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The Total Mass of the Merging Galaxy NGC 1614 Using ALMA Observations

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Abstract
To examine the total mass of the merging galaxy NGC1614, the findings of this paper are presented in the CO(3-2) transition using the Atacama Large Millimeter/submillimeter Array (ALMA). The total mass of the NGC1614 galaxy is determined in this study within a radius of 0.5 kpc, which is based on the line-of-sight rotational velocity. According to the findings, the total mass is about $(2.8\pm0.08)\times10^{9}$ M⊙. The derived mass of NGC 1614 is an important feature to know its mass distributions and dynamical structure. The latter might be a key to study the missing matter mass and stellar mass, where baryonic mass and missing matter in each galaxy become affected by the approaching galaxy during the merger.

Keywords: Individual (NGC 1614); Kinematics and dynamics, Evolution.

الكتلة الكلية للمجرة المدمجة NGC 1614 باستخدام أرصاد ALMA

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الخلاصة
لدراسة الكتلة الكلية لمجرة الاندماج NGC1614، تم تقديم نتائج هذه العمل في خط الانتقال CO(2−3) و باستخدام ارصادات ALMA. حيث تم تحديد دراسة الكتلة الكلية للمجرة NGC1614 ضمن نصف القطر 0.5 kpc والتي تعتمد على السرعة الدورانية لخط البصر. و بذلك تبين بأن الكتلة الكلية للمجرة المذكورة حوالي(2.8± 0.08) × 10^{9} كتلة شمسية. تعتبر الكتلة المشتقة من NGC 1614 ميزة مهمة لمعرفة توزيعاتها الكتلية وبنيتها الديناميكية. قد يكون الأخير مفتاحًا لدراسة كتلة المادة المفقودة والكتلة النجمية ، حيث تتأثر الكتلة الباريونية والمادة المفقودة أثناء الاندماج.

1. Introduction

It is impossible to trace the history of galaxies without considering the role that mergers and interactions have played. During hierarchical growth, dark matter haloes merge in cold dark matter cosmology, leading to the merger of their baryonic counterparts. The galaxies at

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the centres of the dark matter halos are impacted by this interaction [1]. As galaxies are pulled and warped by tidal forces, stars move from the disk to the spheroid. However, recent studies show that this is not always the case; mergers have the potential to increase a galactic nucleus's activity [2].

After the merging of two or more galaxies, the resulting structure may not have any similarity to the galaxies' individual components in any way. The relative masses as well as the different sorts of mergers are what determine the fundamental processes. A merger remnant is created as a result of major mergers, which happen when two galaxies with about the same mass merge into one. Its appearance is different from either of its parents due to the change in the gravitational field [3]. Minor galaxy mergers are likely to occur whenever one of the galaxies is a large galaxy. Despite the fact that a smaller galaxy has lost the majority of its gas and stars, the structure of the larger galaxy has only been significantly affected [4] [5]. The stars and dark matter in both galaxies are impacted by the merging. As the merging progresses into its latter stages, the gravitational potential undergoes such rapid alterations that the orbits of the stars are drastically altered and eventually lost [6]. A collision between two disk galaxies causes a rotation of the stars along the disk axes. The merging causes the orderly motion to thermalize. The resulting galaxy is dominated by stars that orbit around it in a complex system of interacting orbits [7].

The nearby galaxy NGC1614 (also known as Arp186) is a luminous infrared galaxy (LIRG) with a distance of 64 Mpc, a velocity of 75 kms^{-1} Mpc^{-2}, and an infrared luminosity of about 3×10^{11} $L_{\odot}$ [7]. The inner structure of NGC1614 reveals a bright core flanked by two spiral arms. The outer structure of this galaxy consists of a nearly straight tail that emerges from the nucleus and crosses the extended arm to the top right [8] and a wide, curving extension of one of these arms to the lower right. Based on its shape and nuclear activity, the candidate in this work is thought to be an excellent candidate for a minor merger [9] [5]. Furthermore, merger galaxies significantly impact galaxy evolution by sparking starbursts and active galactic nuclei (AGN) [9].

The present work aims to determine the total mass of the central region of NGC1614. This paper is structured as follows: Section 2 presents the NGC1614 data. Section 3 contains the results and discussion. Summarization is in section 4.

