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The ^{14}N VII 5.6-mm line for studies of WHIM, QSO and hot ISM

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We discuss prospective astrophysical applications of hyperfine structure line of ^{14}N VII ion at 5.65 mm (53 GHz). This line is suitable to probe the warm-hot intergalactic medium (WHIM) at temperatures around 10^6 K, old supernova remnant shock fronts, ionized gas in quasar host galaxies and hot interstellar medium (ISM). In case of Galactic and low-z objects the ^{14}N VII line observations may be performed from high-altitude sites like Chajnantor, where atmospheric attenuation diminishes line intensity by only a factor of about two. Though, the atmosphere is transparent in case of observations of the line from extragalactic objects with $z > 0.15$.

With the advent of the Square Kilometer Array (SKA), this line will be detected on many pathways to quasars and will become another probe for WHIM and high-z galaxy ISM studies. It enters the planned SKA frequency range for observed object redshifts $z > 1.1$. The nitrogen line will also allow to examine the hot gas content of quasar hosts thanks to resonant scattering of the quasar radio emission. Scattered line intensity will be proportional to the product of ion density and distance from the quasar squared, thus emphasizing contents of outskirts of the host galaxy.

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1. Introduction

Hyperfine structure (HFS) lines of highly-charged ions may open a new window in observations of hot astrophysical plasmas. Radio observations of these HFS lines will allow to obtain information about velocity field, mass, temperature and chemical abundance distribution of hot, warm and highly photoionized gas. The first discussion of the astrophysical applications of HFS lines was given by Ref. [1], especially pointing out millimeter lines of ^{14}N VII and ^{57}Fe XXIV.

The latter line was predicted to be bright in hot intracluster gas at temperatures of about 2×10^7 K. The line should also be bright in spectra of young supernova remnants, such as Cas A, if isotopic composition of iron in ejecta is close to solar.

The ^{14}N VII line was not considered interesting for galactic astronomy, as its rest frequency 53.043(10) GHz [2] is in the wing of atmospheric absorption band. Sunyaev and Churazov [1] proposed to use it for observations of objects having small positive redshifts, when the observed frequency moves out of the strongly attenuated spectral band. Following this idea, both theoretical studies [3] and experimental searches [4] have been performed recently, aiming at the line detection from objects at redshifts $z > 0.15$. The ^{14}N VII HFS line is unique in the sense that it allows to study from the ground astrophysical plasma at temperatures around 10^6 K, that otherwise can be explored only by rocked-based and space ultraviolet and soft X-ray missions.

Below we discuss some astrophysical applications of HFS line observations that will become possible with the SKA[1]. They include observations of various types of objects: warm-hot intergalactic medium (WHIM), quasar hosts, starburst galaxies, galactic halos, hot interstellar medium and supernova remnants (especially in emission). Most of the applications was discussed in detail in Ref. [3]. Below we concentrate only on application to the WHIM and quasar hosts.

2. Nitrogen line on pathways to quasars and in quasar host galaxies

We determine the amount of nitrogen HFS lines from WHIM using the same method as in Ref. [3]. Because of extremely low values of optical depth (around 10^{-5} and lower) it is obvious that demands to spectral calibration are very high.

The values of optical depth are compared to the expected SKA brightness temperature uncertainties in Figure 1. One-hour on-source observations of bright ($S > 2$ Jy) high-redshift quasars with spectral channel width of 30 km/s are assumed. It is seen that typical 3-σ statistical uncertainty is below expected optical depth for considerable redshift range, showing that in a very moderate time SKA will be able to probe the WHIM on a large set of pathways to quasars. Such HFS line detections will be complementary to the O VI far ultraviolet line observations, as they probe higher temperatures. SKA will also permit to observe much higher redshifts ($1.1 < z < 2.5$).

Now let us discuss the nitrogen line from the quasar hosts. As discussed in Ref. [3], the HFS line optical depth depends on the radiation field around the ion, as strong radiation at the transition frequency may significantly change hyperfine sublevel population. Frequent collisions with electrons and protons will have the same effect, also dinimishing both line optical depth and emissivity.

In our case of negligibly low electron density, but very high radiation intensity at ^{14}N VII line frequency, the multiplicative correction factor takes the form $D_{\rm N\ VII} = [1+3(N_{\rm CMB}+N_{\rm QSO})]^{-1}$,

