Rotational Velocity and Dynamical Mass for the Nuclear Disk of the ULIRG Arp 220

Jazeel H. Azeez¹, Ammar A. Zghair¹, Sadeem A. Fadhil¹, Zamri Zainal Abidin²

¹Al-Nahrain University, College of Science, Department of Physics, Baghdad, 10072, Iraq
²University of Malaya, College of Science, Department of Physics, Kuala Lumpur, 50603, Malaysia

E-mail: jazeelhussein@yahoo.com, jazeel.azeez@ced.nahrainuniv.edu.iq

Abstract. In this manuscript we use a very high spatial resolution CO (J = 6 – 5) data from Atacama Large Millimeter/Sub-millimeter Array (ALMA) focused to the center region of Arp 220, at distance D = 77.4 Mpc (1 arcsecond = 375 parsec). The CO emission is resolved efficiently by ALMA beam (0.43″ × 0.26″). We use long-slit along different direction of our sample to study the kinematic properties of the warm molecular gas within the inner region of Arp 220. We find the observed position – velocity (PV) diagram for this galaxy from its emission line. The major part of the molecular gas in Arp 220 was located mainly in the east and west nucleus. We measure 0.23 × 10¹⁰ Mʘ dynamical mass in the central of this galaxy.

1. Introduction
The majority of the observational studies dedicated in last years to figure out the galaxy formation and evolution. A fundamental result in galactic astronomy within the recent 25 years was the discovery of ultra-luminous infrared galaxies (ULIRGs, [1]). In spite of these galaxies are less with in local universe, their merger form suggests that they indicate an extremely active and significant phase in galaxy evolution.

ULIRGs have distinguished tidal tails on big scales and luminous star forming regions, at their centers. In spite of ULIRGs and mergers as a category are temporary targets suffering from fast evolution, this provide an affordable example of the dynamic characteristics for the structures they finally develop into. Previous theoretical models and observations of merger galaxy showed that mergers can convert spirals to ellipticals [2,3], also the results of these models and observations suggest that the two nuclei will merge at less than ~ 1 kiloparsec and then quickly agglomerate, the systems have essentially amount to their stable values of dispersion, rotation and high-order kinematic moments on spatial scales within half mass radius or bigger [4,5].

Large surveys of CO(1-0) and CO(2-1) was found a lot of abundance of molecular gas within center kpc of ULIRGs [6,7]. Several studies suggest that a high luminosities for low CO transition produced as a result for the emission of widespread gas slightly correlated with regions of active star formation (SF) [8]. In fact, single-dish and interferometry millimetre and sub- millimetre observations discovered that the intensities and locative distributions of SF within ultra-luminous infrared galaxies have stronger correlation with those of higher transition CO lines, that explore denser and warmer gas than low transitions CO emissions [9,10].
Among the ULIRGs, Arp 220 is the most repeatedly cited example, having a distance of 77 Mpc which provide a scale of 375 pc per arcsecond. High resolution observations of molecular gas can give basic important information about gas kinematics and thermal construction within the nuclear disk region of Arp 220. However, more recently, this galaxy has been observed with ALMA cycle – 0 in high transition CO (6 – 5) with very high resolution (less than 1″). This transition was observed in the same galaxy with Sub-millimeter Array (SMA) [11] but with lesser resolution and lower sensitivity.

This research is intended to study the rotation curves and calculate the molecular and the dynamical mass for Arp 220. This manuscript is outlined as follows: Description for the galaxy and data is explained in Part 2. Part 3 detail the results and of our data, which include deriving the P-V diagram, rotation curve and dynamical mass and interpret the results. In Part 4, we summarized our results and conclusion

2. ARP 220 - a prototypical ULIRG

Arp 220 (also known as IC4553/4) is one of the closest ULIRG with IR luminosity L8-1000μm = 1.4 × 10^{12} L⊙ [12]. This galaxy is considered to be in a high merger stage of two galaxies and has a huge concentration of gas in its nuclear region [13,14]. Arp 220 was the subject of a plenty of previous studied at different wavelength. It was imaged at CO (1 – 0) line [15], HCN [16], CO (2 – 1) [17] and in the CO (3 – 2) and HCO⁺ lines [18].

