Analysis of APEX CO(2-1) emission line observation of a nearby galaxy

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We study the molecular line transition CO(2-1) of IRAS 13120-5453 with data obtained from APEX observations. By performing a Gaussian curve fit to the data, we are able to study the physical properties and kinematics of the emitting gas. We found CO(2-1) to be optically thick and distributed on regular rotating disks. From the Gaussian, we estimated the total molecular mass to be 1.72 $\cdot 10^{10} \pm 4.06 \cdot 10^{9} [M_{\odot}]$.

I. INTRODUCTION

Emission lines from a galaxy are indicative of star formation. They also provide information about the physical properties such as optical depth, τ_ν, and the kinematics of the emitting or absorbing gas [1]. Hydrogen H_2 is the most abundant element in the universe, but in higher volume densities of the gas from which stars form, it is extremely hard to observe. Minimum gas temperature of T $\sim$ 150K is required for appreciable excitation via collisions, making H_2 a bad tracer for itself which is mostly cold at $T = 10 - 20K$. The most common proxy for cold H_2 is Carbon monoxide CO, the second most abundant molecule in the interstellar medium after H_2 [1]. We detect emission lines from CO when photons escape from de-exciting CO molecules, as a result of collision between CO molecules and H_2 prior [1]. In our case, we will be studying the CO(2-1) emission line of a nearby ultra-luminous infrared galaxy (ULIRG), IRAS 13120-5453. We will be studying the physical properties mentioned above, but also estimating the total molecular gas mass.

II. THEORY

A. Single-dish

The primary mirror is the first optical element of a telescope, encountered by light. The telescope's primary mirror is called a dish or antenna in radio/(sub-) mm bands (bands meaning frequency observation windows). Radio/(sub-)mm telescopes are either made with 1) A single dish meaning one single antenna connected to one or several receivers 2) $N \geq 2$ antennas working as an interferometer. The second option provides a larger collecting area and better spatial resolution. However, single dishes are optimal for studying very extended, low surface brightness structures and for surveys of large areas of the sky [1].

Examples of radio and sub-millimeter single-dish facilities are APEX and LMT. Atacama Pathfinder Experiment, APEX, operates at millimeter and submillimetre wavelengths - between infrared light and radio waves. It is placed at an elevation of 5100 meters in Chile's Atacama region [7]. The Large Millimeter Telescope is situated in Volcán Sierra Negra at an altitude of 4600 meters and is specifically designed to observe in the wavelength range of 0.85 - 4 mm [3].

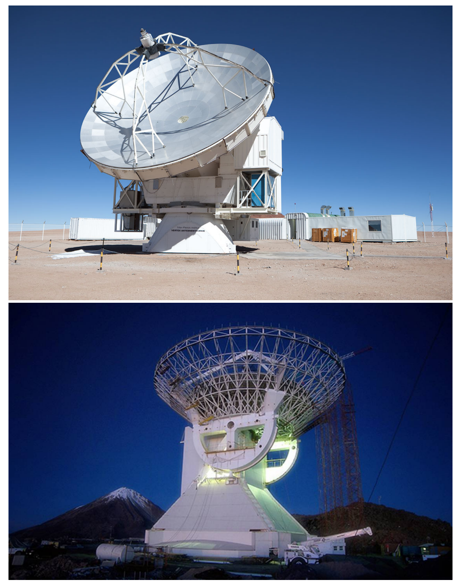

Figure 1. APEX depicted in the image on top [4] and LMT depicted on the bottom [5].

B. Antenna temperature

The actual output of the single-dish observations is the antenna temperature. It is equal to the brightness temperature of the source convolved with the normalized beam pattern of the antenna [1]. However, flux density F_ν is more commonly used to measure the emission from astronomical sources. Conversion between these quantities can be done with the equation below:

$$T_A^* \equiv \Gamma F_\nu \Rightarrow F_\nu = \Gamma^{-1} T_A^*. \tag{1}$$

The inverse factor for the APEX telescope is

$$\Gamma^{-1} = \frac{24.4152}{\eta_A} [\text{ Jy K}^{-1}] \tag{2}$$

where T_A^* is the antenna temperature corrected for atmospheric losses, F_ν is flux density, and η_A is aperture efficiency (which depends on the antenna used for observation and varies with observation frequencies).

