Hyperfine structure spectral lines of hot intergalactic gas

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We report on studies of hyperfine structure (HFS) lines of highly-ionized ions abundant in hot intergalactic gas. Existence of these lines was predicted by Sunyaev and Churazov in 1984. Since then, only the line of ^{57}Fe^{23+} *was studied. We extend study of mm and sub-mm HFS lines on all relevant ions, such as* ^{25}Mg^{11+}, ^{29}Si^{13+}, ^{57}Fe^{21+} *and others.*

In the calculations of the spectral line intensity we account for the effects of electronic and protonic direct and indirect collisional excitation, radiation fields of cosmic microwave background and resonant lines. In the absence of central radio source the line will be present in emission. We calculate excess brightness temperature distribution for some clusters of galaxies, where temperature, density and elemental abundance distributions are known from X-ray observations. This excess brightness in HFS lines is found to be on the order of 10 μ*K, which is on the detection limit of modern radio telescopes.*

Comparing the intensity of HFS line to X-ray lines, mainly produced by most abundant ^{56}Fe *isotope, it would be possible to measure the gas isotopic abundance. The resolution of mm detectors is much better than of X-ray ones and would allow measuring the HFS line profile. This way the intergalactic gas (IGG) velocity structure could be studied. Wide spectral coverage of modern radio detectors would allow to use these lines to determine cluster redshift.*

