Extremely low frequency radio spectroscopy of the interstellar medium as important instrument of studies of the tenuous, cold, and partially ionized objects.

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Abstract

Radio spectroscopy at extremely low frequencies provides unique opportunities for studies of the cold low-density partially ionized interstellar medium. The radio recombination lines (RRL) of carbon are observed in many galactic directions up to the middle decametric waves. The biggest atoms which have been detected in space with RRL correspond to quantum numbers as big as 1009. Such atoms have a classical diameter of about 108 μ (~0.1 mm) and they are larger by a factor of ~ 10^6 compared to the ground state atom. The partially ionized and cold interstellar plasma can play significant role in many astrophysical phenomena (among them, for example, are processes of star formation). The experience obtained with the biggest low frequency instruments such as UTR-2 (Ukraine) shows that the low frequency carbon RRL can be observed not only against strong background source like Cassiopeia A but also against non thermal background galactic radio emission. It is confirmed by the detection of absorption carbon RRL in the direction of galactic plane at frequencies near 25 - 26 MHz. Low intensity of such features causes the necessity of really big instruments in order to carry out these investigations and LOFAR can open new spectrum of opportunities in the field.

Theory of RRL

RRLs are produced by transitions of recombining electrons between two atom levels in ionized gas. Their frequencies can be calculated using Rydberg's formula:

$$\nu_n = cZ^{\text{٢}} R(\text{١} - \frac{m_e}{M_a})(\frac{\text{١}}{n^{\text{٢}}} - \frac{\text{١}}{(n + \Delta n)^{\text{٢}}})$$

c **is speed of light,** ***Z*** **is the nuclear charge of the ion ,** ***R*** **is the Rydberg constant for the taken species,** m_e **and** M_a **are electron and nuclear mass,** ***n*** **and** ***Δn*** **are principal quantum number and its change.**

The possibility of RRL observation was predicted by Kardashev in 1959. They were detected in 1963-1964 by Dravskikh and Dravskikh at 5.7 GHz (n=105) and Sorochenko and Borodzich at 8.9 GHz (n=91). A lot of high frequency RRL have been observed towards classical hot HII regions. Also, for example, they have been detected in planetary nebulae, external galaxies, and in some circumstellar envelopes.

$n>600,\ \nu< 30\ MHz$

$$\Delta T_L/T_C = -\tau_L^* b_n \beta_n = f(\underline{N}_e, \underline{T}_e, S, ME)$$

$$\tau_L^* = 2*10^6\ N_e^2\ S/T_e^{2.5}$$

The profile of RRL is determined by several broadening effects.

Doppler broadening caused both by thermal particles motion and turbulence in the ISM leads to a Gaussian shape.

Collisions in the gas (Stark effect) and influence of background radiation are responsible for a Lorentzian curve.

$$\Delta\nu_D = \Delta\nu_L\ \Delta V/c$$

$$\Delta\nu_p \sim \underline{N}_e\, n^{5.2}$$

$$\Delta\nu_R \sim n^{5.8}$$

The distance between adjacent features $\delta\nu_L \sim 3\nu/n$

In 20 … 30 MHz band there are ~ 90 lines.

RRL profile

The combination of Doppler and Lorentzian broadening effect produces a Voigt profile which is the convolution of the Gaussian and Lorentzian curves

$$V(\nu) = \frac{2\sqrt{\ln 2}}{\sqrt{\pi}\,\Delta\nu_D}\,\frac{a}{\pi}\int_{-\infty}^{\infty}\frac{e^{-t^2}\,dt}{a^2+\left(\frac{2\sqrt{\ln 2}\,(\nu-\nu_0)}{\Delta\nu_D}-t\right)^2}$$

where

$$a = \frac{\sqrt{\ln 2}\,\Delta\nu_L}{\Delta\nu_D}$$

Observations of the very low frequency RRLs

Detection of carbon RRLs at 26 MHz in 1980 opened new field of extremely low frequency radio spectroscopy of the ISM.

The dependence of line parameters against conditions in the interstellar medium (such as temperature, density, and turbulence in the clouds) are stronger than this at high frequencies.

Carbon RRLs at frequencies less than 100 MHz arising in cold clouds have been observed at UTR-2 (Ukraine), Gee-Tee (34.5 MHz, Bangalore, India), NRAO (34-78 MH, USA), DKR-1000 (42 MHz, Russia), Parkes 64-m telescope in Australia (76.5 MHz)

Carbon in the ISM

Carbon is the most abundant element having the ionization potential less than H

(C/H=0.00037, Ec=11.2eV, EH=13.6eV).