C. Line luminosity

Line luminosity is calculated from the total line flux $\int_{\Delta\nu} S_\nu d\nu$ of our data

$$L'_{CO}[\text{K km s}^{-1}\text{pc}^2] = (3.25 \cdot 10^7)\frac{D_L^2}{\nu_{obs^2}(1+z)^3}\int_{\Delta\nu} S_\nu d\nu \tag{3}$$

where D_L is the luminosity distance of the galaxy in [Mpc], z is the redshift of the galaxy, and ν_{obs} is the observed frequency related to rest frequency by the (optical) Doppler formula

$$\nu_{obs} = \frac{\nu_{rest}}{(1+z)}[1]. \tag{4}$$

D. Total molecular mas

$$M_{H_2+He}[M_\odot] = \alpha_{CO} L'_{CO} \tag{5}$$

where $\alpha_{CO} \sim 1.7 \pm 0.4 M_\odot(\text{K km s}^{-1}\text{pc}^2)^{-1}$ is the ULIRG-type CO-to-H_2 conversion factor [6]. This factor has been empirically proved to work and usually inlcudes a correction for Helium and heavy elements, so it gives the total gas mass in the molecular medium [1].

III. METHOD

The data obtained from APEX consist of observations from different sources, among other things, the observation of the molecular line transition CO(2-1) of the galaxy IRAS 13120-5453, a nearby ultraluminous infrared galaxy (ULIRG). The data was reduced to only CO(2-1) line transition in CLASS, Gildas. The redshift of this galaxy is $z = 0.0308$, which corresponds to a luminosity distance of $D_L = 139.4 Mpc$ (using $H_0 = 67.8 km/s$, $\Omega_M = 0.307$, $\Omega_\Lambda = 0.693$ and $k = 0$, i.e. flat geometry) [6].

A. Aperture efficiency

Our observations are in the frequency range of ~ 230 GHz, where the $\eta_A = 0.64 \pm 0.05$ (using NFLASH203 receiver, 2022)[7]. This gives us the following conversion factor from antenna temperature to flux density

$$\Gamma^{-1} = 36 \pm 3 \text{ Jy/K } [7] \tag{6}$$

B. Curve fit by Gaussian profile

Our goal is to analyze the CO(2-1) emission line. As emission lines closely resemble a Gaussian curve, it is, therefore, an interest to curve fit a Gaussian profile to the emission line.

$$g(x, \mathbf{P}) = ae^{-\frac{(x-b)^2}{2c^2}} + d;\ \mathbf{P} = (a, b, c, d) \tag{7}$$

The fitting aims to optimize the parameters in P based on the data. The parameters are as follows

a: the amplitude of the Gaussian. The difference in the minimum value of your spectral line and the minimum.

b: the mean of the Gaussian. The position of the peak on the x-axis.

c: width of the Gaussian.

d. y-value of the baseline. The maximum value of the spectrum

This is done numerically using `spicy.optimize_curve`. The following arguments are inserted into the function: eq. 7, doppler velocities (values on the x-axis), flux densities (values on the y-axis), and estimated parameters (a, b, c, d).

C. Full-Width Half Maximum

$$\text{FWHM} = 2\sqrt{2\ln 2}\sigma \tag{8}$$

The width of the Gaussian σ (parameter c) obtained from the curve fit can be used to calculate the FWHM of the Gaussian i.e. the width of the curve. We use eq. 8 to do so.

D. S/N noise ratio

The S/N ratio is usually defined as the maximum flux density divided by the RMS noise of the data [1],

$$\frac{S}{N} = \frac{peak}{RMS} \tag{9}$$

where the peak is the parameter a of the Gaussian and RMS is the square root of the average of squared errors [8]. The following method can calculate the RMS: `sklearn.metrics.mean_squared_error(data, Gaussian)`. A S/N ratio higher than 1:1 indicates more signal than noise (greater than 0dB) [9]. Therefore, in observational astronomy, we always aim to maximize the S/N ratio.

