*Azeez* *Iraqi Journal of Science, 2024, Vol. 65, No. 10(SI), pp: 5900-5908*
*DOI: 10.24996/ijs.2024.65. 10(SI).1*

**ISSN: 0067-2904**

# Spatially Resolved Characteristic of the Merging Galaxy VV114 as Seen by ALMA

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Received: 27/9/2023 Accepted: 14/**7**/2024 Published: 15/11/2024

**Abstract**

Merging galaxies provide an excellent laboratory for investigating several physical properties related to the merging processes. In this research, high-resolution $^{12}$CO (J= 1 – 0) data of the molecular gas was reported in the merging galaxy VV114 from the Atacama Large Millimetre/Sub-millimetre Array (ALMA) to study some of the physical characteristics at the sub-kpc scale. Infrared (IR) data from the Spitzer Space Telescope was used to determine the star formation rate (SFR) and were compared with the properties of the molecular gas. The molecular gas map was divided into 12 regions with a scale of (500 – 600) pc in the CO (1 – 0) integrated intensity and velocity dispersion map. The findings showed a low value for the index of the star formation law for both northeast VV114E and southwest VV114W regions, this may be due to a strong turbulent pressure that could restrict star-formation activity in galaxies at hundreds-parsec scales, causing the Kennicutt-Schmid (KS) law power index to reduce. A significant positive correlation between CO (1 – 0) luminosity surface density and velocity dispersion. The correlation between the SFR surface density and the velocity dispersion was moderate for the VV114E and strong for the VV114W.

**Keywords:** Galaxies, Star formation, Velocity dispersion, ALMA, VV114.

# الخصائص المحللة مكانيا" للمجرة المدمجة (VV114) كما شوهدت بواسطة الما

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**الخلاصة**

المجرات المدمجة تزودنا بمختبر ممتاز لفحص عدد من الخصائص الفيزيائية المتعلقة بهذه العملية. في هذا البحث نستخدم بيانات عالية الدقة من الخط الطيفي للغاز الجزيئي أحادي أوكسيد الكاربون في المجرة المدمجة VV114 من تلسكوب (الما) لغرض دراسة بعض الخصائص الفيزيائية في نطاق أجزاء من الكيلو فرسخ فلكي. تم استخدام بيانات الأشعة تحت الحمراء (IR) من تلسكوب سبيتزر الفضائي لتحديد معدل تكوين النجوم (SFR) ومقارنتها بخصائص الغاز الجزيئي. تم تقسيم خريطة الغاز الجزيئي الى 12 منطقة بمقياس (500– 600) فرسخ فلكي. أظهرت النتائج التي توصلنا إليها قيمة منخفضة لمعامل قانون تكوين النجوم لكلا من المنطقة الشمالية الشرقية VV114E والمنطقة الجنوبية الغربية VV114W للمجرة، وقد يكون هذا بسبب ضغط مضطرب قوي يمكن أن يحد من نشاط تشكل النجوم في المجرات على مقياس مئات من الفرسخ فلكي،

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مما يتسبب في تقليل معامل قانون تكون النجوم. هناك علاقة إيجابية معنوية بين كثافة سطح لمعان احادي أكسيد الكربون (1 – 0) وتشتت السرعة. كان الارتباط بين كثافة سطح SFR وتشتت السرعة معتدلاً بالنسبة لـ VV114E وقويًا بالنسبة لـ VV114W.

## 1. Introduction

Stars are essential elements of galaxies, so they should be investigated in studies of galaxies' backstories and future growth paths. The precise method by which gas transforms into stars remains a mystery [1]. Star formation is thought to be regulated by gas dispersion in the interstellar medium (ISM) [2].

The physical processes that govern galaxy development result in correlations between galaxies' characteristics and their invisible haloes. Various parameters of galaxies (e.g., star formation rate SFR, star mass, brightness, velocity dispersion) may thus be studied and compared to get insight into these processes [3]. As a result, many empirical scaling rules have been discovered. An accurate, quantitative estimation of the relationship between SFR and gas density is essential to understanding galaxy evolution because it describes how efficiently galaxies convert their gas into stars and constrains theoretical models of star formation.