2. DATA

NGC1614 data were taken from the ALMA telescope with band 7 as part of Cycle 0 observations of project 2011.0.00768.S using 27 antennae. The band 7 data were observed from 14 July to 14 August in 2012 (total integration time= 20342 min.) as three data sets using the four spectral windows. Each spectral window has 3840 channels and a bandwidth of 1.875 GHz. The ^{12}CO(3-2) data cube was produced using the Common Astronomy Software Application (CASA) from the continuum subtracted visibilities (See Figure 1).

Then, images were cleaned using Briggs weighting with robust = 0.5 and 20 km s^{-1} channel widths for ^{12} CO(3 - 2). The beam size of these images is 0.59″× 0.39″ and a position angle (PA.) of 271˚. The HST image at F814W is used in this work to show the morphology of NGC 1614 galaxy as shown in Figure 2.

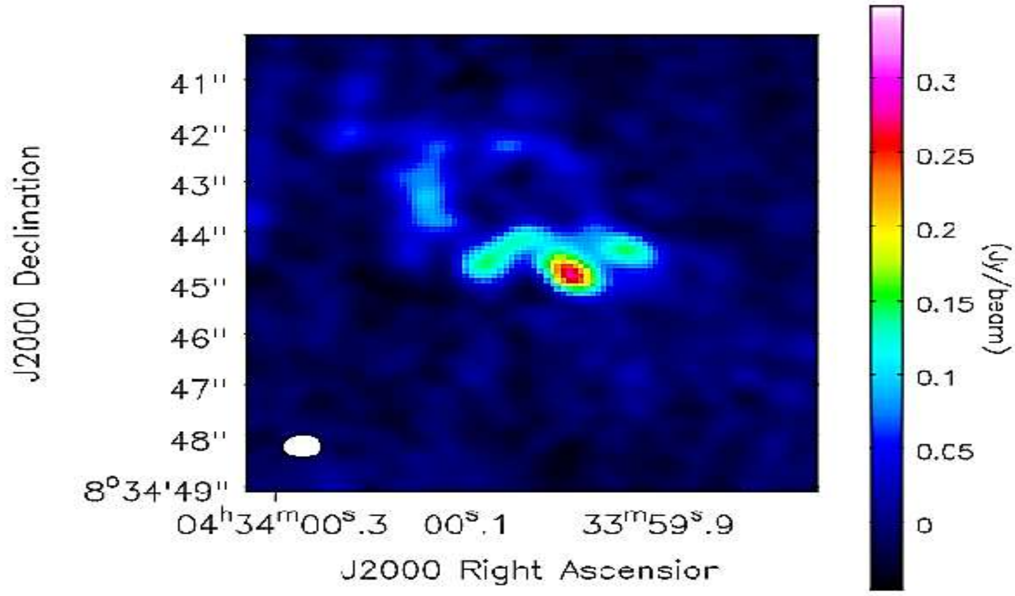

Figure 1: CO(3-2) cube map of the galaxy NGC 1614 (brightness). The wedge on the right illustrates the color scale range in units of Jy/beam. The synthesized beam is $0.59'' \times 0.39''$ with a PA. of 271°, which can be seen in the lower left corner.

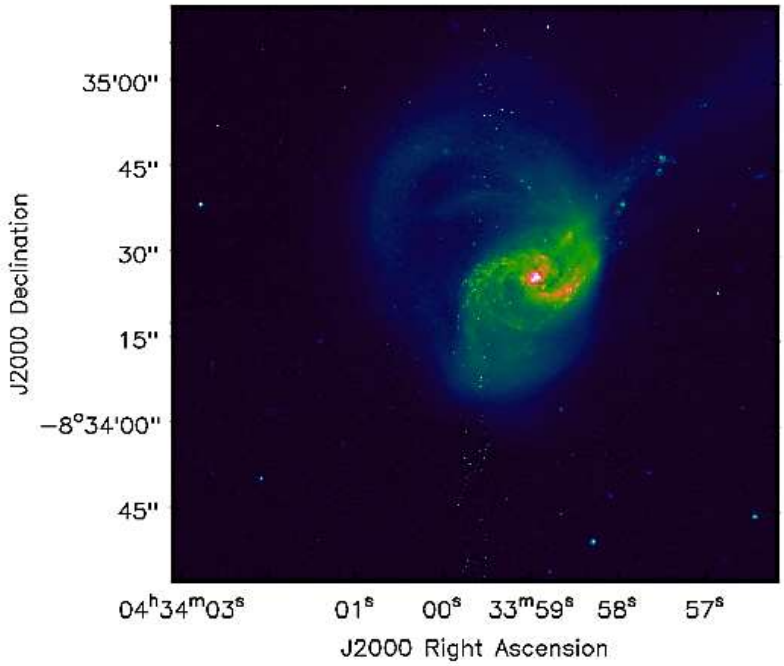

Figure 2: 2MASS image of NGC 1614 at Ks band.