E. Total line flux

In order to determine the total line flux $\int_{\Delta\nu} S_\nu d\nu$, we need to integrate the Gaussian using `scipy.integrate`. We choose integration limits from $-\infty$ to ∞. It is equivalent to only integrating where the peak is. There is only a contribution from the emission line and not from the flat part of the curve.

IV. RESULTS

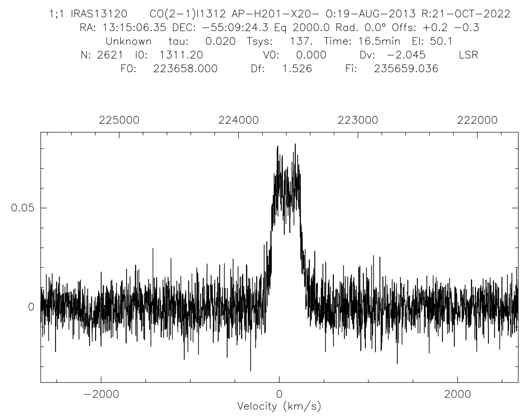

Figure 2. Reduced data in CLASS, GILDAS to only include the CO(2-1) emission line of the galaxy IRAS 13120-5453. On the x-axis, we have doppler velocities [km/s] and on the y-axis, we have antenna temperature [K].

From fig. 2 we have our reduced data in CLASS which includes only the CO(2-1) emission line. From the plot, we obtain the rest frequency $f_0 = 223658$ GHz and binned channel width of $\Delta v = 2.045$ km/s.

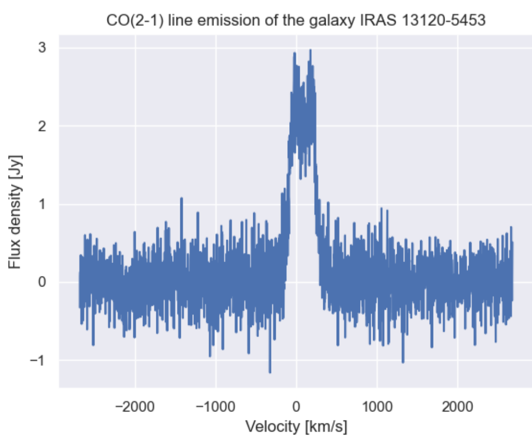

Figure 3. CO(2-1) line emission of IRAS 13120-5453 with doppler velocities [km/s] on the x-axis and flux density [Jy/K] on the y-axis.

Figure 3 is a plot of the same data as in fig. 2, but with antenna temperature [K] on the y-axis converted to flux density [Jy].

Figure 4 shows the Gaussian fitting of the data, in which we were able to retrieve the values given in table I.

The RMS of this spectrum is 0.309K. The S/N ratio of our data is therefore 7.92 ± 0.11.

Figure 5 shows the FWHM and S_ν^{peak} marked on the Gaussian and the value.

From fig. 6 shows the area under the curved filled-in

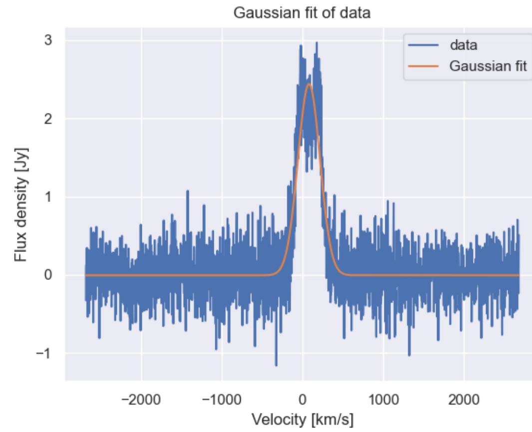

Figure 4. Gaussian fit of the CO(2-1) emission line

Table I. Optimized parameters from Gaussian fit

a, amplitude [Jy]	2.45 ± 0.035
b, mean [km/s]	$8.17 \cdot 10^1 \pm 2.245$
c, width [km/s]	$1.37 \cdot 10^2 \pm 2.30$
d, baseline [Jy]	$-8.0 \cdot 10^{-3} \pm 0.006$