ALMA cycle-0 long baseline data for the ^12CO (J = 6 – 5) line emission (band 9) were observed in December 2012 for project #2011.0.00403.S. The data were taken with 25 antenna with a time of 26.8 minutes on source. The angular resolution is 0.42″ × 0.26″. The CO emission detected with ALMA showed two nuclear disks within center region of the galaxy. The overall integrated flux is 3480.9 Jy km/s. The CO J = 6 - 5 integrated intensity map is displayed in Figure 1. The CO moment map exhibits two nuclei in the central disk.

![Figure 1. CO (J = 6 – 5) integrated intensity image (zeroth moment map) for Arp 220 observed with ALMA. The contour levels are [2, 4, 6, 8] × 25.44 Jy km / s. beam.](image)
3. Results and Discussions

3.1. CO(6-5) Rotation Curve

Rotation curves are one of the most essential sources of information on the dynamics of galaxies. Rotation curves of galaxies are usually derived from position – velocity (PV) diagrams by radio (CO, HI) line observations [19]. Figure 2, shows the observed P-V diagrams through the major axis of the data with slits of 1 arcsec width passing through the center of elongated nuclear disk and between flux peaks of the two nuclei. Primarily, these diagrams are useful to obtain the rotation velocity of the molecular gas for Arp 220 at galacto-centric radius using the following formula [20]:

\[ V_{\text{rot}} = \frac{|V_{\text{obs}} - V_{\text{sys}}|}{\sin i} \]  

(1)

Where \( V_{\text{obs}} \) represents observed velocity, \( V_{\text{sys}} \) represents systematic velocity and \( i \) is the inclination angle. We choose the systematic velocity with value of half the velocity range of the two CO peaks along the major axis which is equal to 5434 km s\(^{-1}\). Concerning the inclination angle, \( i \), it was calculated using minor/major axis ratio for CO sources, with \( i = \cos^{-1} \) (minor/major). The best value of the inclination angle was found to equal 45\(^{\circ}\). Within the central 0.6” (220 pc), the rotation velocity increases as the radius increased, which represents a rigid rotation as shown in Figure 3. The rotational velocity was found to be about 212 km/s through 4\(^{th}\) polynomial fit at the central region of Arp220. The rotation time scale of the central gas is \( 1.6 \times 10^7 \times \sin (i) \) years. Arp 220 has formed from merging of two spirals with gas rich [13]. During merging, the stellar system on both spirals forms non-axisymmetric potentials which takes a bar shape [6]. The bar shape potential can attract a huge amount from molecular gas to center region. Cloud- cloud collisions may occur frequently if a molecular gas with \( 10^{10} \) M\(_{\odot}\) is accumulated in the central 1kpc. The collisions induce the relaxation of the gas and may be responsible on the large quantity of molecular gas that moved into the center in a short time scale within \( (1.4 \times 10^7 \) years), in spite of the both galactic nuclei have not been merged yet [21].

**Figure 2.** P–V diagrams of Arp 220 with position angle (a) P.A. = 101\(^{\circ}\) along the major axis of the elongated center region and (b) P.A. = 40\(^{\circ}\) between the twin CO peaks.
3.2. Molecular and Dynamical Mass

The CO J = 6–5 emission is a good candidate for tracing peaks of the hot molecular gas within center of the western and eastern nuclei. These features are well determined at 0.43” × 0.26” resolution of the CO map as shown in Figure 1, which have an expanded component around the two nuclei. In this paper the center of Arp 220 was divided into two regions following the same procedure in references [22,23]. The molecular and total gas mass can be calculated using the following formulas [24]:

\[
\frac{M_{H_2}}{M_\odot} = \alpha_{CO} L'_{CO}
\]

\[
M_{gas} = 1.36 \times M_{H_2}
\]

where \(\alpha_{CO}\) is CO-to-H\(_2\) gas mass transformation factor that is about 4.6 \(M_\odot\) (K. km/ s. pc\(^2\))\(^{-1}\) [25], \(L'_{CO}\) is CO luminosity, and the constant 1.36 was considered for the presence of He gas [26]. CO(6-5) explain that there is a vast supply of gas within central two nuclei for Arp 220. For adopted distance 77.2 Mpc, the total gas mass in east and west nuclei of this galaxy are \(1.24 \times 10^9\) \(M_\odot\) and \(1.17 \times 10^9\) \(M_\odot\) respectively. Thus, the angular momentum may have a crucial role in the gas distribution which lead to relaxation for molecular gas to a disk-like configuration which also lead to advance collapse processes toward the center.