Kennicutt investigated the global average link between SFR and gas density in 61 neighbouring normal spiral galaxies and 36 starburst galaxies. Over several orders of magnitude, this study demonstrated that Schmidt's law connects the total gas surface density, to the star formation surface density, SFR [4]. Other researchers investigated a local Schmidt law utilizing radial distributions of SFR and gas. The wide variety of power-law indices reported in the literature shows either various star formation laws occur throughout various galaxies or that the index $N$ is extremely sensitive to systematic changes in observation methods.

In this paper, Atacama Large Millimetre Sub-Millimetre Array (ALMA) data of the merging galaxy VV 114 (also, known as IC1623 and ARP236) was presented. It is a close Luminous Infrared Galaxy (LIRG) that has two unique progenitor galaxies, which represents one of the most suitable examples for investigating gas characteristics during the essential stage whilst two distinct gas disks interact [5], [6]. VV 114 is a gas-rich ($M_{H2} = 5.1 \times 10^{10} M_{\odot}$; [7]) nearby (D = 82 Mpc) interacting system [8]. This research aims to measure the relation between SFR, CO line luminosity, and velocity dispersion in the merging galaxy VV114 on a rising spatially resolved scale of about 600 pc. The manuscript is structured as follows. The description of high-resolution data from ALMA is presented in Section 2. Section 3 explains and interprets the results. Lastly, in Section 4 the findings are summarized.

## 2. Data Description

Observation of merged galaxy VV 114 was taken from the archival data of (ALMA) [9]. The $^{12}$CO (1-0) emission line with a rest frequency of 115.27 GHz was obtained on May 4, 2012. The restoring beam of $^{12}$CO (1-0) was 1.33″ × 1.081″ with a position angle = 85.92°. The observation was centred on RA = $01^h07^m47.208^s$, Dec = -17° 30′ 24.480″. The delivered calibrated data was used and the imaging was accomplished using the Common Astronomy Software Applications (CASA). The velocity resolution for the CO line is about 10 km/s with the total on-source time about 2425 s. The root mean square (rms) level of the moment 0 map is 4.84 Jy km/s. The flux density is about 78.42 Jy km/s. The integrated intensity and the velocity dispersion maps are shown in Figures 1a, and 1b respectively. The properties of

VV114 are listed in Table 1. At a luminosity distance 82 Mpc, the 1.33″ × 1.08″ restoring beam of the $^{12}CO(1\text{–}0)$ observation provides a resolution of 532 pc × 432 pc.