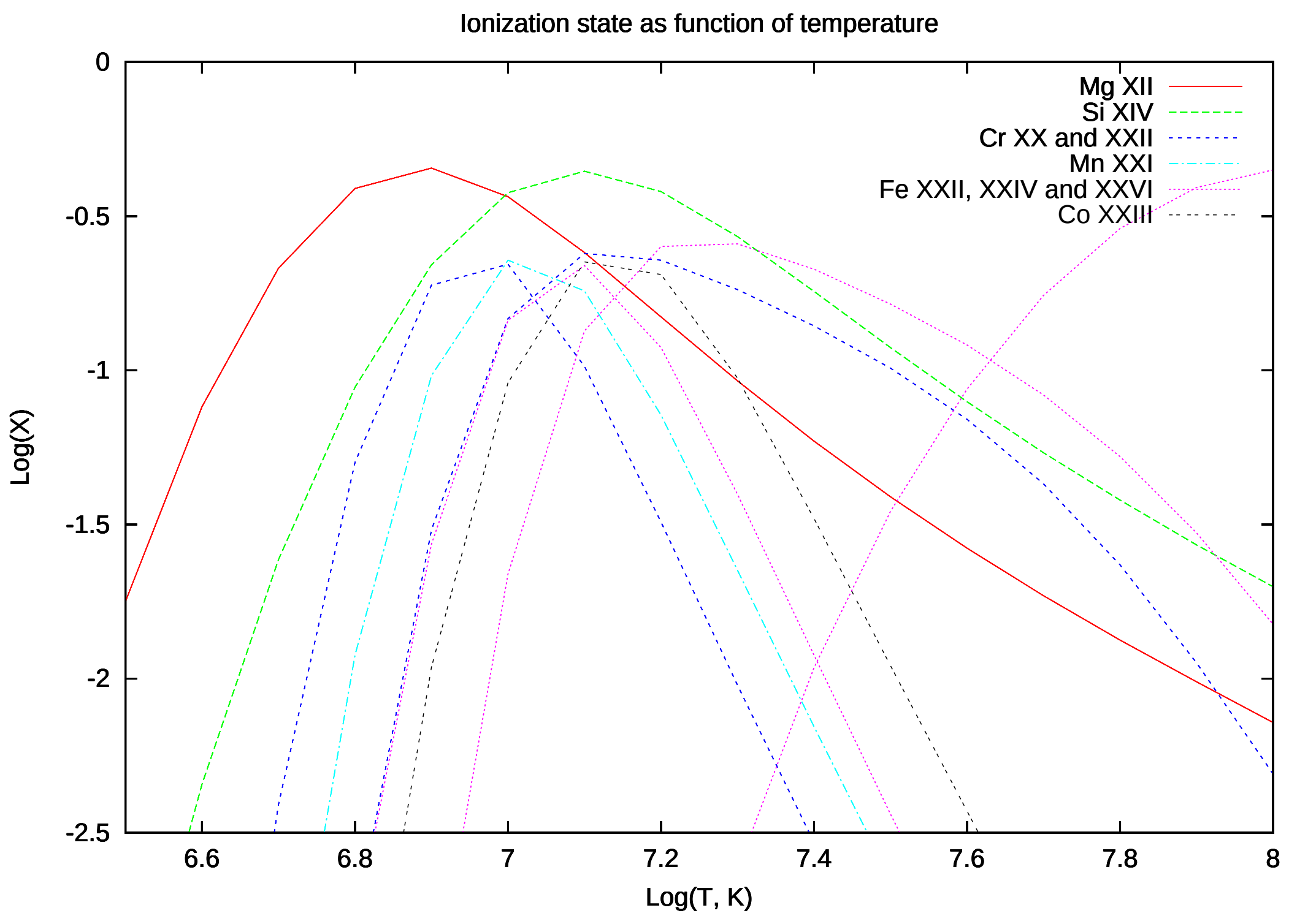
Introduction

From simulations of clusters of galaxies it is known that the hot intergalactic gas (temperature T from 1 to 10 keV, electron number density n_e below 0.2 cm^{-3}, sound speed c_s about 1000-1500 km/s) is turbulent. One of reasons of this turbulence is cluster mergers. This line broadening due to turbulence for heavy ions is appreciably larger than the thermal broadening. In presence of turbulence the line shape becomes different from Gaussian. Its measurement is important to understand the large-scale hydrodynamic processes in the intergalactic gas. One of possibilities to widen the observational window of hot IGG is to observe its millimeter and sub-millimeter lines arising in transition between hyperfine sub-levels of the ground state of abundant ions.

In this poster we discuss these hyperfine structure (HFS) lines of the hot gas. They are analogous to the famous 21-cm line of neutral hydrogen. The Li-like ^{57}Fe ion HFS spectral line (wavelength λ = 3.071 mm) was already discussed in the literature (Sunyaev and Churazov, 1984; D'Cruz, Sarazin and Dubau 1998), but we point out also several other mm and sub-mm lines arising in the hot IGG that have not been studied in detail.

Hyperfine structure

