Hubbles Law

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- Jupyter Notebooks by Rasmus Groth (https://github.com/bliiir)
- Inspiration from zonination (https://www.reddit.com/r/dataisbeautiful/comments/5st2qn/i_got_a_dataset_of_4240_galaxies_and_calculated/)
- Mentoring by Peter Lauersen (https://www.dark-cosmology.dk/~pela/index.html)

In the following we will use Python and data from Leda (http://leda.univ-lyon1.fr/leda/fullsql.html), the database of physics of galaxies, to verify Hubbles law (https://en.wikipedia.org/wiki/Hubble%27s_law):

$$v = H_0 \times d$$

Symbol	Description	Units	
v	Velocity	Km/s	Kilometer per second
H	Hubbles constant	Km/s/Mpc	Kilometer per second per Megaparsec
d	Distance	Mpc	Megaparsec

In other words, there is a linear relationship between the distance of a galaxy and it's speed relating to us - or that it follows the structure of a normal linear equation:

$$y = a \times b + c$$

Import Python packages

```
In [1]: import pandas as pd

        import numpy as np
        from numpy import log10,sqrt

        import matplotlib.pyplot as plt

        from astropy import units as u
        from astropy.cosmology import Planck15
        import astropy.constants as cc

        from scipy.optimize import curve_fit
```

Aquire the data

Query

The following query was passed to the [leda database interface (http://leda.univ-lyon1.fr/leda/fullsql.html)](http://leda.univ-lyon1.fr/leda/fullsql.html):

```
SELECT objname, v3k, mod0 WHERE (objtype='G') AND (v3k>3000) AND (v3k<30000) AND (m
od0 IS NOT NULL) AND (v3k IS NOT NULL)
```

Symbol	Type	Units	Description
mod0	float	mag	Distance modulus from distance measurements
v3k	float	km/s	Radial velocity (cz) with respect to the CMB radiation

We are elliminating objects that are not galaxies, (objtype='G'), objects with very low velocities (v3k>3000) because their local velocities and rotations skew the results, objects with very high velocities (v3k<30000) because the light we are getting from them only reflects their velocities in the early universe when the accelleration was significantly different.

The results were saved in a text file called, `leda.txt` locally and then loaded into a pandas dataframe in Python

```
In [2]: # Load Leda data
        df = pd.read_csv('leda.txt')
```

Tidy the data

In [3]:
```
# Remove empty column at the end
df = df.iloc[:,0:3]

# Remove rows with missing values
df = df.dropna()

# Remove whitespace from the headers
df = df.rename(columns=lambda x: x.strip())

# Rename the objname column to galaxy
df = df.rename(columns={'objname':'galaxy'})

# Display a sample of the dataframe
df.head()
```

Out[3]:

	galaxy	v3k	mod0
0	2MASXJ00024910+0045055	25649	37.28
1	2MASXJ01415126-0052365	27737	37.43
2	2MASXJ01270614+1906587	12621	36.10
3	2MASXJ01454460-5605518	26258	37.83
4	2MASXJ03372260-3302350	11603	35.73

Luminosity Based Distance, d_l

Convert the magnitude (`mod0`) to [Luminosity-distance (https://en.wikipedia.org/wiki/Luminosity_distance)](https://en.wikipedia.org/wiki/Luminosity_distance) d_l in parsec:

$$d_l = 10^{\frac{m-M+5}{5}}$$

Where $mod0 = m - M$

In [4]:
```
df['dl_mpc'] = 10**((df['mod0']+5)/5) / 1000000
df.head()
```

Out[4]:

	galaxy	v3k	mod0	dl_mpc
0	2MASXJ00024910+0045055	25649	37.28	285.759054
1	2MASXJ01415126-0052365	27737	37.43	306.196343
2	2MASXJ01270614+1906587	12621	36.10	165.958691
3	2MASXJ01454460-5605518	26258	37.83	368.128974
4	2MASXJ03372260-3302350	11603	35.73	139.958732

Physical Distance, d

The luminosity distance does not account for redshift and time dilation caused by differences in velocity and gravitational effects as the photons travel from the source to us.

To get the proper distance, we first need the redshift factor, z, which we get by dividing the velocity with the speed of light (cc.c):

In [5]:
```
df['z'] = df['v3k'] / cc.c
```

And then we divide the luminosity distance, d_l, with the redshift factor $1 + z$:

In [6]:
```
# Calculate the proper redshift etc kompensated distance in parsec
df['d_mpc'] = df['dl_mpc'] / (1+df['z'])
```

In [7]:
```
df.head()
```

Out[7]:

	galaxy	v3k	mod0	dl_mpc	z	d_mpc
0	2MASXJ00024910+0045055	25649	37.28	285.759054	0.000086	285.734608
1	2MASXJ01415126-0052365	27737	37.43	306.196343	0.000093	306.168016
2	2MASXJ01270614+1906587	12621	36.10	165.958691	0.000042	165.951704
3	2MASXJ01454460-5605518	26258	37.83	368.128974	0.000088	368.096733
4	2MASXJ03372260-3302350	11603	35.73	139.958732	0.000039	139.953316