3. Results and Discussion

3.1 CO Distributions

Figure 3 shows the integrated intensity (moment 0) map of $^{12}CO(3\text{-}2)$ line from ALMA observations. CO(3-2) emission appears in different regions beyond the ring of the molecular gas. Indeed, the total flux of the CO(3-2) line emission is about 1677 Jy km s^{-1}. Previous observations with the James Clerk Maxwell Telescope indicate that around 13% of the total flux observed with a single-dish telescope appears to be missing flux. Furthermore, when compared to the values obtained by Wilson et al. [9] using the JCMT, the missing flux of CO(3-2) is estimated to be roughly 25% in the core 2.6 arcsec region.

Figure 4 shows channel map of the CO(3-2) line of the galaxy NGC 1614 with a velocity channel width of 20.32 km s^{-1}. CO(3-2) line emission is detectable from 4504.19 km s^{-1} to 4890.25 km s^{-1}. The channel maps explain the ring spatially and the characteristics of the gas distribution in NGC 1614. It is clear from Figure 4 that there is a velocity gradient in the ring from north to south. The southern portion of the ring displays brighter than the northern portion at higher velocities.

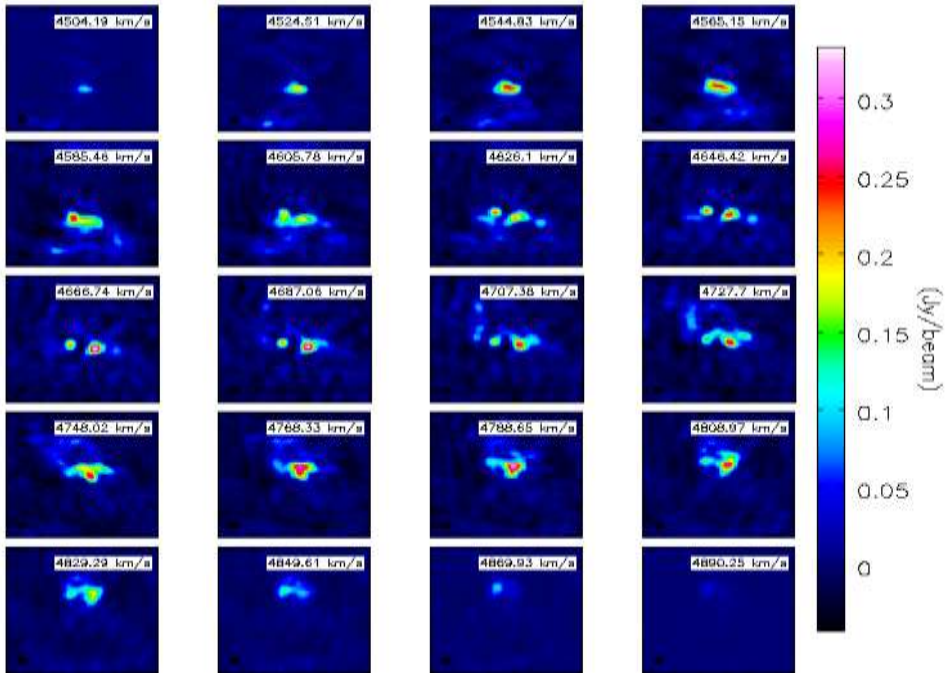

Figure 3: Moment 0 map of CO (3-2) line in the central region of NGC 1614 with the synthesized beam size 0.59"× 0.39" (referred to the white ellipse that was located in the bottom left corner of the panel).

