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Multi-line CO imaging of two ULIRGs

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ABSTRACT

Key Words Galaxy: ULIRGs - surveys - catalogues - radio continuum: galaxies - program: Difimap

The ultra-luminous galaxies IRAS 15250 and IRAS 17208 whose data was obtained from the IRAM as part of ULIRGs were provided to us with two sets of emissions lines, CO(1 - 0) lines and 2 sets for CO(2 - 1), per galaxy. Key properties relating to these galaxies such as velocity ranges, redshift, continuum and spectral line emission, molecular gas mass, flux ratios, and dynamical mass were determined from the data analysis.

INTRODUCTION

ULIRGs are Ultraluminous Infrared Galaxies. These galaxies are can get to be 1000 times brighter in the infrared wavelength than any other galaxies in the universe. ULIRGs are the most luminous galaxies in the universe, radiating a minimum of 90 percent of their light in the infrared wavelength. A majority of these galaxies are found in interacting galaxy systems, leading many to believe that their brightness is produced by galactic collisions. The observations of ULIRGs are used to estimate the total mass of a galaxy's molecular cloud, as well as the total gravitational mass (dynamical mass) of these particular galaxies. We were provided with four sets of ULIRG observations, which were two sets of ultraluminous infrared galaxies. Two observations were for CO(1 - 0) lines and two observations were for CO(2 - 1) lines. With the given files, iras15250co10.uvf, iras15250co21, iras17208co10.uvf, and iras17208co21.uvf, we set out to determine the following;

1. Key properties of the spectral axis of each dataset provided.
2. Range of velocities relative to systemic redshift over which each galaxy shows CO emission.
3. Whether each data set shows evidence of continuum emission, and if so how to correct the estimates of spectral flux due to the contribution of such emission.
4. The total molecular gas mass of each galaxy.
5. Estimate the flux ratio of the CO(2 - 1) and CO(1 - 0).
6. The total dynamical mass of each galaxy.
7. The total molecular gas mass fraction for each of our targets.

Each of the above mentioned calculations build upon one another, with the results from one problem tying into the next. Throughout this paper you will see that the solutions from within each subsection, play a role in finding the solution of the subsection to follow. This ultimately shows that the goal of these analyses, although all were vital to the process, was to estimate/calculate both the total dynamical mass and the total molecular gas mass. In the sections to follow, you will find our process of analyzing the provided observations, and ultimately what we came to find.

PROCEDURE

To begin, the tools and software used to complete the above mentioned analyses were Astrolab servers, the Difmap software, and Jupyter Notebooks (Python). With these tools, the overall procedure to analyze the given observational data began with the use of the Difmap software. The analysis of each of the four sets of data began the same way; with determining the key properties of the spectral axis.

KEY PROPERTIES OF THE SPECTRAL AXIS

Each of the individual four observations we were provided with had to be analyzed in order to determine their key properties of the spectral axis. These properties included, how many frequency channels does the spectral axis have; what is the central frequency to redshift of the dataset; and how wide is each channel in frequency to velocity. Each set was individually loaded into Difmap, where we then began to cycle through the one-hundred and twelve available frequency channels of data. We found that the most effective way to do this was through the creation of pseudo-continuum data sets of frequency channels to observe for when a clear indication of CO emission both began and subsided. We initially worked through ten channels at a time, but then decreased each pseudo-continuum data set to view five channels at a time. This allowed to find a more accurate span of frequency channels where there was a clear indication of peak CO emission within the observations. The table below shows the range of channels that show peak CO emission in each of the provided observational data sets.

	iras15250co10	iras15250co21	iras17208co10	iras17208co21
Channels	40 to 80	30 to 75	30 to 85	3 to 112
Range	41 Channel	46 Channels	56 Channels	110 Channels

Table 1. This table shows the channel range for each of the four data sets where CO emission can be observed.

Now that we know the channel ranges for each of the four observational data sets, the next task is finding what the central frequency to redshift is of each data set. This was easily done with the use of the following equation:

$$z = \frac{\nu_0}{\nu} - 1; \text{ where for data sets (1-0): } \nu_0 = 115.271 \text{ GHz, and data sets (2-1): } \nu_0 = 230.538\text{GHz}. \tag{1}$$

Here, within Difmap, when initially loading in each observational file, the central frequency of the observation was given (nu). The table below provides both the nu and the calculated redshift values as a result of the aforementioned equation above. These are the final results after taking the channel offset into consideration.

	iras15250co10	iras15250co21	iras17208co10	iras17208co21
ν	1.09508e11	2.18736e11	1.0828e11	2.2377e11
Redshift	0.0554	0.552	0.0428	0.0427

Table 2. This table shows the calculated redshift for each observation with its specified nu value.