Export tidy dataset

In [8]:
```
# Save to file
df.to_csv('galaxies.csv')
```

Best linear fit

In [9]:
```
def lin(x, a):
    return a * x

coeff, cov= curve_fit(lin, df['d_mpc'], df['v3k'])

# The slope of the best linear fit
a = coeff[0]
a
```

Out[9]: 66.59753735677145

Age of the Universe

Seconds

In [10]:
```
# Convert a from mpc based to km based
a_km = a / 1000000 / 30856775814913.67
age_sec = (1/a_km)
age_sec = age_sec
age_sec
```

Out[10]: 4.6333208463264954e+17

Years

In [11]:
```
# Age of the universe in years
age_year = age_sec / (60*60*24*365)
"{:,}".format(int(age_year))
```

Out[11]: '14,692,164,023'

Tolerance

Co-variance

In [12]:
```
cov[0][0]
```

Out[12]: 0.20239139101111292

R^2

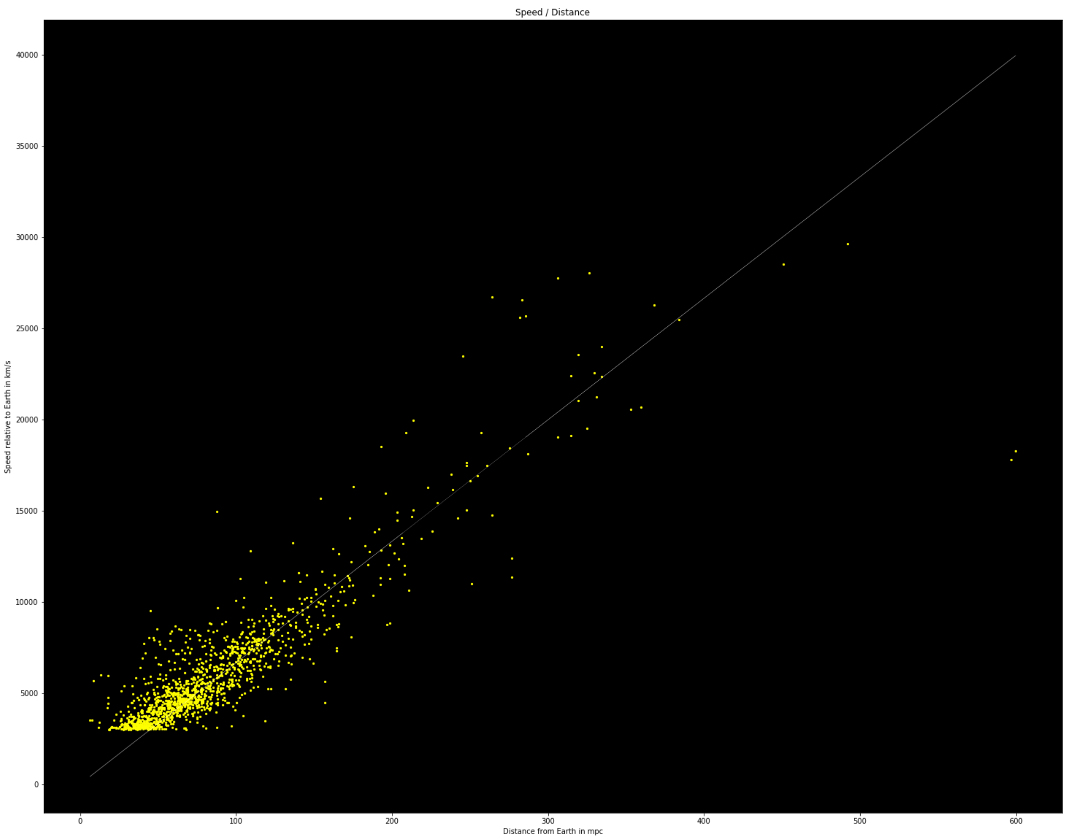
In [13]:
```
# Residual sum of squares (ss_tot)
residuals = df['v3k'] - lin(df['d_mpc'], coeff)
ss_res = np.sum(residuals**2)

# Total sum of squares (ss_tot)
ss_tot = np.sum((df['v3k']-np.mean(df['v3k']))**2)

# R squared
r_squared = 1 - (ss_res / ss_tot)
r_squared
```

Out[13]: 0.7590999713188041

Plot

In [14]:
```
# Store the distance in mpc in an array
x = df['d_mpc'].values

# Store the velocity in km/s in an array
y = df['v3k'].values # v3k
```

In [15]:
```
# Least Square Best Fit line
f = lambda x: a * x

# Initialize plot and subplot
fig2 = plt.figure(figsize=(25,20))
g2 = fig2.add_subplot(1, 1, 1)

# Set background color to black
g2.set_facecolor((0, 0, 0))

# Plot dataset
g2.scatter(df['d_mpc'], df['v3k'], c='yellow', s=5)

# Plot best fit line
g2.plot(x,f(x), c="white", label="fit line", linewidth=0.2)

# Add labels
g2.set_title('Speed / Distance')
g2.set_xlabel('Distance from Earth in mpc')
g2.set_ylabel('Speed relative to Earth in km/s')

# Show plot
plt.show()
```



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