The Contribution of Black Holes to Wouthuysen-Field Signal and its Detection by Sci-HI

Omar A. Ruiz Macias

CINVESTAV

oaruiz@fis.cinvestav.mx

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Contenido

The 21cm emission line from neutral hydrogen

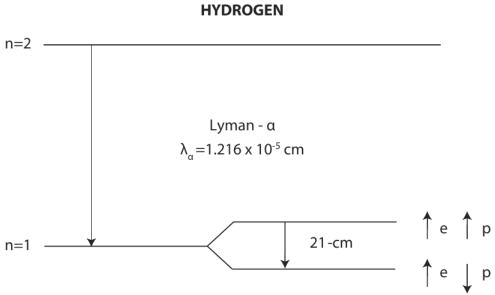


Figure : Two important transitions of the hydrogen atom. The 21-cm transition of hydrogen is between two slightly separated (hyperfine) states of the ground energy level. A spin flip of the electron results in the emission of a photon with a wavelength of 21 cm (or frequency of 420 MHz). The second transition is between the $n = 2$ and the $n = 1$ levels, resulting in the emission of a Lyα photon of wavelength $\lambda_\alpha = 1.216 \times 10^{-5}$ cm (or a frequency of 2.468×10^{15} Hz).

The 21cm emission line from neutral hydrogen

Three processes determine the spin temperature:

- Absorption (emission) of 21 cm photons from (to) the radio background
- Collisions with other hydrogen atoms and with electrons
- Resonant scattering of Lyα photons

The Wouthuysen-Field effect

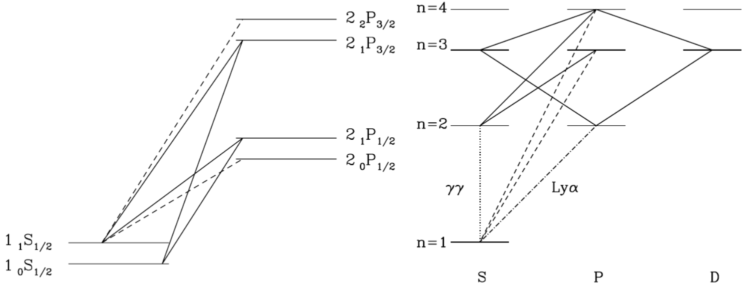


Figure : Hyperfine structure of the hydrogen atom and the transitions relevant for the Wouthuysen-Field effect.

The brightness temperature

$$\delta T_b \simeq 27(1-\overline{x_i})\left(\frac{\Omega_{b,0}h^2}{0.023}\right)\left(\frac{0.15}{\Omega_{m,0}h^2}\,\frac{1+z}{10}\right)^{1/2}\left(1-\frac{T_\gamma}{T_S}\right) \tag{1}$$

Spin temperature

$$T_S^{-1} \approx \frac{T_\gamma^{-1} + x_c T_K^{-1} + x_\alpha T_\alpha^{-1}}{1 + x_c + x_\alpha} \tag{2}$$

Global 21-cm signal

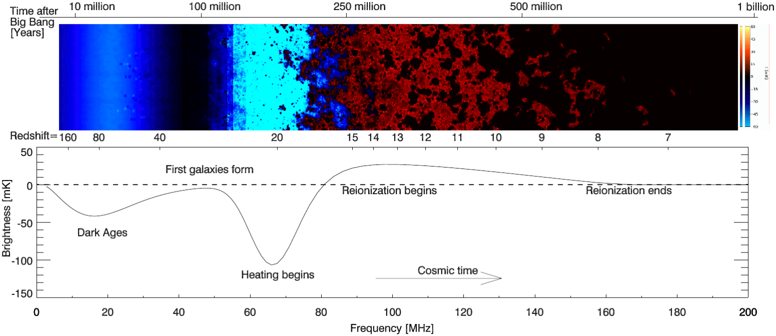


Figure : The 21-cm cosmic hydrogen signal.