To calculate the width of each channel, the following equation was used:

$$\frac{\Delta v}{c} = \frac{\Delta \nu}{\nu}; \; \Delta v = \frac{\Delta \nu}{\nu} * c; \text{ where } \Delta\nu = \text{ the frequency offset per channel.} \tag{2}$$

This frequency offset per channel is provided for each data observation with the initial observe command in Difmap. This $\Delta\nu$ value is the same for all data sets provided: $\Delta\nu = 4.9996e - 3$. Taking this $\Delta\nu$ value and the previously mentioned ν values for each of the four observations, the below table contains the calculated width of each channel for each of the data sets provided.

	iras15250co10	iras15250co21	iras17208co10	iras17208co21
$\Delta\nu$	4.9996e-3	4.9996e-3	4.9996e-3	4.9996e-3
Δ v	13.721km/s	6.862km/s	13.558km/s	6.779km/s

Table 3. This table shows the calculated v-width of each channel for each of the observations with its specified $\Delta\nu$ and ν value.

With all the key properties calculated and collected, the next step is to determine the range of velocities relative to systemic redshift over which each galaxy shows CO emission.

RANGE OF VELOCITIES RELATIVE TO SYSTEMATIC REDSHIFT

The goal in this step was to find the range of velocities relative to the systemic redshift over which each galaxy showed CO emission. With the initial step completed in the previous section, where we calculated the v-width (Δv) for each of the four observations; we were able to then take each of the Δv values (table 3) and simply multiply them by the number of channels in the CO emission's range. This value was also previously determined and can be found in table 1. With this simple multiplication, we get velocity over all channels. We need the range of velocities, meaning the range of velocities from the center channel, moving out. By simply dividing by two, we were able to get the range of velocities. We provide a simple equation we used to determine this value below.

$$\text{Range of Velocities} = \frac{(\Delta v * \text{Channel Width})}{2} \tag{3}$$

Since this value is halved, it indicates the range of velocities moving out from the center, meaning in both the positive and negative directions. Below is a table containing the calculated values.

	iras15250co10	iras15250co21	iras17208co10	iras17208co21
Δ v	13.721km/s	6.862km/s	13.558km/s	6.779km/s
Ch.Width	41 Channels = 745.69km/s	46 Channels = 315.652km/s	56 Channels = 759.248km/s	110 Channels = 745.69km/s
Range of Vel.	+/-372.845km/s	+/-157.826km/s	+/-379.624km/s	+372.845km/s -379.624km/s

Table 4. This table shows the calculated range of velocities of each channel for each of the observations.

With these calculated ranges of velocities, we can see that as a result of the systematic redshift, the velocity of the channels range within each channels respective range of velocities. We can see a slight discrepancy with the range found for iras17208co21. This is strictly due the lack of some data which we were not able to observe due to that part of the CO emission being present past our available channels. So this data was essentially just cut off from our available observation files. With the range of velocities now calculated for each of the provided observation files, the next step in our procedure is to determine whether each dataset shows evidence of continuum emission, and if so how to correct the estimates of spectral line flux due to the contribution of such emission. This too will require the use of Difmap, along with our found ranges of channels to be used as pseudo-continuum data sets in order to observe the correct data collected and find where there is emission, and how to account for it.

EVIDENCE OF CONTINUUM EMISSION

We required the use of difmap again to observe the galaxy and select a range of their frequency channels as a pseudo-continuum data set. When we have our selected range of channels for the galaxy, we would put a box on the emission peak and clean it by typing the command 'clean50'. This would return the continuum flux density for the galaxy and would repeat this process for each galaxy and their CO lines. Next, we would repeat the process of selecting a range of channels again for the galaxy and type the command 'clean50', however this would return the spectral line flux density. Now that we have both the continuum flux density and spectral line flux density, we can calculate the continuum line flux and spectral line flux by using the velocity width we solved for earlier. From here, we can take the difference between the continuum flux and spectral line flux in order to get the corrected spectral line flux due to the contribution of the emission. All in all, the corrected spectral line flux with the contribution of continuum emission is the difference between spectral line flux(uncorrected) and continuum flux present. The calculated values for this are in the table displayed below.