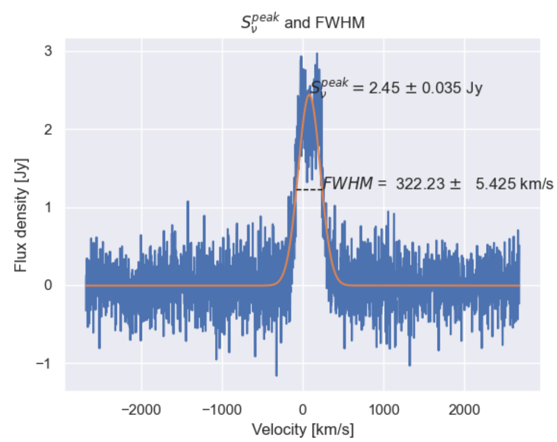

Figure 5. Flux density corresponding to the peak and FWHM of the Gaussian plotted and their values.

and the total line flux which was found by integrating over the Gaussian.

By using eq. 3 we found the line luminosity is approximately $L'_{\mathrm{CO(2\text{-}1)}} = 1.02{\cdot}10^{10} \pm 123.5[\mathrm{K\ km/s\ pc}^2]$, and with eq. 5 we found total molecular gas mass to be $M_{H_2+He} = 1.72 \cdot 10^{10} \pm 4.06 \cdot 10^9 [M_\odot]$

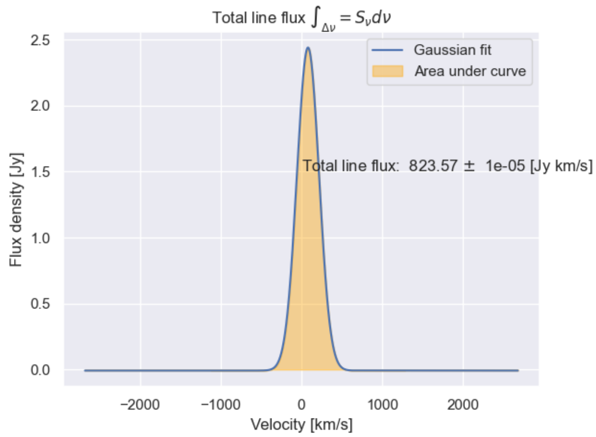

Figure 6. Total line flux of the Gaussian i.e. area under the curve

V. DISCUSSION

A. Aperture efficiency

Receivers on the APEX telescope are regularly calibrated and documented on APEX's website. However, the website does not provide documentation on receivers prior to 2017. Since our data is from 2013 we have used a receiver equivalent to our observed range of $\sim$ 230 GHz which is NFLASH230. The value is similar to $\Gamma^{-1}_{230\mathrm{GHz}} \sim 35 - 40$ Jy/K throughout 2019-2020 from [1].

B. Reduced data

In CLASS (fig. 2) we chose to re-bin the spectrum of CO(2-1) so that the channel width is Dv $= \Delta v = 2.045$ km/s. It is during the data reduction stage we can play with the channel size to improve the S/N. In our case, S/N $= 7.92 \pm 0.11$ (calculated from the maximum flux density of the Gaussian, S_ν^{peak}). For any S/N ≥ 5, we have a clear detection. This is why we are able to visibly see an emission line without any help from numerical tools. Yet, the S/N could still have been further improved by re-binning the spectrum once more.

The x-axis of the data is given in Doppler velocities [km/s] to give a more intuitive understanding of the gas dynamic. By doing so, Gildas also sets the rest frame to be at the redshift of the galaxy which is why the line is centered at around 0 km/s. In fig. 3 we see the same data, but with units on the y-axis converted from antenna temperature [K] to flux density [Jy] by utilizing the conversion factor given in eq. 6. This was done due to line luminosity, eq. 3, and total molecular gas mass, eq. 5, having a dependence on flux density and not antenna temperature, as the data was originally given in.