The hyperfine splitting arise due to interaction between electron and nuclear moments. Hence, to have non-zero hyperfine splitting of the ground state, the nucleus must have non-zero spin, and the total electron angular momentum must be different from zero. This excludes the most abundant isotopes (such as ^{56}Fe, ^{32}S, ^{28}Si, ^{24}Mg, etc.) and half of the ion species (He-like, Be-like, C-like, etc.). It is know that even for Fe ions the N-like ion abundance drops sharply above 1 keV. Hence previous studies concerned only about H-like and Li-like ions (Sunyaev and Churazov, 1984). This is, though, the first analysis of B-like ion HFS lines in hot gas.



Hyperfine structure splitting values of the ground state of H-like and Li-like ions was taken from the literature (and corrected, if more precise newer input data were available). For B-like ions the splitting energy ΔE_{HFS} as a function of total atomic angular moment F for the ground state $2s^2 2p\ ^2P_{1/2}$ was computed from the formula

$$\Delta E_{HFS}(F) = \frac{1}{2} A \Delta C,$$

where A is the magnetic hyperfine constant, $C = F(F+1) - J(J+1) - I(I+1)$, J is the total electronic angular momentum and I is the nuclear spin. The constant A is estimated from a non-relativistic expression (Sobelman 1980)

$$A = \frac{8}{3} \zeta_{\text{gr.}} \frac{\mu}{I Z_i} \frac{m_e}{m_p},$$

where $\zeta_{\text{gr.}}$ is found from fine-structure (multiplet) splitting of the ground electron configuration as $\zeta_{\text{gr.}} = (E_{J+1} - E_J)/(L + 1/2)$ and an "effective" nuclear charge Z_i is computed from the fine structure splitting and quantum defect of the level.