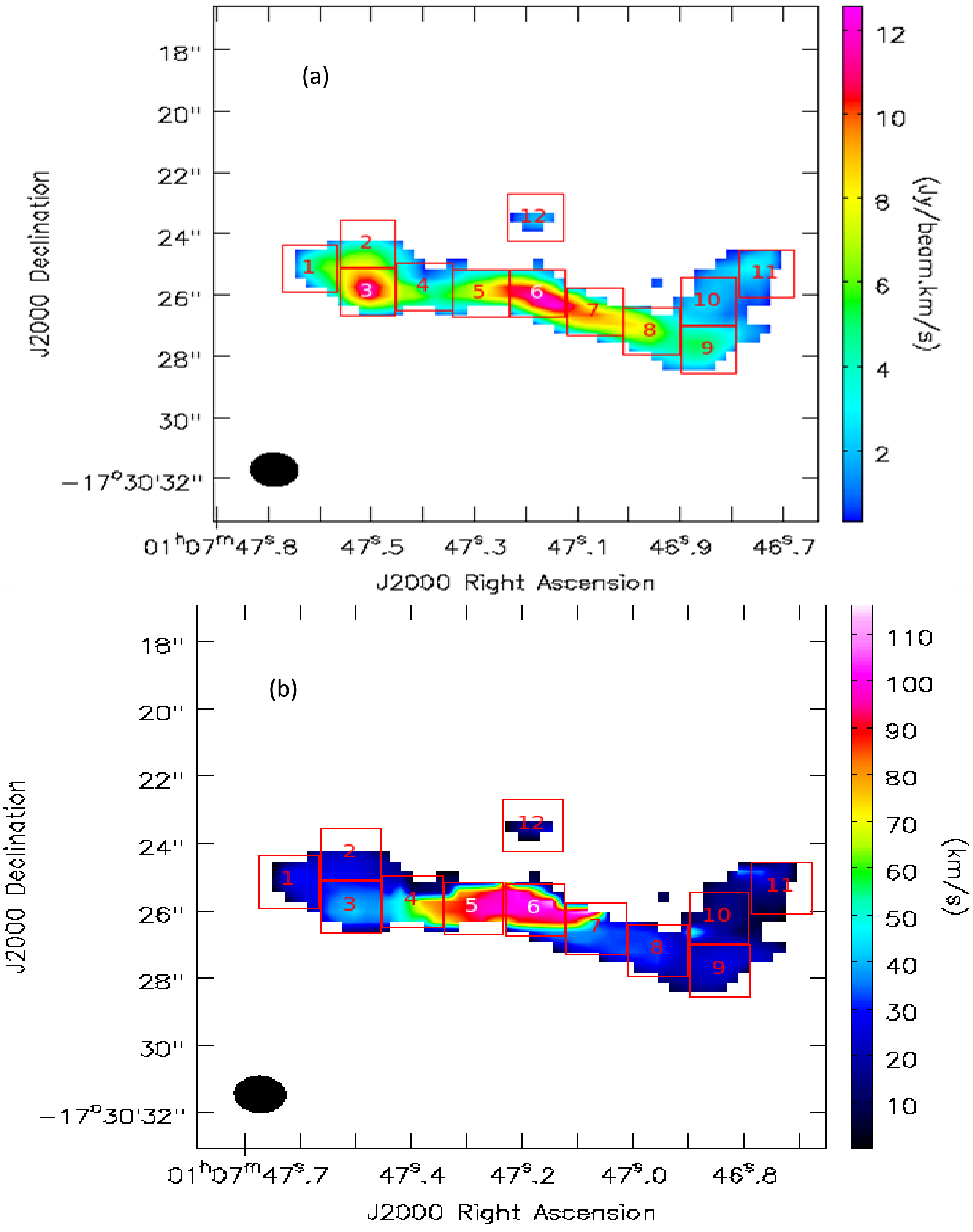



**Figure 1:** (a) The $^{12}CO$ (1-0) integrated intensity (moment 0) map for VV114 from ALMA, and (b) the velocity dispersion (moment 2) map for VV114 from ALMA. Both maps are divided into boxes with a size of 1.5″ × 1.5″ for each box, which corresponds to 0.6 kpc × 0.6 kpc. Boxes numbered (R1-R5, and R12) represent the northeast region (VV114E), and the boxes numbered (R6-R11) represent the southwest region (VV114W).

**Table 1:** Properties of the merging galaxy VV114

| Property | Value | Reference |
|---|---|---|
| Object type | Gpair | NED |
| Other Name | IC 1623 | NED |
| Redshift | 0.02007 | NED |
| Distance | 82 Mpc | [8] |
| Rest frequency | 115.271 GHz | This Work |
| Restoring beam | 1.33″ × 1.081″ | This Work |
| Position angle | 85.92° | This Work |
| Velocity Resolution | 10 km/s | This Work |
| Systematic Velocity | 6040 km/s | [7] |

## 3. Results and Discussions

To estimate some physical characteristics such as SFR surface density, CO luminosity distance, and velocity dispersion the galaxy region is divided into 12 boxes, which are numbered (R1 – R12). As it is well known this galaxy is composed of the merging of two galaxies; the first lies in the northeast region (VV114E) and the other in the southwest region (VV114W). Therefore, this will be considered in the present study [8]. The size of each box is 1.5″ × 1.5″ which is equivalent to 600 pc × 600 pc (see Figure 1a and 1b). The boxes' dimensions are selected approximately close to (not smaller than) the size of the beam. The coordinates of each region are listed in Table 2.