The dynamical mass for the molecular gas is usually calculated by considering the inclination angle for the rotating gas with its radius. Applying this to Arp 220 and taking \(M_{dyn}\) as a dynamical mass [20,27]:

\[
M_{dyn} = \frac{r V_{rot}^2(r)}{G} = 2 \cdot 3 \times 10^5 \left(\frac{r}{kpc}\right) \left[\frac{V_{rot}(r)}{kms^{-1}}\right]^2 M_\odot
\]

Where \(V_{rot}(r)\) represents rotation velocity at radius \(r\), \(r\) represents radius of the gas disk, and \(i\) represents inclination angle for the disk. We find that the dynamical mass within the central 0.6” is \(0.23 \times 10^9\) \(M_\odot\) which is consistent with [28].

![Figure 3. CO rotation curve within center region of Arp 220 at P.A. = 101°. Blue dots with error bar represent the data point and the solid curve represent the 4th polynomial fit.](image-url)
4. Conclusion
We studied and analyzed the measurements of the high-transition CO ($J=6–5$) emission of the ULIRG Arp 220 with ALMA. Our findings, shortly, reveal the following points:

- The best value for the inclination angle was found to equal 45º, which lead to 212 km/s of the rotational velocity that calculated from the 4th polynomial fit at the central region of Arp220.
- The rotation time scale of the central gas is equal to $1.4 \times 10^7$ years. Arp 220 has formed from merging of two spirals with gas rich. The collisions between molecular clouds that have accumulated in the central region induced the relaxation of the gas and may be responsible on the large quantity of molecular gas that moved into the center in a short time scale in spite of the both galactic nuclei have not been merged yet.
- The total gas mass in east and west nuclei of this galaxy are $1.24 \times 10^9$ $M_\odot$ and $1.17 \times 10^9$ $M_\odot$ respectively. The angular momentum might consider a main part in the distribution of the gas which lead to molecular gas to a disk-like configuration which also lead to advance collapse processes toward the center.
- Lastly we determined the dynamical mass within central 0.6" equals to $0.23 \times 10^{10}$ $M_\odot$, which is consistent with previous works.

References
[1] Lonsdale C J, Farrah D and Smith H E 2006 Ultraluminous Infrared Galaxies BT - Astrophysics Update 2 ed J W Mason (Berlin, Heidelberg: Springer Berlin Heidelberg) pp 285–336
[2] Veilleux S, Kim D-C and D. B. Sanders 2002 Optical and Near-Infrared Imaging of the Iras 1-Jy Sample of Ultraluminous Infrared Galaxies II. The Analysis Astrophys. J. Suppl. Ser. 143 315–76
[3] Dasyra K M, Tacconi L J, Davies R I, Genzel R, Naab T, Burkert A, Veilleux S and Sanders D B 2006 Dynamical Properties of Ultraluminous Infrared Galaxies. I. Mass Ratio Conditions for ULIRG Activity in Interacting Pairs Astrophys. J. 638 745–58
[4] Mihos C 1999 Dynamics of mergers Astrophys. Space Sci. 266 195–205
[5] Bendo G J and Barnes J E 2000 The line-of-sight velocity distributions of simulated merger remnants Mon. Not. R. Astron. Soc. 316 315–25
[6] Gao Y and Solomon P M 1999 Molecular Gas Depletion and Starbursts in Luminous Infrared Galaxy Mergers Astron. J. 512 L99–103
[7] Evans A S, Mazzarella J M, Surace J A and Sanders D B 2002 Molecular Gas and Nuclear Activity in Ultraluminous Infrared Galaxies with Double Nuclei Astrophys. J. 580 749–62
[8] Gao Y, Lo K Y, Lee S -W. and Lee T -H. 2001 Molecular Gas and the Modest Star Formation Efficiency in the “Antennae” Galaxies: Arp 244 = NGC 4038/9 Astrophys. J. 548 172–89
[9] Sakamoto K, Aalto S, Costagliola F, Martin S, Ohyama Y, Wiedner M C and Wilner D J 2013 Submillimeter interferometry of the luminous infrared galaxy NGC 4418: A hidden hot nucleus with an inflow and an outflow Astrophys. J. 764 42
[10] Xu C K, Cao C, Lu N, Gao Y, Van Der Werf P, Evans A S, Mazzarella J M, Chu J, Haan S, Diaz-Santos T, Meijerink R, Zhao Y H, Appleton P, Armus L, Charmandaris V, Lord S, Murphy E J, Sanders D B, Schulz B and Stierwalt S 2014 ALMA observations of warm molecular gas and cold dust in NGC 34 Astrophys. J. 787 48
[11] Matsushita S, Iono D, Pettipas G R, Chou R C Y, Gurwell M A, Hunter T R, Muller J L S, Peck A B, Sakamoto K, Satoh S S, Wiedner M C, Wilner D J and Wilson C D 2009 SMA 12CO(J = 6 − 5) and 435 μm Interferometric Imaging of the Nuclear Region of Arp 220 Astrophys. J. 693 56–68
[12] Sanders D B, Mazzarella J M, Kim D-C, Surace J A and Soifer B T 2003 the Iras Revised Bright Galaxy Sample Astrophys. J. 126 1607–64
[13] Scoville N Z, Sanders D B, Sargent A I, Soifer B T, Scott S L and Lo K Y 1986 Millimeter Interferometry of the Molecular Gas in ARP 220 Astrophys. J. 311 L47–50
[14] Scoville N Z, Yun M S and Bryant P M 1997 Arcsecond Imaging of CO Emission in the Nucleus
of Arp 220 *Astrophys. J.* **484** 702–19

