Astrophysics V   Observational Cosmology

Sheet 1: Assignments

Prof. Jean-Paul Kneib

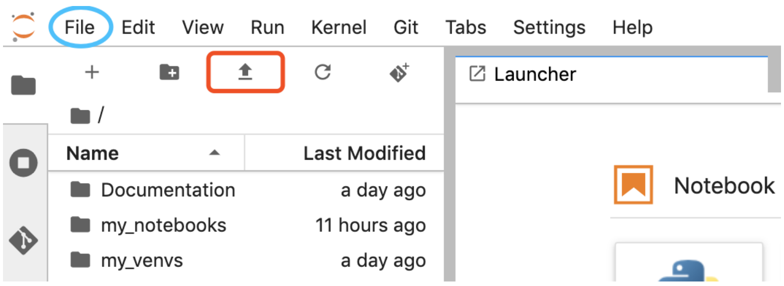
Teaching assistants: Dr. Rafaela Gsponer, Dr. Antoine Rocher,
Mathilde Guitton, Shengyu He, Ashutosh Mishra & Aurélien Verdier

Laboratoire d'astrophysique   http://lastro.epfl.ch
Ecole Polytechnique Fédérale de Lausanne, Spring Semester 2025

Exercise 1 : Setup of the Astro-V Jupyter environment

We shall make use of the `NOTO` JupyterLab Server [1] for the hands-on `Python` coding exercises. The steps for setting up the Jupyter environment for this course are listed as below :

1. Download the bash script file "`setup_astro-v.sh`" from the moodle page of the course [2] (shown as "Jupyter setup script" in the section of today's course).
2. Log in to the `NOTO` server using your EPFL gaspar account.
3. Click the (“`Upload Files`”) button on the top of the left sidebar (indicated by the red box in the screenshot below), and select the local script file "`setup_astro-v.sh`" to upload it to the `NOTO` server.



A screenshot of the `NOTO` Jupyter interface.

4. Open a terminal window on the Jupyter server by clicking the "`File`" menu (see the cyan oval in the screenshot above) and selecting "`New`" > "`Terminal`".

1. https://noto.epfl.ch
2. https://moodle.epfl.ch/course/view.php?id=14922

5. In the terminal window, type in the command "`bash setup_astro-v.sh`" and press the Enter key.

Once the script finishes (in roughly half an hour), a new Jupyter kernel "`Astro-V`" is installed. However, you need to refresh your browser's page to use this kernel.

To get started with a `Python` notebook, click the "`File`" menu and select "`New`" > "`Notebook`", and then choose the "`Astro-V`" kernel. Note that the name of the kernel is shown on the top right corner of the notebook page, and by clicking the name one can change the kernel for this notebook. In the text box, type in the following codes :

```
In []: import matplotlib.pyplot as plt
       %matplotlib inline
       import numpy as np

       name = ['Observable Universe', 'Milky Way', 'Sun', \
               'Earth', 'Khufu Pyramid', 'Human', 'Mosquito', \
               'Bacterium', 'Hydrogen Atom']
       size = [1e27, 2e21, 1e9, 1e7, 1e2, 1, 1e-3, 1e-6, 1e-15]
       mass = [6e52, 1e42, 2e30, 6e24, 6e9, 70, 2e-6, 1e-15, 2e-27]

       plt.plot(size, mass, 'or')
       for nm, sz, ms in zip(name, size, mass):
           plt.annotate(nm, (sz, ms), ha='center', va='bottom')

       plt.xlabel('Size [m]')
       plt.ylabel('Mass [kg]')
       plt.xscale('log')
       plt.yscale('log')
```

To run the codes, press the ▶ button on the top panel of the notebook page, or the "`Shift`" + "`Enter`" keys. Then, plot the mass-size relation for matter with the water density.

Exercise 2 : The Hubble law

In 1929, Edwin Hubble published the first observational evidence that the Universe was expanding [3]. In this paper, Hubble reported the distance and radial velocity for 24 galaxies (see the table below), and found that galaxies which are further have a higher velocity.