CO emission is the best molecular hydrogen tracer for two reasons. It is the most prevalent molecule after $H_2$ and it is an extremely stable molecule. In addition, a minimal dipole moment indicates that collisions with $H_2$ at low densities excite and thermalize CO rotational levels. Significant CO emission from $H_2$-dominated interstellar gas is widespread due to the abundance of these gases in the galaxies and within the interstellar medium. The majority of the molecular gas is tracked by CO (1-0). Using the CO flux, it is possible to determine the line luminosity from the CO (1 – 0) integrated intensity (moment 0) map from ALMA for the merging galaxy VV114. The CO flux density may be transformed into the line luminosity $L_{line}$ using the following formula (assuming the distance $D_L$ = 82 Mpc)[8]:

$$\left(\frac{L_{line}}{L_\odot}\right) = 1.04 \times 10^{-3}\left(\frac{v_{rest}}{GHz}\right)(1+z)^{-1}\left(\frac{S\Delta v}{Jy.km/s}\right)\left(\frac{D_L}{Mpc}\right)^2 \quad (1)$$

where $v_{rest}$ is the rest frequency, $z$ is the redshift, and $S\Delta v$ is the integrated flux density (see Table 2). The Infrared data was utilized to calculate the rate of star formation. The IR data at 24 μm come from the public archive of the Multiband Imaging Photometer (MIPS) of the Spitzer Space Telescope. Wu demonstrated that the dust emission at 24 μm may be employed for estimating star formation [10]. Using the Spitzer MIPS 24μm fluxes, the SFR was calculated using the following formula [11]:

$$\frac{SFR}{M_\odot yr^{-1}} = \frac{v\,L_v[24\mu m]}{6.66\times10^{8} L_\odot} \quad (2)$$

where $v\,L_v[24\mu m]$ is the integrated luminosity at $24\mu m$. Within each region at a box size of 1.5" × 1.5", we converted the SFR and CO line luminosity into units of surface density. These values are listed in Table 2.

Figure 2 displays the comparison between SFR surface density and CO luminosity density in the northeast and southwest regions of the merging galaxy VV114. It is well known that

VV114 is an interacting galaxy, therefore the merging process may influence the high molecular density in this galaxy. Though there are various methods for determining correlation, the most frequent is the so-called Pearson ***r*** or simple linear correlation. As a result, this correlation will be used. The SFR surface density and CO luminosity density for the northeast component and the southwest component exhibited a strong positive correlation. The correlation coefficient ***r*** and probability value ***p*** for VV114E were 0.86 and 97.4%, while for the VV114W were 0.90 and 98.5%, respectively. The power-law index found for both components of VV114 has a lower value than the typical KS law. The cause of the deviation from the KS law index is yet unknown. Onodera noticed, that the KS law on the Local Group spiral galaxy M33 is strongly correlated in the 1 kpc scale but breaks down at the giant molecular clouds (GMC) scale [12]; the breakdown might be ascribed to the distinguished evolutionary phases of GMCs. On the other hand, strong turbulent pressure could restrict star-formation activity in galaxies at hundreds-parsec scales, causing the KS law power index to reduce. Kruijssen, for example, discovered that when there is significant turbulent pressure in the core molecular zone (CMZ, i.e., the center 500 pc), the volume density threshold for star formation increases [13].

