Ex 1

28 April 2020 13:45

ZAH - Astronomisches Rechen-Institut
Galactic and Extragalactic Astronomy (MVAstro3) - Summer semester 2020
Hitesh Lala `Hitesh.Lala@uni-heidelberg.de`

Exercise Sheet #1

Submit by Tuesday 05-05-2020

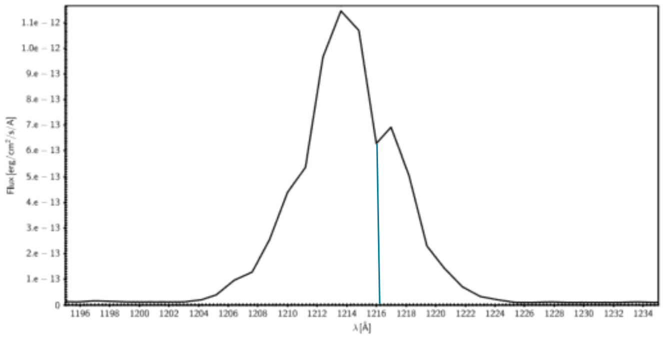

Figure 1: Integrated spectrum of Andromeda in the range 1195 – 1235 Å taken from the NASA/IPAC Extragalactic Database (Kinney et al. 1993, `https://ned.ipac.caltech.edu/`)

Exercise 1. According to the Hubble law $v = H_0 D$, the expansion of the Universe causes distant objects to move away from our rest-frame faster than objects in the vicinity of our Local Group of galaxies. The Fig. 1 displays the UV part of Andromeda's spectrum, where the most prominent emission line represents the Lyman-α transition.

(a) Determine the redshift of the Andromeda galaxy and its radial velocity with respect to an observer on Earth. (10 points)

(b) Andromeda lies roughly at a distance of 780 kpc from the Milky Way. Derive its expected radial velocity using the Hubble law and assuming a Hubble constant $H_0 = 71$ km/s/Mpc. Are expectations and measurements consistent with one another? Comment, briefly, on your results. (10 points)

(c) Let's now assume that we observe the spectrum of a distant galaxy which shows a redshift of $z = 0.05$. Calculate its radial velocity and distance from the Milky Way. (10 points)

Exercise 2. During the first seconds of the Universe the conditions for the existence of baryonic matter, and thus life, were set. As the temperature, and thus the energy of the photons ($E \sim k_b T$), dropped with the expansion of the Universe ($(T/K) \sim 1.5 \cdot 10^{10} \cdot (t/s)^{-1/2}$ * during the radiation dominated era), reactions needing a high amount of energy could no longer take place.

* This is a convention followed by many astrophysics texts. (T/K) stands for Temperature in kelvins; similarly, (t/s) stands for Time in seconds.

(a) Consider the electron-positron pair production $\gamma + \gamma \rightarrow e^- + e^+$. At which temperature will this reaction freeze out and why?, thus leading to the progressive annihilation of the e^- and e^+. (10 points)

After the matter anti-matter annihilation, at $t \sim 1$ s the baryons left in the Universe started reacting to form heavier nuclei.

(b) What is the ratio between photons and baryons at this time? Calculate the temperature and energy of the photons. (HINT: Lecture-1) (10 points)

(c) Deuterons were the first isotopes to be produced through the very efficient reaction $p + n \rightleftharpoons D + \gamma$. Calculate which energy is needed to photo-disintegrate deuteron. What is the frequency of these photons capable of disintegrating the deuterons? How can you explain that deuterons are present in such small amount in the Universe? (10 points)

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Solution

Exercise 1.

a) The Lyman alpha emission line is $\lambda = 1215.67\ A°$
The observed line in power spectrum is at $\lambda \approx 1216.25\ A°$
The redshift is defined as $z = \frac{\lambda_{obs}}{\lambda_{rest}} - 1 \approx \frac{1216.25}{1215.67} - 1 \approx 4.77 \cdot 10^{-4}$
The radial velocity of the Andromeda galaxy is then $v = c \cdot z \approx 143\frac{km}{s} \approx 143\frac{pc}{Myr}$

b) The expected radial velocity is $v = H_0 D \approx 71\frac{km}{s \cdot Mpc} \cdot 780\ kpc \approx 55.38\frac{km}{s}$
The expectation and the measurements are not consistent. The reasons could be that the orbital velocity of the Earth around the Sun, that of the Sun around galactic centre, as well as the rotation of the Andromeda galaxy are also taken into account in the measured value.

c) The radial velocity of the galaxy is $v = cz \approx 3 \cdot 10^8 \cdot 0.05 = 15000\frac{km}{s}$
The distance from the Milky Way is $D = \frac{v}{H_0} \approx 211\ Mpc$

Exercise 2.

a) The energy of electron and positron is $E_e = m_e c^2 \approx 0.511\ MeV$
The temperature corresponding to the energy is $T = \frac{E_e}{k_B} \approx \frac{0.511\ MeV}{8.62 \cdot 10^{-5}\frac{eV}{K}} \approx 5.93 \cdot 10^9$ K
Below this critical temperature the energy of photons is then too low to produce electron and positron.

b) The ratio between photons and baryons at $t \sim 1s$ is $\sim 10^9$
The temperature of the photons is $\sim 1.5 \cdot 10^{10} \cdot 1^{-\frac{1}{2}} = 1.5 \cdot 10^{10} K$
The energy of the photons is $E \sim k_B T = 8.62 \cdot 10^{-5}\frac{eV}{K} \cdot 1.5 \cdot 10^{10} K = 1.293\ MeV$

c) The binding energy of a deuteron is ~ 2.2 MeV. Thus this is the least energy needed for photo-disintegration.
The frequency of needed photons $\nu = \frac{E}{h} \approx \frac{2.2 MeV}{4.14 \cdot 10^{-15} eV \cdot s} \approx 5.3 \cdot 10^{20} Hz$
Deuterons are present in such small amount in the Universe is because: in the early stage the binding energy of deuteron is so small that it can be easily break down to positron and neutron. Later when the photon energy is not large enough for photo-disintegration, more protons and neutrons can bind to deuteron to synthesis more stable element with higher nucleon number.

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4. Upload your scanned solutions as PDF to this repository on every Tuesday by 14:00 pm (or any other time that we finalize)

5. The PDF filename should be in the format YourName_Week_Number.pdf (For example: JohnDoe_Week_01.pdf)

6. If you are stuck, plenty of GitHub tutorials are available online. Please contact me if none of them solve your problem.