	iras15250co10	iras15250co21	iras17208co10	iras17208co21
Continuum Flux Density	0.00311Jy	0.0225Jy	0.0120296Jy	0.0904736 Jy
Spectral Line Flux Density	0.0148Jy	0.0738Jy	0.0987376Jy	0.422559 Jy
Continuum Flux Present	1.75Jy km/s	7.11Jy km/s	9.133Jy km/s	67.4765 Jy km/s
Spectral Line Flux(Uncorrected)	8.31Jy km/s	23.31Jy km/s	74.966Jy km/s	315.098 Jy km/s
Spectral Line Flux(Corrected)	6.56Jy km/s	16.2Jy km/s	65.833Jy km/s	247.642 Jy km/s

Table 5. This table shows the calculated Continuum Flux Density, Spectral Line Flux Density, Continuum Flux Present, Spectral Line Flux(Uncorrected), and Spectral Line Flux(Corrected) of each channel for each of the observations.

FLUX

ESTIMATING FLUX RATIOS

Examining and comparing flux ratios from different galaxies can provide significant information about the relative brightness of objects and how it decreases over distances. One goal of our observations was to estimate and determine any potential significance of the flux ratios of each of our galaxies' emission states and to compare the aforementioned galaxies flux ratios to one another. The data for our individual values of galaxy flux and how they were determined can be found above in Evidence of Continuum Emission. The ratio of CO(J = 2 - 1) and CO(J = 1 - 0) lines of all channels were compared to that galaxies' middle channel. The determination of the total channels examined for emission as well as the center or middle channel and the methodology for its determination can both be found above in Range of Velocities relative to Systematic Redshift5.

$$\text{flux ratio} = \frac{f_{2-1}}{f_{1-0}} \tag{4}$$

This equation shows the flux ratio calculation

The results seem to be the averages tend toward a value for the flux ratios within the same galaxy that are smaller than those determined from only emissions collected from center channels alone. This is reasonable since we know that flux falls of at a rate of $f \propto 1/r^2$. The degenerative nature of CO emission would inform us that those particles moving from CO(J = 2 - 1) have greater flux ratios than those moving from CO(J = 1 - 0). Based on the flux and our previously recorded emissions we can state comfortably that IRAS15250 has a smaller velocity than that of IRAS17208.Flux, as a measure of density, leads us to the clear understanding that galaxies of higher flux ratios of particle emission, which in this case refers to IRAS17208, have higher temperature ranges too. This correlates with our understanding. We know density and temperature should be inversely proportional, however, we aren't examining density, but a ratio of one density over another So as the two flux densities shift further from one another, becoming more red and blueshifted, as a higher flux ratio is observed, we could determine that the overall temperature of that galaxy is much higher. This is also sensible since ejecting particles very quickly in all directions at higher velocities would be something we expect to see from more massive galaxies.

GAS FRACTION

TOTAL MOLECULAR GAS MASS

One of our goals was to determine the gas fraction of each of the two galaxies we analyzed. Our first step in order to do this would be to calculate the total molecular gas mass of each galaxy. To achieve this we utilized the following equations:

$$\frac{M_{H_2}}{M_\odot} = 1.180 \times 10^4 (\frac{D}{Mpc})^2 (\frac{X}{3 \times 10^{20}}) (\frac{F_{co(1-0)}}{Jykms^{-1}}) \tag{5}$$

$$D \approx cz/H_0 \tag{6}$$

$$X \equiv N_{H_2}/I_{co(1-0)} = 3 \times 10^{20} cm^{-2} (Kkms^{-1})^{-1} \tag{7}$$

We are assumed for the sake of calculation that the conversion factor (7) for neutral hydrogen was similar to the Milky Way's. For our distance calculation we assumed the Hubble parameter to be $H_0 \approx 70kms^{-1}Mpc^{-1}$ and our red shift was the systemic redshift calculated before in relation to the spectral line flux for each galaxy. Our results are stored in table 6.

	iras15250	iras17208
Mass	4.36×10^9	2.60×10^{10}

Table 6. Total molecular gas masses in solar mass, $M_\odot$.