**Table 2:** Data information from each region with a box size 1.5" × 1.5"

| Region No. | Right Ascension | Declination | Flux Density (Jy.km/s) | $F_{24\,\mu m} \times 10^{-2}$ (Jy) | ∑SFR ($M_\odot\ yr^{-1}\ kpc^{-2}$) | σ (km/s) | $\sum L_{co} \times 10^{12}$ ($L_\odot\ kpc^{-2}$) |
|---|---|---|---|---|---|---|---|
| 1 | $01^h\ 07^m\ 47^s.619$ | -17°.30′.25″.109 | 4.82 | 3.53 | 3.79 | 18.50 | 4.70 |
| 2 | $01^h\ 07^m\ 47^s.507$ | -17°.30′.24″.285 | 6.73 | 3.59 | 3.86 | 22.66 | 6.57 |
| 3 | $01^h\ 07^m\ 47^s.507$ | -17°.30′.25″.852 | 13.29 | 5.28 | 5.67 | 30.49 | 12.97 |
| 4 | $01^h\ 07^m\ 47^s.396$ | -17°.30′.25″.687 | 6.67 | 3.23 | 3.47 | 38.60 | 6.51 |
| 5 | $01^h\ 07^m\ 47^s.287$ | -17°.30′.25″.902 | 9.13 | 3.23 | 3.47 | 67.66 | 8.91 |
| 6 | $01^h\ 07^m\ 47^s.176$ | -17°.30′.25″.922 | 13.23 | 1.81 | 1.94 | 66.04 | 12.91 |
| 7 | $01^h\ 07^m\ 47^s.065$ | -17°.30′.26″.506 | 11.44 | 1.61 | 1.73 | 41.99 | 11.16 |
| 8 | $01^h\ 07^m\ 46^s.955$ | -17°.30′.27″.162 | 8.84 | 1.61 | 1.73 | 24.48 | 8.62 |
| 9 | $01^h\ 07^m\ 46^s.844$ | -17°.30′.27″.766 | 5.75 | 1.53 | 1.64 | 19.68 | 5.61 |
| 10 | $01^h\ 07^m\ 46^s.845$ | -17°.30′.26″.168 | 3.44 | 1.50 | 1.61 | 15.80 | 3.36 |
| 11 | $01^h\ 07^m\ 46^s.733$ | -17°.30′.25″.281 | 2.27 | 1.15 | 1.24 | 13.12 | 2.21 |
| 12 | $01^h\ 07^m\ 47^s.179$ | -17°.30′.23″.449 | 0.79 | 2.23 | 2.39 | 8.52 | 0.79 |

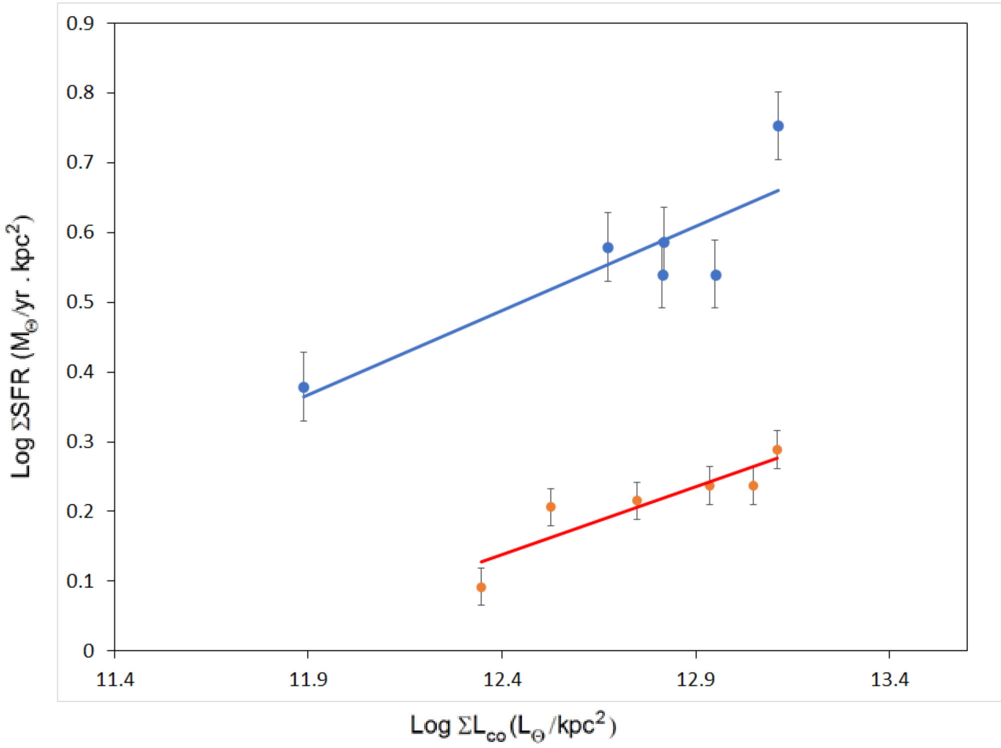
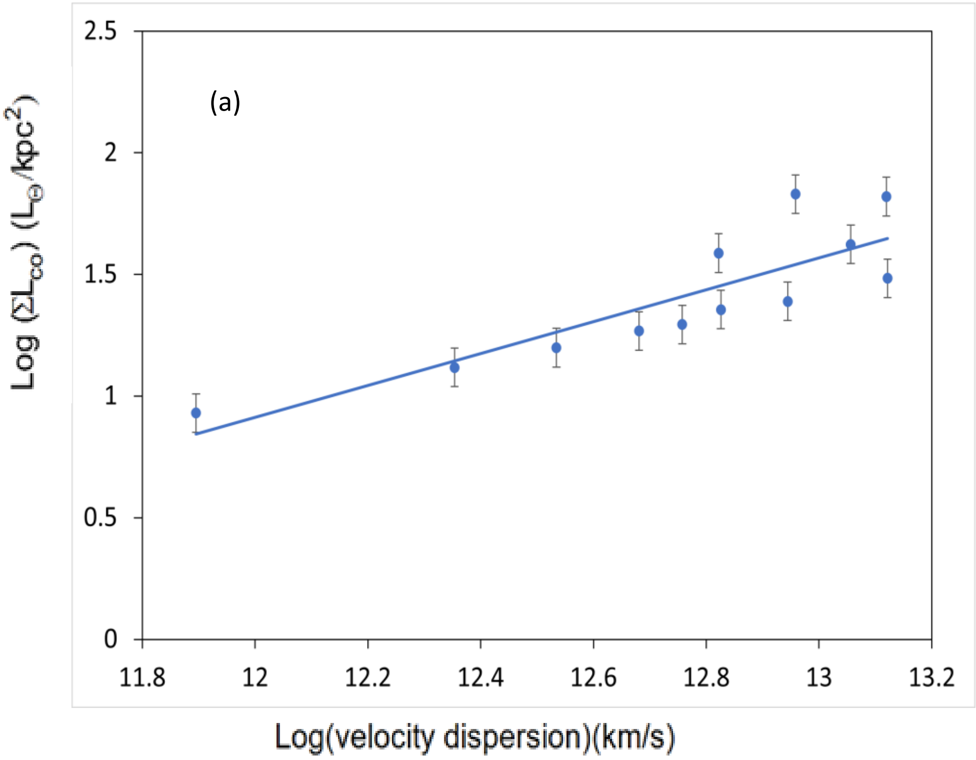