It is almost completely ionized in the diffuse interstellar gas outside HII regions by ultraviolet photons

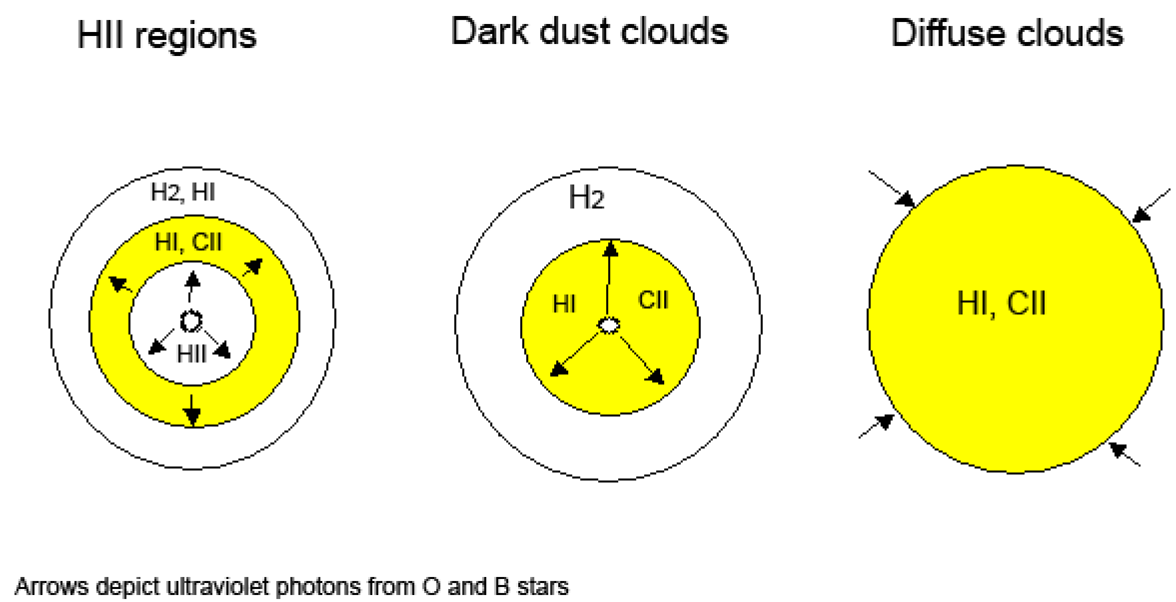
(912 Å<λ<1100 Å);

Carbon plays key role in cooling and thermostatic processes in the HI clouds due to fine structure transitions

$^2P_{3/2}$ — $^2P_{1/2}$ **with** $\lambda = 158\ \mu$

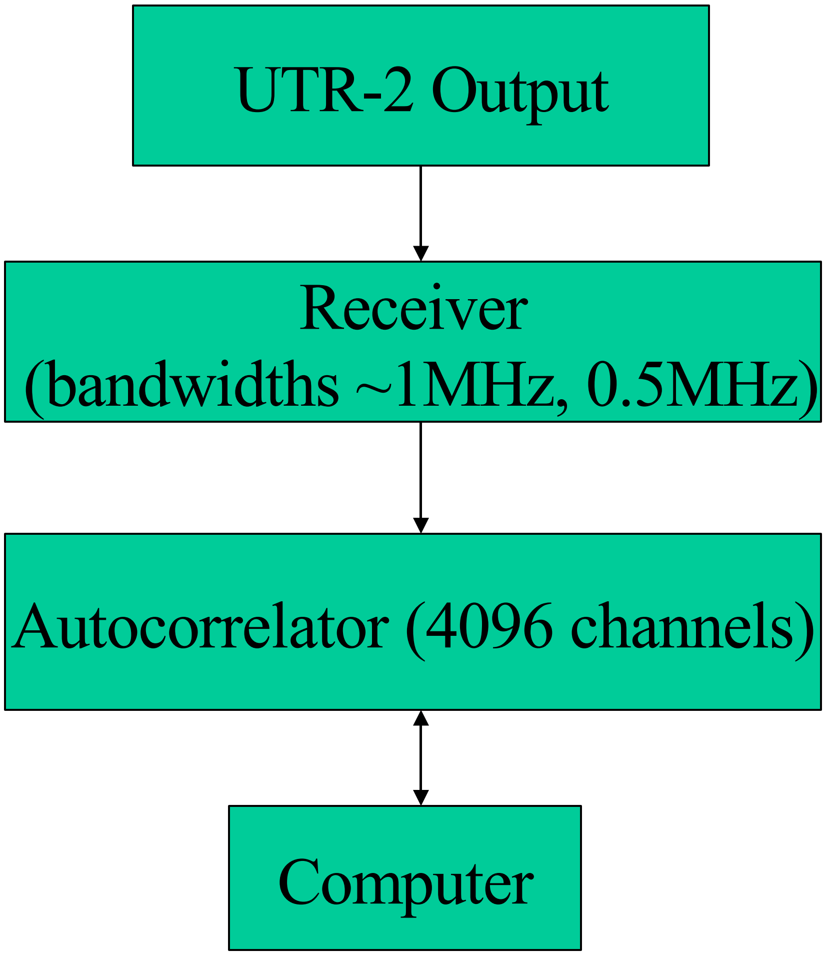
Most of the interstellar molecules contain carbon atoms and carbon plays a significant role in gas-phase chemical reactions in the ISM