[15] Scoville N Z, Sargent A I, Sanders D B and Soifer B T 1991 Dust and Gas in the Core of ARP 220 (IC 4553) *Astrophys. J.* **366** L5–9

[16] Radford S J E, Delannoy J, Downes D, Guélin M, Guilloteau S, Greve A, Lucas R, Morris D and Wink J 1991 The Dense Molecular Core of ARP 220 *Dynamics of Galaxies and Their Molecular Cloud Distributions: Proceedings of the 146th Symposium of the International Astronomical Union* p 303

[17] Sakamoto K, Scoville N Z, Yun M S, Crosas M, Genzel R and Tacconi L J 1999 Counterrotating Nuclear Disks in Arp 220 *Astrophys. J.* **514** 68–76

[18] Sakamoto K, Aalto S, Wilner D J, Black J H, Conway J E, Costagliola F, Peck A B, Spaans M, Wang J and Wiedner M C 2009 P Cygni profiles of molecular lines toward ARP 220 nuclei *Astrophys. J.* **700** L104–8

[19] Sofue Y and Rubin V 2001 Rotation Curves of Spiral Galaxies *Annu. Rev. Astron. Astrophys.* **39** 137–74

[20] Azeez J H, Abidin Z Z, Ibrahim Z A and Hwang C Y 2015 Rotation curve and dynamical mass in the inner region of M100 with ALMA *International Conference on Space Science and Communication, IconSpace* pp 329–34

[21] Graham J R, Carico D P, Matthews K, Neugebauer G, Soifer B T and Wilson T D 1990 The double nucleus of ARP 220 unveiled *Astrophys. J.* **354** L5–8

[22] Azeez J H, Hwang C Y, Abidin Z Z and Ibrahim Z A 2016 Kennicutt-Schmidt Law in the Central Region of NGC 4321 as Seen by ALMA *Sci. Rep.* **6** 1–12

[23] Azeez J H, Abidin Z Z, Hwang C Y and Ibrahim Z A 2017 Star Formation Law at Sub-kpc Scale in the Elliptical Galaxy Centaurus A as Seen by ALMA *Adv. Astron.* **2017**

[24] Azeez J H, Fadhil S A, Naser-Alla Z K and Abidin Z Z 2018 ALMA Study of the Lensed Galaxy SDP.81 *Al-Nahrain J. Sci.* **1** 69–71

[25] Higdon S J U, Armus L, Higdon J L, Soifer B T and Spoon H W W 2006 A Spitzer Space Telescope Infrared Spectrograph Survey of Warm Molecular Hydrogen in Ultraluminous Infrared Galaxies *Astrophys. J.* **648** 323–39

[26] Sakamoto K and Okumura S 1995 Bar-Driven Gas Structure and Star Formation in the Center of M100 *Astron. J.* **110** 2075

[27] Kohno K, Tosaki T, Okuda T, Nakanishi K, Kamazaki T, Muraoka K, Onodera S, Sofue Y, Okumura S K, Kun o N, Nakai N, Ohta K, Ishizuki S, Kawabe R and Kawai N 2005 Nobeyama Millimeter Array observations of GRB 030329: A Decay of afterglow with bumps and molecular gas in the host galaxy *Publ. Astron. Soc. Japan* **57** 147–53

[28] Downes D and Eckart A 2007 Black hole in the West nucleus of Arp 220 *Astron. Astrophys.* **468** L57–61