Astrophysical Thinking (FS 2018)

hand in by May 17th

May 10, 2018

Week 12: 21cm Signals from Redshift 17 (Yoo)

- no need to look up any text books! no need to type your answers!

Out of 2 year observations, the EDGES (Experiment to Detect Global Epoch of Reionization Signature) has reported in early 2018 the absorption signal at $z = 17$ by measuring the sky average (global signal) of the 21cm brightness temperature from neutral hydrogens:

$$\delta T_b = \frac{T_s - T_\gamma}{1+z}\,\tau = -500^{200}_{-500}\ \text{mK}\ , \tag{1}$$

where T_s is the spin temperature, $T_\gamma = 50$ K is the CMB temperature at $z = 17$, and τ is the optical depth. This observation has generated quite a stir (and papers as well), because the maximum possible absorption signals in the standard model are $\delta T_b = -200$ mK. We want to understand why it is the case and how we can reconcile with the observation (of course, under the assumption that the observation is indeed correct).

The hyper-fine transition of the spin states of the neutral hydrogens give $\lambda = 21$ cm or $\nu = 1.4$ GHz, corresponding to $\lambda = 3.8$ m or $\nu = 78$ MHz at $z = 17$ (the experiment is as big as about 30 m$\times$30 m). The CMB temperature is $T_\gamma = 2.78$ K, and it peaks at $\lambda = 0.1$ cm. Since the CMB radiation is the dominant in its frequency range, 21cm signals are always measured against CMB signals, hence we have $T_s - T_\gamma$. Since the line is extremely narrow, the frequency observation gives the redshift. The optical depth for 21cm radiation is,

$$\tau \propto \frac{1}{T_s}\frac{n_{\rm H_I}}{H(z)}\ , \tag{2}$$

essentially determined by the neutral hydrogen number density and the Hubble parameter, both of which are known better than 10%, in addition to the spin temperature. In other words, the only remaining uncertainty is the spin temperature T_s of the gas, and we have to further lower the spin temperature than expected in the standard model, in order to explain the observation.

The gas temperature follows the CMB temperature up to $z \sim 150$, from which it cools faster as $T_g \propto 1/a^2$ than the CMB $T_\gamma \propto 1/a$ (**Q1**). So, the gas is colder than CMB! The spin temperature follows the gas temperature down to $z \sim 80$ due to efficient collisions, and it would appear as absorption in δT_b. At lower redshift, however, the collision becomes inefficient, and the spin temperature decouples from the gas, again following the CMB temperature up to around $z \sim 30$ (hence no signal in δT_b at all). Up to this point, the calculations are well understood and simple.

However, below $z \sim 30$, the first objects start to form, emitting X-rays and Lyα photons, which in turn couple the spin temperature with the gas temperature, so it would again appear as absorption in δT_b. This procedure at the same time heats up the gas, and eventually by the time the Universe reionizes around $z \simeq 10 - 6$, the gas is hotter than the CMB, and it would appear as emission in δT_b. Apparently, this part of the history is full of uncertainties. However, what we need to explain the observations is the gas with colder temperature. The only way we can do is simply to let the gas cool and not heat up, i.e., no first objects form or they form, but do not heat up the gas somehow (**Q2**). In this case, the gas can cool down to $T_g \sim 7$ K at $z = 17$, resulting in the maximum possible absorption signal $\delta T_b = -200$ mK (**Q3**).

Certainly, any scenarios in the standard model cannot explain the observation, hence the alternatives are proposed. The only component in the Universe that is colder than the gas is dark matter. By invoking some interaction between dark matter and gas, we can transfer somehow some energy of the gas into dark matter, thereby cooling the gas further below expected in the standard model (**Q4**).

Remember this is the first observation at $z > 10$, except CMB. This high-redshifted 21cm radiation is significantly overwhelmed by the Galactic synchrotron radiation. So, what is your conclusion?

- ***Question 1.***— Why $z = 150$, not $z = 1050$? and why $T_g \propto 1/a^2$?

- ***Question 2.***— If the first objects do not heat up the gas by emitting radiations, what would happen to the spin temperature?

- ***Question 3.***— Compute by yourself the gas temperature $T_g \sim 7$ K at $z = 17$ in this scenario. What gas temperature is needed to explain the observation? Can we get it with other (standard) means? What possibilities are there?

- ***Question 4.***— Why is dark matter colder to begin with? What are the consequences if dark matter starts to interact with ordinary matter?