C. Gaussian fit

Before fitting the data we noticed two peaks present in our data. The line profile traces the kinematics of the emitting gas. The double-peaked line profile (or "two-horned" profile) is typical of rotating disk distribution [1], an indication of spirals and star-forming galaxies. Still, it is one emission line of CO(2-1). Fig. 4 shows the Gaussian fit of the emission line and the values extracted from this curve fit can be found in table I.

From the line profile, we are able to determine the optical depth of CO(2-1). Optical thin lines are characterized by narrow line profiles with a rather sharp peak, meanwhile, optically thick lines have a broad line profile and a "flat" peak. Based on this, the Gaussian of CO(2-1) suits the description of being optically thin. This turns out to be false, as lower-J CO lines such as CO(1-0) and CO(2-1) transitions are usually optically thick [1]. The issue may be our profile choice when performing a curve fit. Even though spectra usually resemble a Gaussian, the double-peaked profile in CO(2-1) emission may have caused a different result than expected. Another commonly used spectral line profile is Lorentzian [10] which perhaps could have given us different results. Something like a broader peak than a Gaussian due to the double-peak profile.

D. Total molecular gas mass

To calculate the total molecular gas mass, one would need at least one optically thin and one optically thick transition to measure gas (ideally) [1]. In most cases, we only have the luminosity of a CO transition, $L^{'}_{CO}$. Gas mass can instead be estimated from the luminosity by a CO(2-1)-to-H_2 scaling factor indicated by α_{CO}. We calculated the total molecular gas mass to be $1.72 \cdot 10^{10} \pm 4.06[M_\odot]$. This was compared to findings in the following publication: "Cold molecular outflows in the local Universe and their feedback effect on galaxies" [11]. In which they stated $\log(M_{H_2})[M_\odot] = 9.59 \Rightarrow M_{H_2}[M_\odot] = 3.31 \cdot 10^9$ for IRAS 13120-5453, with data obtained from ALMA archive of molecular outflows obtained through analysis of the CO(1-0) and CO(2-1) emission lines.This means our calculations were slightly off by a factor of ≈ 0.19. The uncertainty is high and may be due to the error of $\alpha_{CO} = 0.4$ being quite large itself.

Sources of error may be, as already mentioned in subsection V C, the Gaussian curve fit. The Gaussian may not have been the optimal line profile for an emission line with double-peak line profile. This caused a different result in terms of optical depth of CO. Another issue which was briefly mention in subsection V B is the S/N ratio. During the data reduction stage, the S/N could have been maximized further in order to reduce the noise disturbance in the data. This could have minimized the uncertainties throughout our calculations.

VI. CONCLUSION

The purpose of our investigation was to analyze the molecular transition CO(2-1) of a nearby ULIRG, IRAS 13120-5453, and study its physical properties and estimate the total molecular gas mass.

The data was received from the APEX telescope and reduced in CLASS. During this stage we re-binned the channel width to reach a level of S/N ratio we were satisfied with, which was S/N $= 7.9 \pm 0.11$.

The reduced data set was fitted with a Gaussian line profile in order to extract the maximum flux density, S_ν (amplitude). The S/N ratio was calculated from the amplitude of the Gaussian and RMS of the data. From the Gaussian we determined CO to be optical thick and to be distributed in a rotating disk (i.e. like forming spirals and star-forming galaxies). We also discovered the Gaussian to not be the optimal choice of line profile as it did not describe what we expected.

A curve fitting was necessary in order to determine the total line flux, line luminosity and lastly, total molecular gas mas. Equations 3 and 5 was used to calculate the two things mentioned last. We found the total molecular gas mas to be $M_{H_2+He} = 1.72 \cdot 10^{10} \pm 4.06 \cdot 10^{9}$ which is relatively supported by literature in the context of astrophysical background, with our calculations being a factor ≈ 0.19 off.

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VII. REFERENCES

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