Spontaneous transition rates between HFS components of one level A_{ul} were found, using well-known formula

$$A(\gamma JIF \to \gamma JI, F-1) = \frac{\omega^3}{3\hbar c^3} \cdot \frac{\mu_0^2 g^2}{F(2F+1)} \times$$
$$(J+I+F+1)(J+I-F+1)(F+J-I)(F-J+I),$$

where $\omega = 2\pi\nu = 2\pi c/\lambda$ is cyclic frequency, $\mu_0 = \frac{e\hbar}{2m_e c}$ is the Bohr magneton, g is the Landé factor of the level γSLJ and γ denote all unspecified quantum numbers.

Isotope, ion	X_{iso}	lg(T_{opt}, K)	μ, n.m.	λ, mm	W, s^{-1}
H-like ions					
$^{25}_{12}$Mg XII	$3.8 \cdot 10^{-6}$	6.90	-0.85545	0.657	$1.6 \cdot 10^{-7}$
$^{29}_{14}$Si XIV	$1.7 \cdot 10^{-6}$	7.10	-0.55529	0.381	$4.9 \cdot 10^{-7}$
$^{57}_{26}$Fe XXVI	$6.9 \cdot 10^{-7}$	8.05	+0.090623	0.3525	$6.2 \cdot 10^{-7}$
Li-like ions					
$^{53}_{24}$Cr XXII	$4.6 \cdot 10^{-8}$	7.15	-0.47454	1.14	$2.8 \cdot 10^{-8}$
$^{57}_{26}$Fe XXIV	$6.9 \cdot 10^{-7}$	7.25	+0.090623	3.071	$9.3 \cdot 10^{-10}$
B-like ions					
$^{53}_{24}$Cr XX	$4.6 \cdot 10^{-8}$	7.00	-0.47454	4.4	$5.2 \cdot 10^{-11}$
$^{55}_{25}$Mn XXI	$3.4 \cdot 10^{-7}$	7.05	+3.468718	0.58	$2.6 \cdot 10^{-8}$
$^{57}_{26}$Fe XXII	$6.9 \cdot 10^{-7}$	7.10	+0.090623	11.7	$1.9 \cdot 10^{-12}$
$^{59}_{27}$Co XXIII	$8.1 \cdot 10^{-8}$	7.15	+4.627	0.35	$1.1 \cdot 10^{-7}$

Excitation mechanisms

The upper sub-level of the ground state HFS is excited mainly through the following elementary processes: (a) collisional excitation of the HFS sub-level by electron or proton, (b) collisional excitation of higher-energy levels (of fine structure states, or with change of the principal quantum number n) with following relaxation onto excited HFS sub-level (so-called indirect excitation), (c) stimulated absorption of the cosmic microwave background (CMB) radiation, and (d) resonance scattering of photons. All these effects have been taken into account in an excitation rate computation.

For the hydrogen-like ion resonance processes play a minor role in HFS excitation, and the main influence has the "direct" electronic collisional excitation. For the lithium-like ions, quite opposite, main contribution is due to indirect electronic excitation through 2p states. For boron-like ions, it also has major contribution, but about fourth part of the HFS excitation proceed as the protonic indirect impact excitation through the lowest excited fine-structure level $^2P_{3/2}$.

Hydrogen-like ions Investigations by Zhang and Sampson 1997 and 2001 showed that the main contribution to the collision strength Ω is given by direct electron collisional excitations from lower to upper hyperfine level. Collision strength values for ^{13}C VI and ^{14}N VII were given in the article. Using simple non-relativistic relation ($z^2/B_{hfsc}\Omega(u,l;E/z^2) = f(E)$) they were scaled to all ions of interest. Here E is the incident electron energy and B_{hfsc} is hyperfine structure correction coefficient.