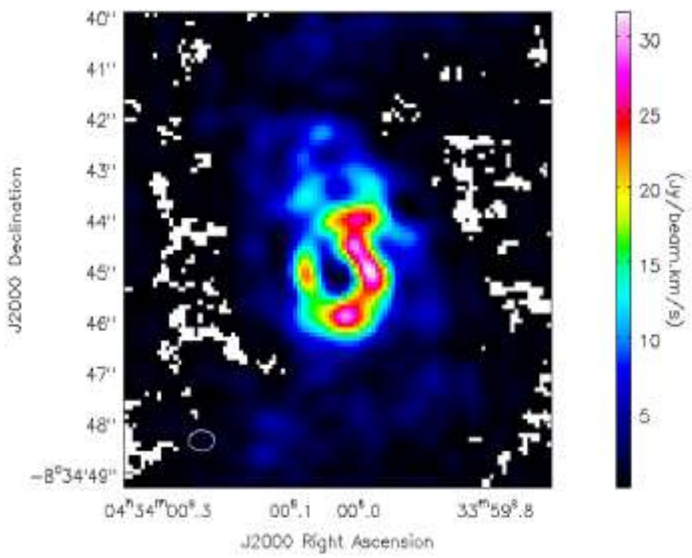

Figure 4: CO (3-2) Channel maps of the galaxy NGC 1614 with a velocity channel width of 20.32 km s^{-1} and a system velocity of 4723 km s^{-1}. The right wedge shows color scale range in Jy $beam^{-1}$.

3.2 Determination of Rotation curve

Rotation curve is still one of the important tools to probe the circular motions within a galaxy. Moreover, it is used as evidence to study the missing matter in the galaxies [10]. However, obtaining the rotation curve parameters is difficult due to the fact that several of galaxies understudy are not very inclined and that the majority of the velocity fields are only sparsely sampled [11]. In this research, CO (3-2) emission is used as a tracer of molecular gas because it is sensitive to warm and dense gas and can measure higher temperatures and densities than other CO transitions. This makes it a useful tool for making the rotation curve.
The rotation of galaxies can be studied in the spatial direction by deriving position-velocity (PV) diagrams along the kinematic axis (major) using the cube map [12]. Figure 5 shows the position- velocity (PV) diagram at different cuts, the major axis (352˚) and the minor axis (82˚) of position angles. Based on the tilted-ring method of previous studies [13] [14], the true velocity (V_{rot}^2) can be obtained from $\mathrm{V}_{\mathrm{obs}}^2\,(\mathrm{r}) = \mathrm{V}_{\mathrm{sys}}^2 + \mathrm{V}_{\mathrm{rot}}^2(\mathrm{r}) \cos\theta \sin i$ (See Figure 6), where the true velocity depends on the parameters: inclination (i), PA, azimuthal angle (θ) in the galactic plane and systemic velocity (V_{sys}^2). The rotation curve can be represented by the sum of disk, halo, and gas contributions [15].

$$\mathrm{V}_{\mathrm{rot}}^2 = \mathrm{V}_{\mathrm{disk}}^2 + \mathrm{V}_{\mathrm{gas}}^2 + \mathrm{V}_{\mathrm{halo}}^2 \qquad (1)$$

Using a 2D Gaussian fit in CASA software, we determined the inclination angle as i=cos-1(b/a) [16], where b and a are the minor and major axes, respectively (See Table 1 for more details). Our results, i=51^{o}, were similar to those obtained by Olsson et al. [17], who also determined that the inclination angle is equal to 51^{o}. We found the midpoint velocity of 4723 km s^{-1} to be more typical of the systemic velocity for NGC 1614 since the CO distribution was obviously asymmetric, with more gas on the approaching side than the receding side (See Figure 7).

Table 1: Properties of the galaxy NGC 1614

Property	Value
RA(J2000)	04:34: 00:036
Dec(J2000)	-08:34 :45:08
Morphology	SB(s)c pec
z	0.015938
Luminosity distance, D_L	64 Mpc
Linear scale	1"= 310pc
vsys	4723
Major axis	3.11±0.47 arcsec
Minor axis	1.94± 0.51 arcsec
i	51^{o}
PA	271^{o}