TOTAL DYNAMICAL MASS

The process for determining the total dynamical mass is a little more involved. We utilized the following equation to calculate the total dynamical mass with the assumption that the galaxy's edge was facing us (the observer).

$$\frac{M_{dyn}(< R)}{M_\odot} = k \times (\frac{R}{kpc})(\frac{v}{kms^{-1}})^2 \tag{8}$$

We assumed that $R \approx 0.5 \times \Delta R$ and $v \approx 0.5 \times \Delta v$, where Δ R is the distance between the peak velocities and Δv is the difference between the peak velocities between the redshifted and blueshifted parts of the galaxy. In order to get the distance between these two points we used difmap to locate them by looking at the emission peak locations at the higher and lower ends of the detected spectral line band and with some trigonometry, we arrived at our distance in arcseconds. To convert that to kpc we used our previously calculated distance to the galaxy along with that arcsecond value to get an R in kpc. k is a constant value that we determined to be 232798.173. Our results for are dynamical mass are in table 7.

	iras15250	iras17208
Mass	4.54×10^9	8.32×10^9

Table 7. Total dynamical masses in solar masses, $M_\odot$.

GAS FRACTION RESULTS

	iras15250	iras17208
Gas Fraction	3.125	0.96035

Table 8. Gas fraction for each of the two galaxies.

Our findings for the gas fraction (obtained by $f_{gas} \equiv M_{H_2}/M_{dyn}$) are stored in 8. As one may observe the numbers are paradoxically high especially in iras17208 which basically says that there is more molecular gas mass than there is mass in the galaxy. We do not believe this is a result of our procedures and methodology but rather of our assumptions regarding our mass calculations. The first assumption to draw attention to would be our conversion factor for the molecular gas mass. We believe that basing that conversion factor on the Milky Way galaxy raises the conversion factor too high which negatively impacted our calculations. This implies that the conversion factor for the Milky Way galaxy is not sufficiently close to the one in ulirg galaxies to accurately represent their composition. The second major assumptions would be the fact that we treated these galaxies as if they were edge-on to us. While this is an ideal scenario, it is also a very unlikely one. This means that our peak emission velocities were probably lower than they actually are due to the galaxies being on an angle to us, thus causing our calculated dynamical masses to be smaller than the actual dynamical masses. If these assumptions can be filled with accurate values via finding an accurate conversion factor for our ulirgs and by determining at what angle the ulirgs are in relation to us, our gas fractions should lower to a more realistic fractions.

CONCLUSION

Setting out to make observations and determinations about two ultraluminous infrared galaxies, both of which were 100 times greater than our own was a challenge. We were provided with two pieces of data per galaxy relating to the emission lines of CO molecules, as they changed states from CO(J = 1 0) as well as CO(J = 2 1). We began by determining the key properties of the spectral axis for each data-set, such as the number of frequency channels, the channel width and range of velocities in relation to redshift. The results from analysis conclude that IRAS17208 possessed significantly broader channel ranges, larger velocities, and smaller redshifts. By comparing the results of both galaxies were determined both were possible candidates for continuum emission.By utilizing difimap and selecting a range of frequency channels, we were able to calculate values for continuum and spectral line flux. However, these values had to be correct for redshift before we could use them to make judgements. The outcome was that while both galaxies showed evidence of continuum and spectral line flux, results for IRAS15250 and IRAS17208 reveal that CO(J = 2 1) lines are consistently higher. Comparing both galaxies, IRAS17208 showed drastically larger values for flux in both spectral line and continuum emission. The evidence from these emissions allowed us to examine the ratios of and between these two galaxies more closely, which allowed use to make determinations about the relative speeds and temperatures of both galaxies, of which, we again say IRAS17208 is seemingly far hotter and heavier galaxy. This does not align with the calculation we performed for total molecular gas mass which informs us the opposite of our results should be true. The total dynamical mass however, does agree with our assertions based on flux density ratio theoretical analysis. When we looked deeper into calculating the gas fraction results to see if the value would make up the difference between our two values, we were disappointed to say it did not. A likely culprit of this is our large assumption about the alignment of each galaxy relative to our observational plane. We assumed both galaxies were observed edge-on an ideal state for observation, however, this is unlikely, and a change in observational angle would explain why both peak emission velocities as well as dynamical mass values are so.

CITATIONS AND REFERENCES

REFERENCES