Lithium-like and boron-like ions For these ions we essentially repeat the analysis of D'Cruz, Sarazin and Dubau, 1998. Spontaneous transition and excitation rates of different ionic state hyperfine sublevels are computed using the branching ratios for the excitation and decay of intermediate HFS states.

Though, B-like ions, in contrary to Li-like ones, have non-zero electronic quadrupole momentum in ground state which allows relatively efficient direct proton collisional excitation. When evaluated, direct protonic rate coefficients are still about 10^5 times less than indirect protonic and electronic ones. For B-like ions we account for indirect excitation through all levels of low-lying electron configurations $2s^2 2p$ and $2s 2p^2$. Unfortunately, electronic excitation data are available for Fe XXII only, so we concentrate on this ion. Excitation rates of Li-like and B-like ions as functions of temperature are given on the figure.

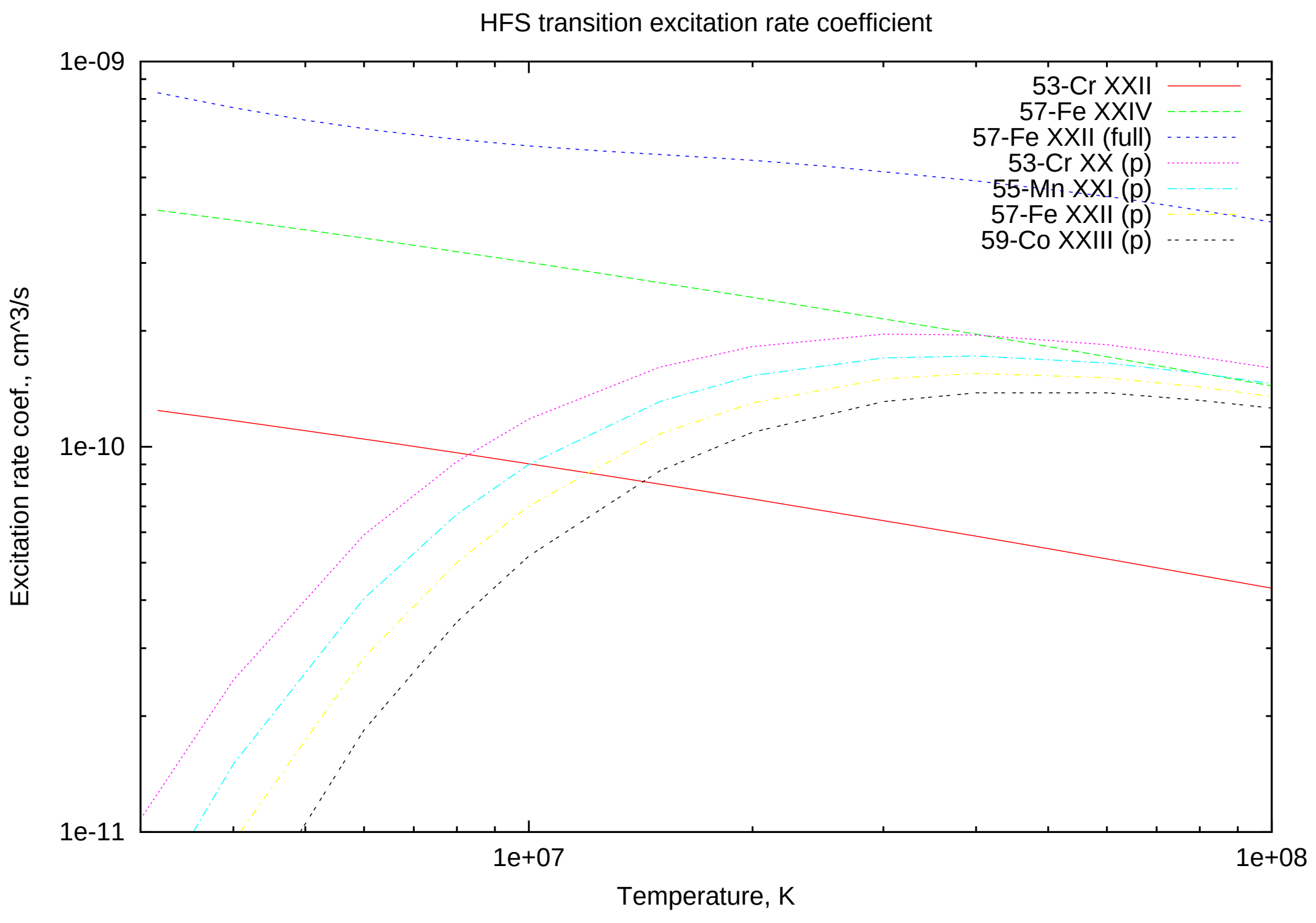
Level population The level population n_u/n_l is computed from the balance equation, which in case of negligible optical pumping can be expressed as