Simplified models of the objects where carbon RRL can arise



Also carbons LF RRls can be connected with molecular gas

Equipment for radio spectroscopy at UTR-2



Usually, for observation is used one of the arms of UTR-2:

North – South or West –East

Fourier transform of averaged auto-correlation function gives power spectra of received emission

Outlook of the North arm of UTR-2

South arm of UTR-2 in winter time

Observations of carbon RRLs towards Cassiopeia A

The interstellar clouds lying against a supernova remnant Cassiopeia A are the best studied objects with low frequency carbon RRLs. They have been observed in wide frequency range from 12 MHz to 1.5 GHz. Up to ~ 120 MHz RRLs are observed in absorption.

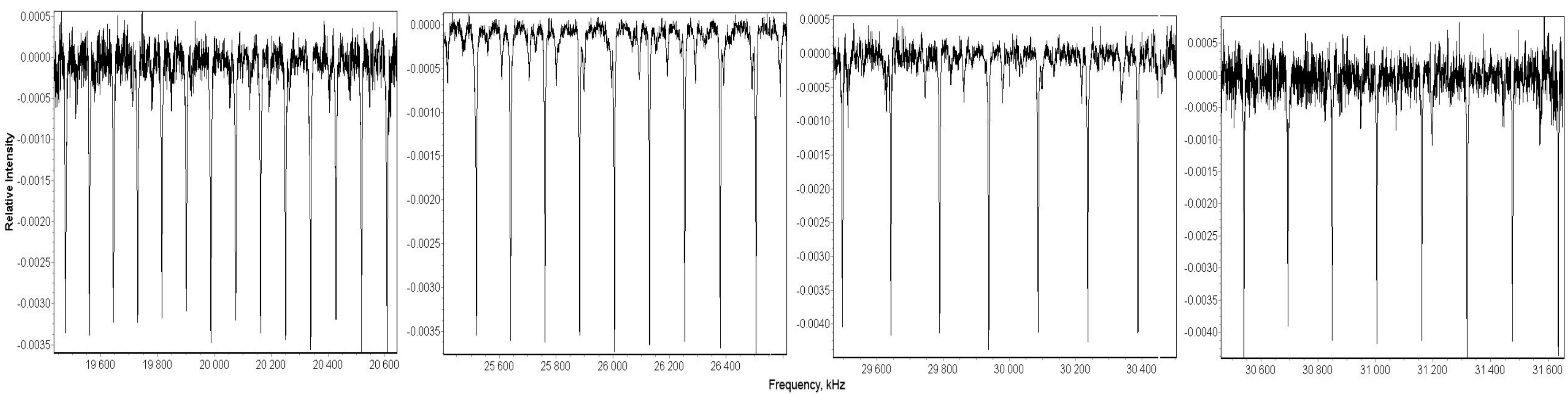
Carbon RRLs measured in the direction towards Cas A with UTR-2

20 MHz range – C683 … C696α , C860 …C877β (~30 h)

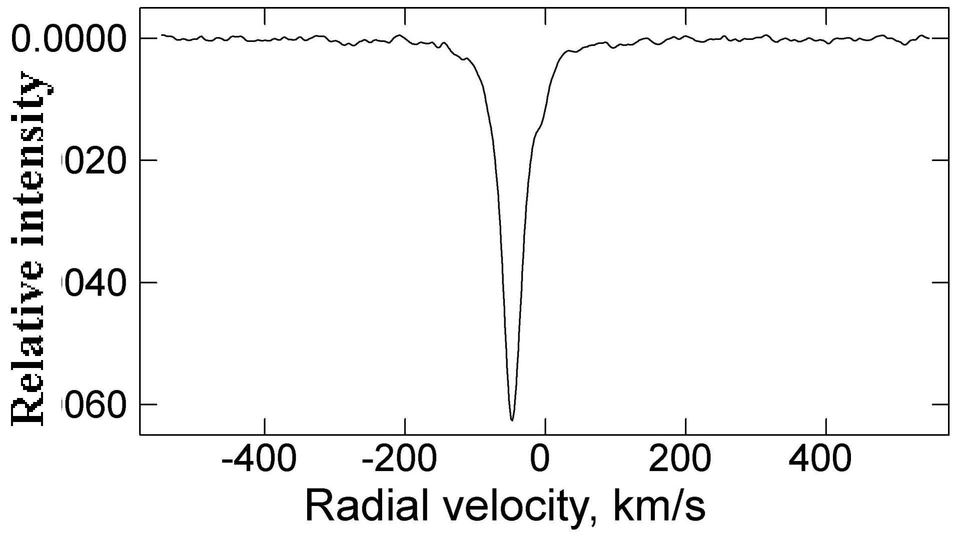
26 MHz range – C627…C636α, C790…C802β, C904…C917γ, C994…C1009 δ (~500h)