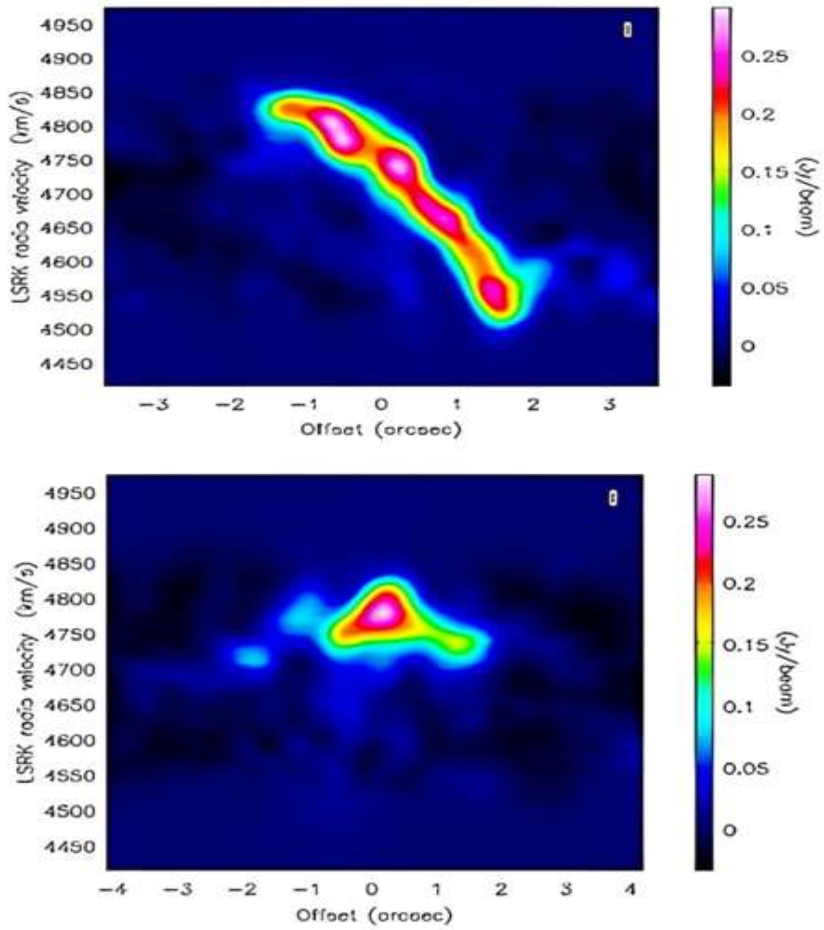

Figure 5: CO Position-Velocity diagrams of NGC 1614 at various position angles. (a) PV with PA.=325° and (b) PV with PA.=82°. The slit width of a PV cut is 1″.

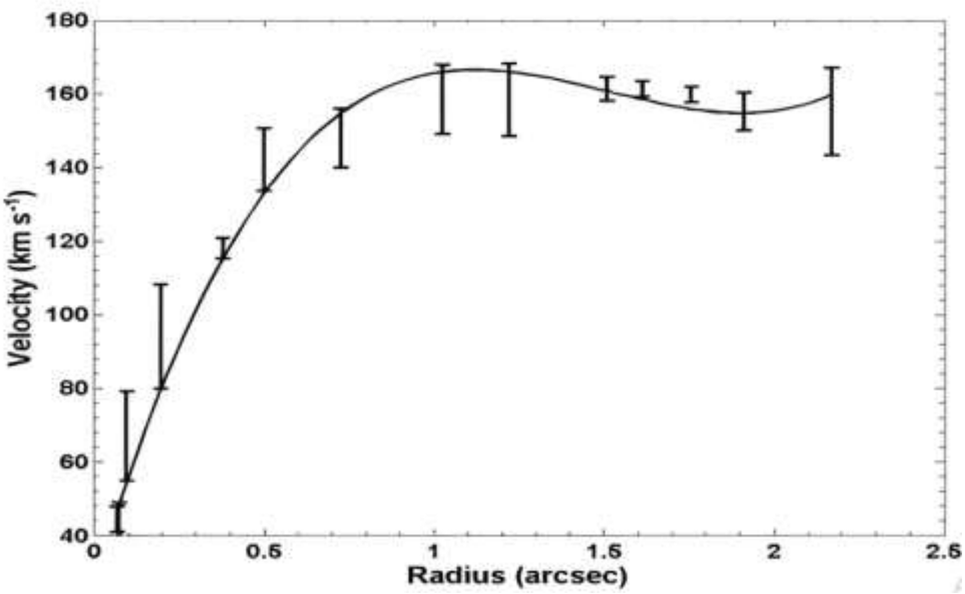

Figure 6: Rotation curve of central region of NGC 1614. The data points are represented by the dots with error bars, and the solid curve represents the fitting.