3. https://ui.adsabs.harvard.edu/abs/1929PNAS...15..168H/abstract

Galaxy	SMC	LMC	6822	598	221	224	5357	4736
V (km/s)	170	290	-130	-70	-185	-220	200	290
D (Mpc)	0.032	0.034	0.214	0.263	0.275	0.275	0.45	0.5
Galaxy	5194	4449	4214	3031	3627	4826	5236	1068
V (km/s)	270	200	300	-30	650	150	500	920
D (Mpc)	0.5	0.63	0.8	0.9	0.9	0.9	0.9	1.0
Galaxy	1055	7331	4258	4151	4382	4472	4486	4649
V (km/s)	450	500	500	960	500	850	800	1090
D (Mpc)	1.1	1.1	1.4	1.7	2.0	2.0	2.0	2.0

The radial velocities were estimated thanks to redshift z, assuming $V = cz$. And the distances were estimated with Cepheids (variable stars).

a) Some radial velocities are negative : is this expected ? What does it mean ?

b) With the measured values reported in the table, estimate a linear least-square fit between the velocity V and the distance D : $V = H_0 \times D$, using the `optimize.leastsq` function of the `scipy` package [4].

c) What is the unit of H_0 ? Interpret it when expressed in $\mathrm{km\,s^{-1}\,Mpc^{-1}}$.

d) Interpret H_0 when expressed in $\mathrm{Gyr^{-1}}$; e.g., imagine that two galaxies are currently separated by a distance D, with a (positive) velocity V : assuming that their velocity has been constant, how long ago were they in contact ?

e) Hubble significantly overestimated H_0, because his distances were significantly underestimated. Since the 1960s, it was known that H_0 is of the order of 50-100 $\mathrm{km\,s^{-1}\,Mpc^{-1}}$. The following table shows the velocities and distances measured with the *Hubble Space Telescope* (Freedman et al. 2001 [5]). For simplicity, we neglect the error of distance measurements. Re-estimate H_0 from this table, and re-compute the previous answer with this more accurate value.

4. https://docs.scipy.org/doc/scipy/reference/generated/scipy.optimize.leastsq.html
5. https://ui.adsabs.harvard.edu/abs/2001ApJ...553...47F/abstract

Galaxy	0300	0925	1326A	1365	1425	2403	2541	2090
V (km/s)	133	664	1794	1594	1473	278	714	882
ΔV (km/s)	273	290	630	437	8	85	222	44
D (Mpc)	2.00	9.16	16.14	17.95	21.88	3.22	11.22	11.75
Galaxy	3031	3198	3351	3368	3621	4321	4414	4496A
V (km/s)	80	772	642	768	609	1433	619	1424
ΔV (km/s)	166	76	533	470	411	3	596	43
D (Mpc)	3.63	13.80	10.00	10.52	6.64	15.21	17.70	14.86
Galaxy	4548	4535	4536	4639	4725	4182	5253	7331
V (km/s)	1384	1444	1423	1403	1103	318	232	999
ΔV (km/s)	37	34	25	45	122	318	568	179
D (Mpc)	16.22	15.78	14.93	21.98	12.36	4.49	3.15	14.72

Exercise 3 : Parsec

a) What is a stellar parallax? Explain with a diagram.

b) What does 'parsec' stand for?

c) What is a parsec in units of AU?

d) Taking into account that $1AU = 1.495978707 \times 10^{11}$m, how many meters are in a parsec?

e) How many light-years does 1 parsec correspond to?

Exercise 4 : Introduction to redshift

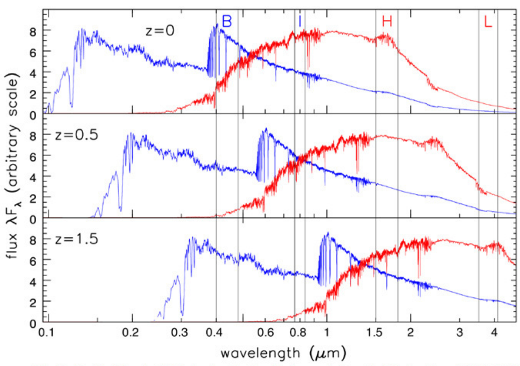


Fig 8.12 (S. Charlot) 'Galaxies in the Universe' Sparke/Gallagher CUP 2007

The optical galaxy spectrum, i.e. the light emitted from its stars, displays some emission and absorption lines at precise, known wavelengths. However, the observed spectra are *shifted* either towards shorter wavelengths (*blueshift*, rarely) or towards longer wavelengths (*redshift*, often).

The *redshift* is observationally defined as : $z = (\lambda_{\text{observed}} - \lambda_{\text{emitted}})/\lambda_{\text{emitted}}$.

Vesto Slipher in 1912 was the first to measure a redshift, actually a blueshift : he found for the Andromeda/M31 galaxy $z = -0.001$.

Assuming this shift is due to non-relativistic Doppler effect (as we are at very low redshift), estimate the measured radial velocity of M31.

Note that in general, the redshift is due to a cosmological effect, not the Doppler effect.