[1]Note that the nitrogen line enter SKA frequency range only at at $z > 1.1$

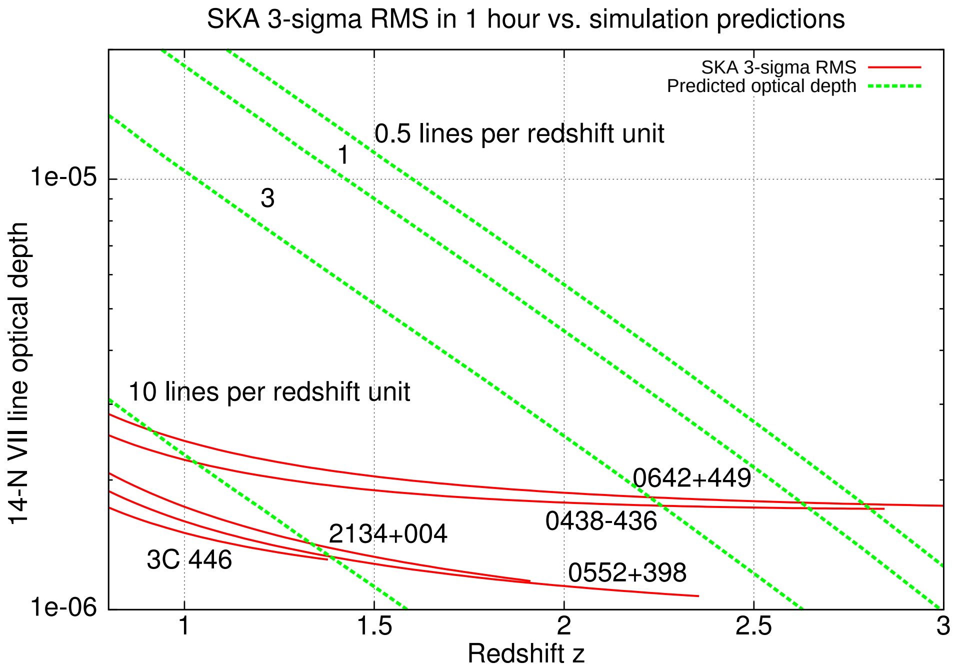

Figure 1: Expected ^{14}N VII line detection rate on the sightlines to some of the brightest high-z quasars. In one hour of integration SKA will be able to detect five to ten lines at 3-σ level and about three lines at 10-σ level in the redshift range from one to two. Green lines denote expected HFS absorption line depth frequency inferred from cosmological simulations [5]. Red lines show expected SKA 3-σ spectral line detection limits for one hour on-source integration.

where N denote photon occupation number at the line frequency and two additional contributions to the intensity within the line profile (cosmic microwave background and quasar) are explicitly specified. As $N_{\rm QSO} \propto r^{-2}$, where r is the distance from the gas element to the quasar, the quasar radiation field inside some radius r_0 will dominate total photon occupation number. For bright quasars this radius exceeds about hundred kpc, therefore HFS level populations of all the ionized gas in the quasar host galaxy will be determined by quasar emission, not the CMB.

Then the HFS line optical depth due to quasar radiation scattering will be

$$\tau_{\rm N\ VII} = \int \sigma\, n_{\rm N\ VII}(r) D_{\rm N\ VII} dr = \sigma\xi \int \frac{n_{\rm N\ VII}}{n_e} n_e(r) r^2 dr, \tag{2.1}$$

where $\xi \equiv D_{\rm N\ VII}/r^2$ is a quantity dependent on properties of a particular quasar. Note that major contribution to the optical depth is coming from outer regions of the gas cloud, as they have larger values of D. Using the definition of the photon occupation number N, we obtain

$$\xi = \frac{8\pi}{3} \frac{h\nu_0^3}{c^2(1+z)^2} \times 10^{23} S_{\rm Jy}^{-1} \times d_L^{-2}, \tag{2.2}$$

where d_L is the luminosity distance to the quasar, z is its redshift and $S_{\rm Jy}$ is the quasar flux at observed line frequency $\nu = \nu_0/(1+z)$. Typical values of ξ are about 1 Mpc^{-2}.

Assuming β-profile of the hot gas density with $\beta = 2/3$, the integral in (2.1) diverges. Therefore to estimate the optical depth we integrate only to 100 kpc, value of the order of the transition scale R of the NFW profile [6] $\rho_{\rm DM}(r) \propto (r/R)^{-1}(1+r/R)^{-2}$, where dark matter density dependence on radius change to $\rho_{\rm DM}(r) \propto r^{-3}$. Then, inserting numerical values, we obtain (n_0 and r_0 are hot gas central number density and core radius)

$$\tau_{\rm N\ VII} \approx \frac{10^{-5}}{(1+z)^2}\left(\frac{n_{\rm N\ VII}/n_e}{10^{-5}}\right)\left(\frac{\Delta\nu}{30\ {\rm km/s}}\right)^{-1}\left(\frac{d_L}{10{\rm Gpc}}\right)^{-2}\left(\frac{S}{1\ {\rm Jy}}\right)^{-1}\left(\frac{r_0}{10\ {\rm kpc}}\right)^{3}\left(\frac{n_0}{0.01\ {\rm cm}^{-3}}\right)$$

One seemingly unexpected relation that is readily seen from this expression is independence of the absorbed flux (in Jy) on the quasar flux. This will be true as long as the quasar will dominate total photon flux at the transition frequency, that for $z > 1$ will be true for quasars brighter than about 0.2 Jy. Typical signal from resonant scattering will thus be about 0.01 mJy for $z \approx 1.5$ quasar and host galaxy similar to a large elliptical galaxy.

As the absorbed radiation will be resonantly scattered in all directions, it will be observable as diffuse emission around the quasar, if the quasar emits considerable amount of radio waves also sideways. Besides, scattered emission intensity will also be proportional to $n_e r^2$, i.e., increase outwards, being most intense in the regions where hot gas density is far from maximum, already decreasing as r^{-2}. This emission, easily resolved already by the SKA core part, will increase our understanding of the *outer* parts of the quasar hosts. Emission will be specially easy to notice in sources, where most of the active nucleus radio emission is being radiated not towards us.

3. Conclusions

Using modern and near-future instruments it appears possible to observe absorption and emission lines of ^{14}N VII at redshifts $z > 0.15$. Using GBT, a 3-σ low-z WHIM detection would take about 10 hours [3]. With SKA, multiple high-z detections may be achieved in less than an hour.

At the quasar redshift, both VLA and SKA will be able to observe the ^{14}N VII line extended emission due to resonant scattering of the quasar radiation in the ionized gas around it. The intensity of this line is estimated to constitute about 0.01 mJy at $z = 1.5$ and is independent of quasar flux. Line intensity and shape will also provide information on the quasar beam width.

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