30MHz range – C599…C606α, C755…C764β (~90 h)

31 MHz range – C592…C598α, C746…C754β (20 h)



Folded C627…C636 α RRLs measured towards Cas A



In our case of very high atom quantum states n>>Δn and adjacent features can be considered as equivalent. Thus, we could fold individual transitions and improve measurement sensitivity considerably. Moreover, such an approach provides more reliable line parameters measurements because different transitions are observed simultaneously with the same antenna and medium conditions.

Interference reduction

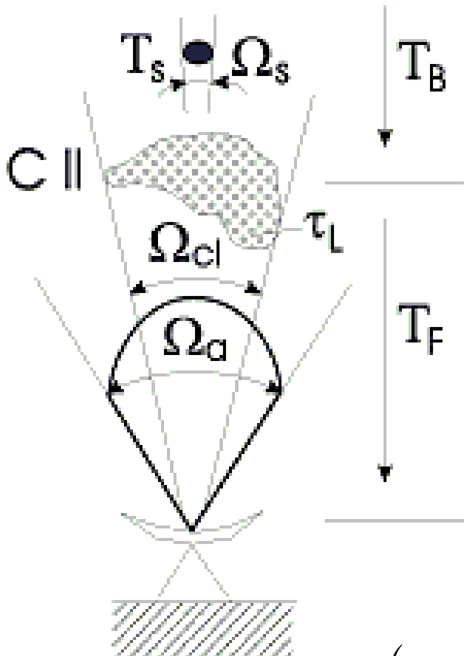
Usually spectroscopic observations at UTR-2 are carried out using four minute frames, which are stored in computer.

In order to remove hindering signal from processed spectrum we subtract from measured autocorrelation function a model of interference. It is described by

$$R[i] = \frac{2A}{r1} \exp\left(- \sqrt{\frac{i\pi \Delta f}{(2 \ln 2)^2 f_d}} \right) \cos\left(2\pi \left(f_o - f \right) \frac{i-1}{f_d} \right)$$

where *R[i]* – autocorrelation function of hindering signal, *A* – amplitude of hindering signal , *r1* – autocorrelation function point number, *Δf* – bandwidth of hindering signal, f_d – sampling frequency *fo* – frequency of the local oscillator.

Observed and real line intensities



$T_S >> T_B$:

$$\left(\frac{\Delta T_L}{T_C}\right)_{obs} = \left(\frac{\Delta T_L}{T_C}\right)_{real} = -\tau_L$$

$T_S << T_B$:

$$\left(\frac{\Delta T_L}{T_C}\right)_{obs} = \left(\frac{\Delta T_L}{T_C}\right)_{real} \frac{\Omega_{cl}}{\Omega_a} \frac{T_B}{T_B + T_F}$$

$T_B >> T_F$ (Cas A case)

$$\left(\frac{\Delta T_L}{TC}\right)_{real} = \left(\frac{\Delta T_L}{TC}\right)_{obs} \left(\frac{T_{CasA} + T_B}{T_{CasA}}\right)$$

The size of the atoms producing decametric carbon RRLs

For transitions at different n, the size of the atom is given by

$$d = 2 a_0 n^2 Z^{-1} \quad \textit{nm}$$

where a_0 ***= 0.05 nm*****, the Bohr radius, Z – effective nuclear charge of recombining ion, it is equal 1 in our case.**

So, for ***n=1009, d=0.108 mm.***

How many levels can be in an atom in space

Alkali and alkaline earth metals like potassium and barium have been excited to high quantum levels (up to n~1,100) in the laboratory by using tunable dye lasers.

When we take into account the typical conditions of the ISM in the Galaxy, the fundamental limit of the highest bound state of a Rydberg atom is near n=1,700. These are arrived at by estimating the quantum level at which the rate of depopulation exceeds the orbital frequency of the electron.

But if we take into account the radiation broadening due to background radiation in the Galaxy (its brightness temperature increases quickly with drop of frequency), the maximum quantum level at an atom could be less then mentioned above value.

Conclusions

- **Study of LF RRLs is important approach of the ISM diagnostic.**
- **In order to obtained high quality LF RRL data we need effective instrument.**
- **Opportunities that will be opened by LOFAR in the field are very promising**

References

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