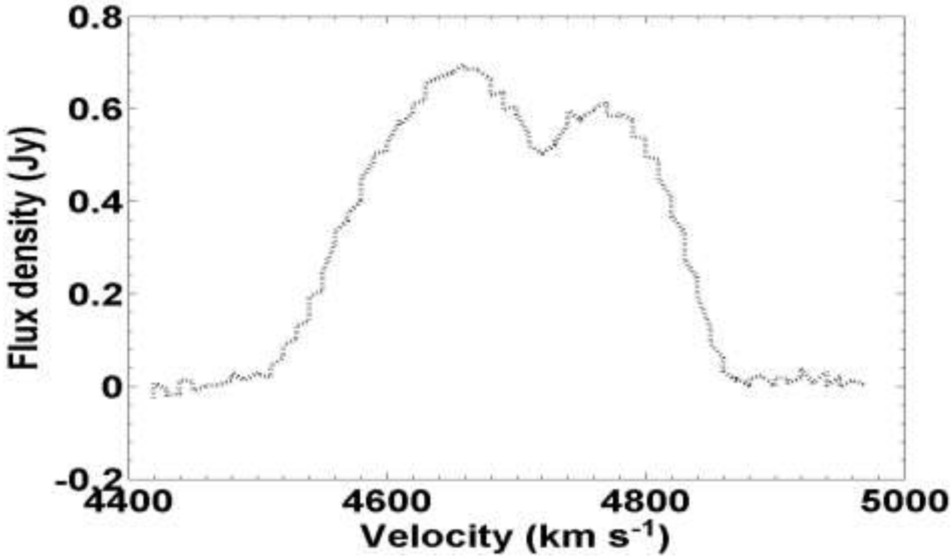

Figure 7: CO(3-2)line profile of NGC 1614 from the ALMA data cube.

3.2 Dynamical Mass

The total mass can be estimated within the radius R using the expression below [18]:

$$M_{tot} = 2.3 \times 10^5 \times R \times v^2 M_{\odot} \quad (2)$$

Where v represents the rotational velocity along the line of sight determined by using the calculation shown above at a center radius of 1.5". As a result, the M_{tot} of NGC 1614 was determined to be $(2.8 \pm 0.08) \times 10^9$ $M_{\odot}$ using the estimated velocity of 161 km s^{-1}. Within a radius of 1.5", the total mass was obtained using the rotation curve, which should include all baryonic masses (stars, gas, SMBH), as well as dark matter. Previous studies found that the velocity structure of all CO emission was controlled by rotation [19]. Toshiki et al. mentioned that the velocity fields of the starburst ring and the outer disk were seamlessly connected, indicating that the kinematics were comparable [20].

A merger is a crucial event in the development and evolution of galaxies in the cosmos, and is linked to the brightest AGN activity and other characteristics, including rapid star production [21] [22]. There have been a lot of theoretical and empirical studies of mergers, and yet there is still a lot we don't know about the process. The mechanism that sets off the burst of star formation during a galactic merger is thought to be the interaction of molecular gas. Tracking how a merger happen through different stages is a convenient way to know more details of the process. Star formation processes, for example the physical and chemical characteristics of molecular gas and its dynamics, need a comprehension the regions of massive star formation, which are mergers and contacts.

4. Total Mass Comparison

Our analysis of ALMA observations of CO (3-2) has demonstrated that the total mass in NGC 1614 is about 2.8 x 10^9 $M_{\odot}$ within a radius of 1.5". This value is slightly higher than the estimates provided by Shier et al. in 1994, who determined the total mass within the same region to be 2×10^9 $M_{\odot}$ using the velocity dispersion of CO (1-0) [23], and Imanishi et al., who obtained a mass of around 2×10^9 $M_{\odot}$ using the HCO+ J = 4-3 line [24].

It is worth mentioning that the various emission lines and methods utilized in previous studies may have contributed to the slight variations in estimated masses. CO (3-2) is commonly preferred for measuring the rotation curve of a galaxy because it is more sensitive to the denser and warmer molecular gas in the central regions of the galaxy, where the rotation curve is most affected by the gravitational potential of the central black hole and the dark matter halo. Furthermore, CO (3-2) has higher spatial resolution than CO (1-0) and HCO+ (4-3), allowing for improved tracing of gas dynamics and more exact rotation curve identification [25].

5. Conclusion

From this work, we can estimate the total mass of inner region in the spiral galaxy NGC 1614 throughout analysing the ALMA data related with emission line CO (3-2), that used mostly for tracking the molecular gas in the galaxies. The (3-2) transition of CO emission is at a frequency of 345.795 GHz, and it is a good tracer of dense and warm molecular gas, which is typically found in the central regions of galaxies. The analysis reveals that the value of the total mass is about 2.8×10^9 $M_\odot$ at 0.5 kpc (1.5"). To accurately determine the dynamical mass, it is crucial to consider all baryonic masses, including stars, gas, and supermassive black holes (SMBHs), as well as dark matter. Therefore, there are plans and motivations in the next paper to investigate the missing matter and gain a deeper understanding of galaxy evolution.

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