**Figure 2:** ∑SFR as a function of ∑Lco$_{(1-0)}$ in the merging galaxy VV114 at 600 pc resolution. The blue dots and line represent the data of the VV114E from the boxes (R1 – R5, R12) and the linear fit to these data points. The red dots and line represent the data of the VV114W from the boxes (R6 – R11) and the linear fit to these data points.

The velocity dispersion for each region was estimated from the moment 2 map (Figure 1b). The velocity dispersion values varied from 8.52 km/s in R12 to 67.66 km/s in R5 with an average value of 30.63 km/s. The relationships between the velocity dispersion and CO (1 – 0) luminosity surface density have been explored for VV114 as denoted in Figure 3a. This Figure is distinguished by a significantly positive correlation between the $^{12}$CO(1 - 0) luminosity surface density and velocity dispersion. The coefficient ***r*** of correlation between the ∑Lco and velocity dispersion is 0.85 with a probability *p* = 99.9%. This result is consistent with the other published studies [14]. Figure (3b) displays the relationships between the velocity dispersion and SFR surface density in the northeast and southwest regions of the merging galaxy VV114. This figure shows a moderate positive correlation between the SFR surface density and velocity dispersion with correlation coefficient ***r*** = 0.47 and probability ***p*** = 64.8% for VV114E, while for the VV114W a strong positive correlation is found between the SFR surface density and velocity dispersion with correlation coefficient ***r*** = 0.82 and probability ***p*** = 95.5%. In general, the data show low-velocity dispersion values. Low-velocity dispersion values are typically related to low SFR values, according to [15]. The calculated average value suggests that star formation is low in this merging galaxy. This implies that there is lacking gravitational collapse and, therefore low star formation.