$$\frac{n_u}{n_l} = \frac{g_u}{g_l} \frac{N + n_e/n_{cr}}{1 + N + n_e/n_{cr}},$$

where N is the occupation number of the CMB at the frequency of the transition and $n_{cr} \equiv A_{ul}/q_{ul}^{eff}$ is so-called critical density and q_{ul}^{eff} is effective excitation rate from upper to lower state, including indirect excitation.

For all ions but Fe XXII the densities present in intergalactic gas are significantly less than the critical density. For Fe XXII (with $n_{cr} \approx 0.015$ cm^{-3}) one has to account for this effect, effectively diminishing the line emission.

Optical pumping Photons of fine structure lines with lower ground state are resonantly scattered in the gas, and this process affects population of the ground HFS states. These fine structure lines could be moderately optically thick ($\tau \leq 10^2$), hence this "optical pumping" might be quite important. Crudely this increases the HFS line intensity ($\tau X_{\text{imf}} + 1$) times, where X_{imf} denote isotopic mole fraction (e.g., $X_{\text{imf}}(^{57}\text{Fe}) = 0.0212$).

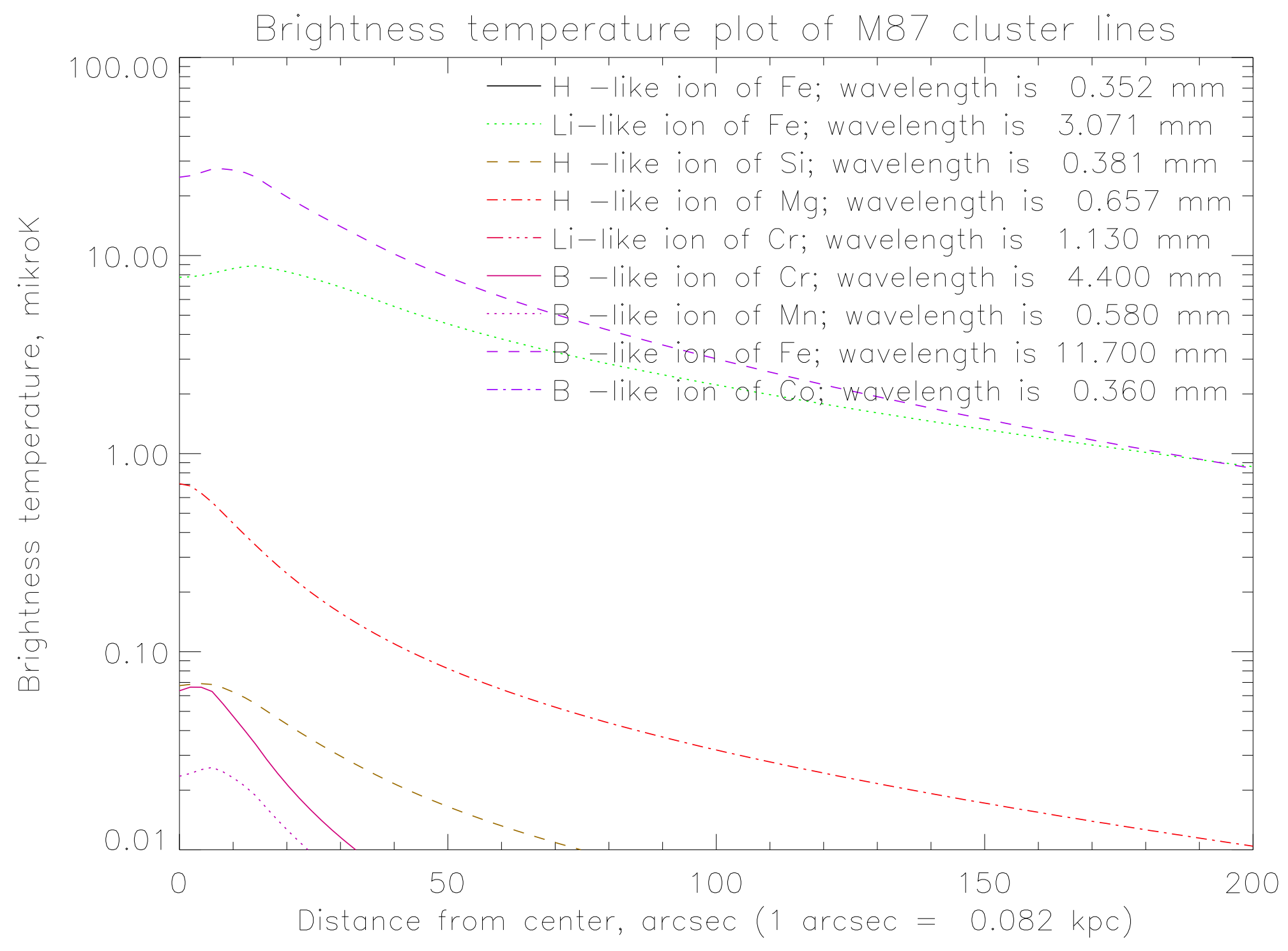


Intensity estimates

Intensity of the line ΔI, erg/cm^2/s/sr/Hz, was computed as

$$\Delta I_\nu = \frac{hc}{4\pi^{3/2}} \int \frac{1}{v_{th}} \cdot \frac{n_e^2 X_{\text{iso}} X q_{lu}^{eff}}{1 + (1 + g_u/g_l) N + (1 + g_u/g_l) \frac{n_e}{n_{cr}}} ds,$$

where v_{th} is the thermal ion velocity, X is the ionic abundance, and ds is the path element. Please note that this is the intensity in the line center, assuming theram velocity spread. The excess brightness temperature was computed from the Rayleigh-Jeans relation $\Delta T_b = \lambda^2/(2k)\Delta I$.



Discussion and conclusions

Typical brightness temperature excess in Fe XXIV and Fe XXII HFS lines is on the order of 1-10 μK. This is just on the border on nowadays detection possibilities. For example, GBT (Green Bank Telescope), according to its sensitivity calculator, has 3-sigma sensitivity of 20 μK (at 12 mm, 100 hours on-source integration time, 150 km/s frequency channel).

Thanks to relatively wide spectral coverage of modern detectors it may become possible to use these lines to determine redshift of galaxy clusters discovered in near future SZ surveys.

Due to turbulent and bulk motions, the spectral line profile broadens. Hence the line intensity (per Hz) is decreasing, as well as the optical pumping efficiency. But from another point of view, high resolution in radio range would allow to observe the turbulence and bulk motions in clusters of galaxies directly.

References

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