Theoretical framework

RTE

$$\left(\frac{\partial}{\partial t} - \nu H(z)\frac{\partial}{\partial \nu}\right) J_\nu(z) + 3H(z)J_\nu(z) = -c\alpha_\nu J_\nu(z) + \frac{c}{4\pi}\epsilon_\nu(z)(1+z)^3$$

Angle-averaged background intensity

$$\hat{J}_\nu(z) = \frac{c}{4\pi}(1+z)^2 \int_z^{z_f} \frac{\hat{\epsilon}_{\nu'}(z')}{H(z')} e^{-\overline{\tau}_\nu} dz' \quad (3)$$

$$\left[\hat{J}_\nu\right] = s^{-1}\, cm^{-2} Hz^{-1} sr^{-1}$$

Redshifted frequency

$$\nu' = \nu \left(\frac{1+z'}{1+z} \right)$$

Optical depth

$$\overline{\tau}_{\nu}(z,z') = \sum_{j} \int_{z}^{z'} n_j(z'')\sigma_{j,\nu''} \frac{dl}{dz''} dz'' \qquad (4)$$

The Lyα background intensity

$$\hat{J}_{\alpha}(z) = \frac{c}{4\pi}(1+z)^2 \sum_{n=2}^{n_{max}} f_{rec}^{(n)} \int_{z}^{z_{max}^{(n)}} \frac{\hat{\epsilon}_{\nu'}(z')}{H(z')} dz' \qquad (5)$$

The approximations

Optical depth

$$\overline{\tau}_\nu(z, z') \simeq \left(\frac{\mu}{\nu}\right)^3 (1+z)^{3/2} \left[1 - \left(\frac{1+z}{1+z'}\right)^{3/2}\right] \tag{6}$$

with

$$\mu^3 \equiv \frac{2}{3} \frac{\overline{n}_H^0 \sigma_0 c}{H_0 \sqrt{\Omega_{m,0}}} (\nu_{H_I}^3 + y \nu_{H_{el}}^3)$$

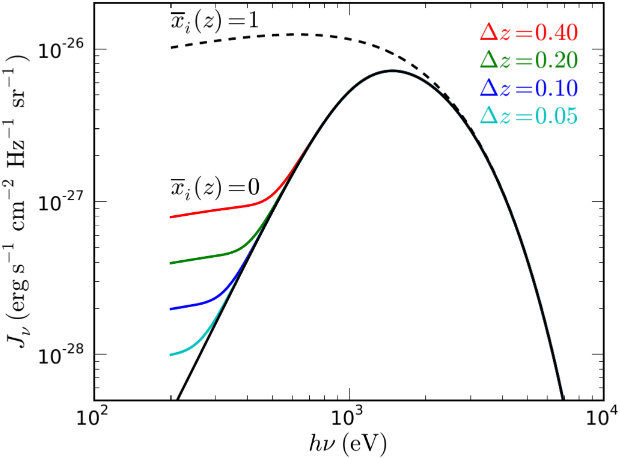

$\overline{x}_i(z)=1$
$\overline{x}_i(z)=0$
$\Delta z=0.40$
$\Delta z=0.20$
$\Delta z=0.10$
$\Delta z=0.05$
J_ν (erg s^{-1} cm^{-2} Hz^{-1} sr^{-1})
10^{-26}
10^{-27}
10^{-28}
10^2
10^3
10^4
$h\nu$ (eV)

Figure :

We made:

$$\tau_\nu(z, z') = 1 \tag{7}$$

and

$$z' + z + \Delta_{z_{bf}} \tag{8}$$

Bound-free horizon

$$\Delta z_{bf} \simeq (1+z)\left[\left(1 - \left(\frac{\nu/\mu}{\sqrt{1+z}}\right)^3\right)^{-2/3} - 1\right] \tag{9}$$

Discrete angle-averaged background intensity

$$\begin{aligned}\hat{J}_{\nu_n}(z_l) &= \frac{c}{4\pi}(1+z_l)^2\int_{z_l}^{z_{l+1}} \frac{\hat{\epsilon}_{\nu_{n'}}(z')}{H(z')}\, e^{-\overline{\tau}_{\nu_n}(z_l,z')}\,dz' \\ &+ \left(\frac{1+z_l}{1+z_{l+1}}\right)^2 \hat{J}_{\nu_{n+1}}(z_{l+1})\, e^{-\overline{\tau}_{\nu_n}(z_l,z_{l+1})} \end{aligned} \tag{10}$$