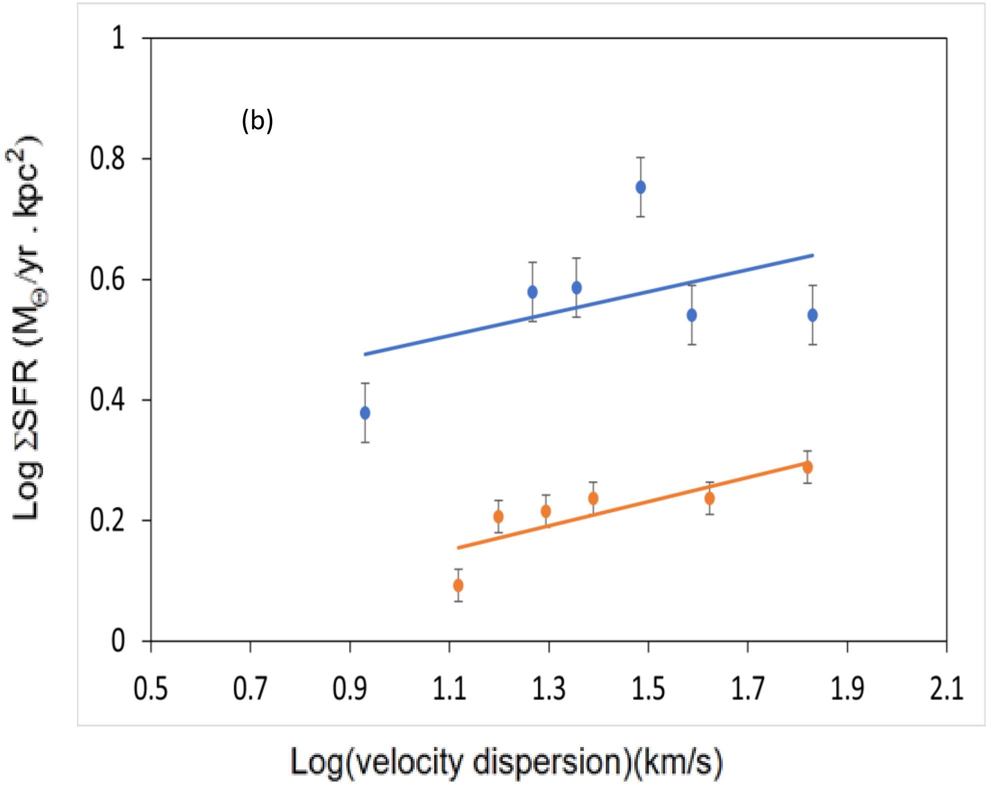




**Figure 3:** (a) The relation between $\sum Lco_{(1-0)}$ and velocity dispersion in the merging galaxy VV114 at 600 pc resolution (b) The relation between $\sum$SFR and velocity dispersion. The blue dots and line represent the data of the VV114E from the boxes (R1 – R5, R12) and the linear fit to these data points. The red dots and line represent the data of the VV114W from the boxes (R6 – R11) and the linear fit to these data points.

## 4. Conclusions

In the present work, high-resolution ALMA data was used with the Spitzer telescope to study some physical characteristics of the galaxy VV114. From the results, the following remarks are noted:

1. The relation between CO luminosity surface density, and star formation rate surface density was investigated. The results showed two regions; the first is the northeast region VV114E and the second is the southwest region VV114W. For both regions the fitting for the power law index when using a data point at a box size of 1.5″ is very low and deviates from KS law, this is because high turbulent pressure can limit star-formation activity in galaxies at hundreds-parsec scales, lowering the KS law power index.
2. The average velocity dispersion value was found close to ($\sigma_{ave}$ = 30.63 km/s), which is consistent with poor star formation due to no gravitational collapse, resulting in no star formation.
3. The velocity dispersion was found to be significantly correlated with the $^{12}$CO (J = 1 - 0) luminosity surface density, the data points showed a unified behavior between the northeast and the southwest regions.
4. The velocity dispersion was found to have a moderate correlation with SFR surface density for the VV114E, while the velocity dispersion showed a strong correlation with SFR surface density in the VV114W.
5. The results showed two different behaviors between the northeast and southwest regions whenever the SFR surface density is found. This indicates different mechanisms that trigger star formation between the VV114E and the VV114W.

## 5. Disclosure and conflict of interest

“Conflict of Interest: The authors declare that they have no conflicts of interest.”

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