Computing Project for CTA200H
Project: Charting the growth of galaxies
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The goal of this computing project is to visualize the molecular carbon monoxide (CO) emission of a distant galaxy. The observations were made with the [Atacama Large Millimeter Array (ALMA)] Band 3. You will learn how to make measurements from an ALMA datacube with Python. The following steps will guide you through this process. You will develop some scripts that will be useful for your project in the following weeks.

Useful softwares

CARTA, astropy.cosmology, astropy.units, numpy, matplotlib, spectral-cube or CASA

Abbreviations

- CO32: ^{12}CO J=3→2
- CW13: Carilli & Walter 2013
- M14: MacKenzie et al. 2014

1. Preparations

a. Install the softwares.
b. Download the ALMA data from the shared folder on OneDrive. For this assignment you will only need the file MS0451-03.line.spw25.100kms.image.fits.

2. Spectrum extraction

a. Open the fits file with CARTA.
b. Extract the spectra of the three multiple images of galaxy 2 (Gal ID 2.a, 2.b and 2.c as defined in M14). You can do that by creating a region (e.g., 1" circle) centered on the source positions, then opening the spectral profiler. Choose FluxDensity Statistic in the spectral profiler.
c. Export the spectra as ascii files by clicking on the Export Data button in the Spectral Profiler. From here on you will treat the three multiple images as separate measurements.

3. Spectral fitting

a. In this exercise you will measure useful quantities from the extracted spectra.
b. Use python to plot the three spectra as histograms, i.e., intensity (Jy/beam) vs observed frequency (GHz). Describe what you see.
c. Fit a 1D Gaussian to the emission line and overplot the best-fit model in the figure. What are the peak observed frequencies and line widths?
d. The observations targeted the ^{12}CO J=3→2 transition of the lensed protocluster. Calculate the spectroscopic redshift of galaxy 2. (Hint: use Table 1 of CW13 or the splatalogue database to determine the rest-frame frequency of this transition. The

relation between redshift, observed and rest-frame frequencies are provided on this page.)

e. Convert the x-axis from observed frequency to velocity with respect to the spectroscopic redshift. Use velocity (in km s^{-1}) as the bottom x-axis, and the observed frequency as the top x-axis. (Hint: Use the radio velocity definition as described on the NRAO website.)
f. For any image without an obvious line detection, estimate the 1σ upper limit by measuring the root-mean-square error of the intensity of the spectrum.
g. Explain your calculation and report the Gaussian fit parameters and derived redshifts in a table.

4. Measuring line luminosity

a. Calculate the line flux $S_{CO32}dv$, in units of Jy km s^{-1}, by integrating the area under the best-fitting Gaussian function.
b. Calculate luminosity distance D_L in Mpc, assuming a flat Lambda Cold Dark Matter Cosmology with H_0 = 70 km s^{-1} Mpc^{-1}, Ω_Λ = 0.7, and Ω_M=0.3. (Hint: Use the astropy.cosmology package)
c. Calculate the CO32 line luminosity L'_{CO32} in units of K km s^{-1} pc^2, using the second last equation on Page 112 of CW13.
d. Explain your calculation and report the computed values in a table.

5. Measuring gas mass

a. CO is a tracer for the overall molecular gas mass (made up of mostly hydrogen) of galaxies. In order to convert an excited CO transition into molecular gas mass, two assumptions need to be made. Firstly, the brighter, excited CO transition will be used to estimate the ground-stated CO J=1$\rightarrow$0 luminosity, using a CO spectral line energy distribution. Then a CO abundance relative to the total molecular gas mass is assumed. The conversion factors vary with the gas conditions of galaxies (Narayanan et al. 2014). For simplicity you will assume that the gas conditions in galaxy 2 resemble those of the Milky Way. Proceed with each multiple image for which an emission line has been detected.
b. Calculate the expected line luminosity for the ground-state transition L'_{CO10}. You can assume that the CO spectral line energy distribution follows that of the Milky Way, using the values reported on Table 2 of CW13.
c. Calculate the apparent cold gas mass, assuming that the CO to molecular gas mass ratio follows that of the Milky Way, α_{CO} = 4.6 $M_\odot$(K km s^{-1} $pc^2)^{-1}$. Refer to Section 4.2 of CW13 for a detailed discussion.
d. The galaxies have been lensed by the foreground galaxy cluster at z=0.55. Their flux amplification factors are listed in Table 1 of M14. Use them to calculate the intrinsic (de-lensed) molecular gas mass of each multiple image. Are the values consistent with each other across the multiple images?
e. Explain your calculation and report the computed values in a table.

6. **Wrapping up**
   a. Create a figure similar to Figure 2 of Oteo et al. 2018. The central image should be an RGB composite image showing the lens system with HST observations with the F814W, F110W and F160W filters. Indicate the extraction apertures on the figure. Include the extracted spectra as subpanels. Explain the figure in the caption.
   b. Report your measurements in a table.
   c. Comment on sources of uncertainties in estimating cold gas mass (Hint: Consider the uncertainties in your measurements as well as systematic uncertainties).
   d. Compute the star formation efficiency, SFE = SFR/Mgas, using the star formation rate provided in Table 2 of M14.

7. **Bonus exercises**
   a. These exercises are not required for the assignment, but you can complete them as time allows.
   b. Visualizing data cubes
      i. When you step through the velocity channels with CARTA, you will find that the CO emission peak of galaxy 2 shifts in position. This suggests that the gas is rotating. You can better visualize this by creating moment maps. Of particular interests are the moment-zero map (integrated intensity), moment-one map (velocity fields), and moment-two map (velocity dispersion).
      ii. You can use spectral-cube or CASA/immoments for this task.
      iii. Plot moment maps for galaxy 2. You may want to mask noisy pixels and adjust the color scale for a more informative representation.
      iv. Plot the position-velocity diagram along the major axis of the CO emission.
   c. Making use of the full ALMA observation
      i. ALMA observations are always done with four spectral windows spanning adjacent frequency ranges. In your computing exercise you have only used one of those four. Extend the frequency range of the spectra by making use of other spectral windows (spw). You can make use of the other fits file with filenames containing spw21, spw23, and spw27.
      ii. Automate the extraction procedure using spectral-cube or CASA/imstat .
      iii. Plot the spectra.
      iv. Extract the spectra for all the known protocluster members listed in Table 1 of M14.
      v. Measure the gas masses of the protocluster members.
   d. Placing your results in context
      i. Most molecular gas mass surveys of distant galaxies focus on lower redshift than the MS0451 protocluster of this analysis. As a reference, you can compare with the PHIBBS CO32 survey of galaxies at z=1-3. Download Table 2 of Tacconi et al. 2013.
      ii. Plot the gas mass against star formation rate for your sample and the PHIBBS survey.
      iii. Describe what you see.