Fraction of the bolometric luminosity density

$$\xi_X(z) \approx \int_{\nu_{min}}^{\nu_{Hub}} I_\nu d\nu \left(\int_{\nu_{min}}^{\nu_{max}} I_\nu d\nu \right)^{-1} \tag{11}$$

Heating rate density

$$\epsilon_X(z) = \xi_X(z) L_{bol}(z) f_{heat} \tag{12}$$

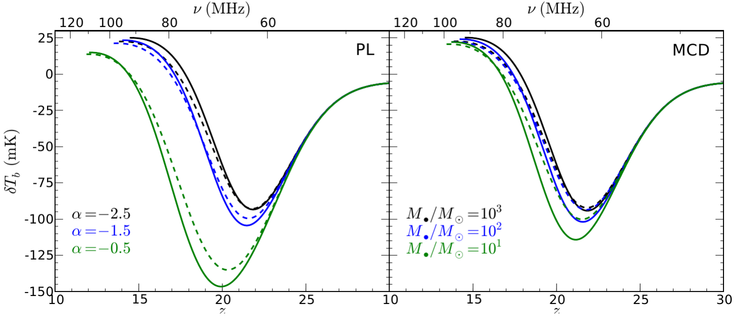


Figure : Testing the approximation of (11) and (12)

Parameters

The parameters that govern the SED of accreting BH:

- The mass of the BH
- The fraction of disk photons that are up-scattered by a hot electron corona (f_{sc})
- The power law index of resulting emission (α)
- The column density of neutral hydrogen that lies between the accreting system and the IGM (N_{H_I})

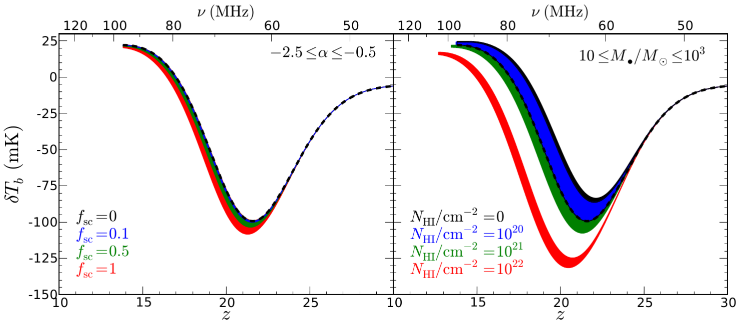
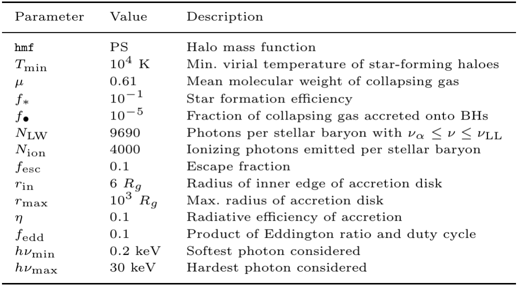


Figure : Evolution of the 21.cm brightness temperature for different BH SED models.



Parameter	Value	Description
`hmf`	PS	Halo mass function
$T_{\rm min}$	10^4 K	Min. virial temperature of star-forming haloes
μ	0.61	Mean molecular weight of collapsing gas
f_*	10^{-1}	Star formation efficiency
$f_\bullet$	10^{-5}	Fraction of collapsing gas accreted onto BHs
$N_{\rm LW}$	9690	Photons per stellar baryon with $\nu_\alpha \leq \nu \leq \nu_{\rm LL}$
$N_{\rm ion}$	4000	Ionizing photons emitted per stellar baryon
$f_{\rm esc}$	0.1	Escape fraction
$r_{\rm in}$	$6\ R_g$	Radius of inner edge of accretion disk
$r_{\rm max}$	$10^3\ R_g$	Max. radius of accretion disk
η	0.1	Radiative efficiency of accretion
$f_{\rm edd}$	0.1	Product of Eddington ratio and duty cycle
$h\nu_{\rm min}$	0.2 keV	Softest photon considered
$h\nu_{\rm max}$	30 keV	Hardest photon considered

Figure : Parameters constants in this work.

Conclusions

The contribution to accreting BH can affect directly in the 21-cm signal significatively.