr/day)

Resolution: 2arcmin

S_{rms}=0.055 Jy/beam

Confusion Limit: 0.21Jy, Resolution (S<Sconf): 0.9 arcmin

3 sigma sources: 1.9e6 sources for whole sky

Confusion Noise

Extragalactic point source:

$$1.13\theta^2 m N(S_{conf}) = 1$$

m=12.9

$$N_>(S) = 1800\,\mathrm{deg}^{-2}\left(\frac{S}{10\mathrm{mJy}}\right)^{-1.3}\left(\frac{\nu}{10\,\mathrm{MHz}}\right)^{-0.7} = 4.5\,\mathrm{deg}^{-2}\left(\frac{S}{\mathrm{Jy}}\right)^{-1.3}\left(\frac{\nu}{10\,\mathrm{MHz}}\right)^{-0.7}$$

$$S_{conf} = 16\mathrm{mJy}\ (\theta/1\,\mathrm{arcmin})^{1.54}\left(\frac{\nu}{74\,\mathrm{MHz}}\right)^{-0.7} = 65\mathrm{mJy}(\theta/1\,\mathrm{arcmin})^{1.54}\left(\frac{\nu}{10\,\mathrm{MHz}}\right)^{-0.7}$$

$$S_{conf} = 65\mathrm{mJy}(\theta/1\,\mathrm{arcmin})^{1.54}\left(\frac{\nu}{10\,\mathrm{MHz}}\right)^{-0.7}$$

M.H. Huang will discuss this issue (esp. lower frequency case) in more details

Dynamic Range

If Cas A and Cyg A are the strongest source in sky, their flux is about 10-100kJy. (A few such sources in the sky?)

If a dynamic range of 10^3 is achieved in the map, the flux limit is about 10-100 Jy during the whole mission.

So the system sensitivity is probably dynamic range limited. To improve the dynamic range, one wants to

(1) sufficient sampling bits
(2) improve the positioning accuracy and phase stability
(3) reduce the hole in uv-plane, i.e. use relatively short baselines

Discussions

- The 3D imaging algorithm
- Calibration method (also important for global spectrum)
- Effects of strong variable source (e.g. Sun)
- Needs much build-in flexibility (raw data transmission mode, re-programmable on-board processor, redundant data storage and processing power)
- But: also must be technically ready

Thanks!

Sensitivity Estimates

flux Sensitivity

$$S_{rms} = \frac{2kT_{sys}}{A\eta_Q\sqrt{n_a(n_a-1)n_{pol}\Delta\nu t}}$$

note: independent of baseline length and coplanarity

integration time: Assume t_{far}=1/3 t_{orb} $\Delta\,\nu = \nu$

$$S_{rms} = 4.2\text{Jy} \quad \text{per orbit}, \qquad S_{rms} = 0.039\text{Jy} \quad \text{mission}; \qquad n_a = 4$$

$$S_{rms} = 0.9\text{Jy} \quad \text{per orbit}, \qquad S_{rms} = 0.0084\text{Jy} \quad \text{mission}; \qquad n_a = 12$$

$$T_{rms} = \frac{T_{sys}}{\eta_Q f\sqrt{\Delta\nu t}}$$

$$f = \frac{A\sqrt{n_a(n_a-1)}}{D^2_{max}}$$

$$T_{rms} = 3\times10^5\text{K} \quad \text{per orbit}, \qquad T_{rms} = 2.8\times10^3\text{K} \quad \text{mission}; \qquad n_a = 4$$

$$T_{rms} = 6.5\times10^4\text{K} \quad \text{per orbit}, \qquad T_{rms} = 6.1\times10^2\text{K} \quad \text{mission}; \qquad n_a = 12$$