NOEMA Observations of CO Emission in Arp 142 and Arp 238

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Abstract

Previous studies have shown significant differences in the enhancement of the star formation rate (SFR) and star formation efficiency (SFE = SFR/M_{mol}) between spiral–spiral and spiral–elliptical mergers. In order to shed light on the physical mechanism of these differences, we present NOEMA observations of the molecular gas distribution and kinematics (linear resolutions of ~2 kpc) in two representative close major-merger star-forming pairs: the spiral–elliptical pair Arp 142 and the spiral–spiral pair Arp 238. The CO in Arp 142 is widely distributed over a highly distorted disk without any nuclear concentration, and an off-center ringlike structure is discovered in channel maps. The SFE varies significantly within Arp 142, with a starburst region (region 1) near the eastern tip of the distorted disk showing an SFE ~ 0.3 dex above the mean of the control sample of isolated galaxies and the SFE of the main disk (region 4) 0.43 dex lower than the mean of the control sample. In contrast, the CO emission in Arp 238 is detected only in two compact sources at the galactic centers. Compared to the control sample, Arp 238-E shows an SFE enhancement of more than 1 dex, whereas Arp 238-W has an enhancement of ~0.7 dex. We suggest that the extended CO distribution and large SFE variation in Arp 142 are due to an expanding large-scale ring triggered by a recent high-speed head-on collision between the spiral galaxy and the elliptical galaxy, and the compact CO sources with high SFEs in Arp 238 are associated with nuclear starbursts induced by gravitational tidal torques in a low-speed coplanar interaction.

Unified Astronomy Thesaurus concepts: Galaxy pairs (610); Interacting galaxies (802); Galaxies (573); Galaxy collisions (585); Galaxy mergers (608)

1. Introduction

It is well documented that mergers can trigger enhanced star formation in galaxies (Kennicutt et al. 1987; Sanders & Mirabel 1996). The most extreme starbursts, such as the ultraluminous infrared galaxies (ULIRGs; L_{IR} ≥ 10^{12} L_{o}), are usually found in the final stage of mergers (Sanders & Mirabel 1996). Strong star formation enhancements are also detected in earlier merger stages, particularly in major mergers (mass ratio less than 3) during close encounters (Xu & Sulentic 1991; Nikolic et al. 2004; Ellison et al. 2010; Scudder et al. 2012). On the other hand, only a small fraction of interacting galaxies show significant star formation enhancement (Horellou et al. 1999; Bergvall et al. 2003; Knappen & James 2009). Spitzer observations of a sample of K-band selected close major-merger pairs (Xu et al. 2010), which preferentially select early mergers during or near the first and second pericentric passages, found that only ~25% of star-forming galaxies in the sample show strong enhancement in specific star formation rate (sSFR = SFR/M_{star}, where SFR is the star formation rate in M_{\odot} yr^{-1} and M_{star} is the stellar mass in M_{\odot}). Furthermore, the far-infrared (FIR) observations by Spitzer and Herschel show that only star-forming galaxies in spiral–spiral (hereafter S+S) pairs have significantly enhanced sSFRs, not those in spiral–elliptical (hereafter S+E) pairs (Xu et al. 2010; Cao et al. 2016). The low fraction of paired galaxies with enhanced sSFR is often interpreted as due to the fact that strong starbursts triggered by interactions are “on” only for short periods (~100 Myr), while at most times, a merging galaxy is in the “off” phase of the starburst (DiMatteo et al. 2008). However, this interpretation cannot explain the nonenhancement of sSFR in star-forming galaxies in S+E pairs, which represent 34% of star-forming galaxies in a complete sample of K-band selected close major-merger pairs (KPAIR; Domingue & Xu et al. 2009). It was suggested (Park & Choi 2009; Hwang et al. 2011) that the lack of star formation enhancement in S+E pairs could be due to stripping of the cold gas of the spiral component by ram pressure of the hot gas halo surrounding the elliptical component. But this hypothesis is rejected by the results of Zuo et al. (2018) and Lisenfeld et al. (2019). Lisenfeld et al. (2019) carried out Institute of Radio-astronomy in the Millimeter (IRAM) CO observations for 78 spiral galaxies selected from the H-KPAIR sample of 88 close major-merger pairs that have Herschel FIR observations (Cao et al. 2016). Combining with the GBT HI observations of Zuo et al. (2018) for pairs selected from the same H-KPAIR sample, Lisenfeld et al. (2019) found no significant difference between the total gas abundances of star-forming galaxies in S+E and S+S pairs. Indeed, their results show that the reason for spiral galaxies in S+E pairs to have a significantly lower sSFR than their counterparts in S+S pairs (Xu et al. 2010; Cao et al. 2016) is that they have significantly lower molecular-to-total gas ratios (M_{H_2}/(M_{HI} + M_{H_2})) and a lower star formation efficiency (SFE = SFR/M_{H_2}).

In this article, we present Northern Extended Millimeter Array (NOEMA) CO imaging observations of two representative pairs: Arp 142 (S+E) and Arp 238 (S+S). In the sample of Lisenfeld et al. (2019), the spiral component of Arp 142 (NGC 2936) has the highest SFR among galaxies in S+E pairs.
Arp 238-E (UGC 8335-E), a luminous infrared galaxy (LIRG; $L_{IR} > 10^{11} L_{\odot}$), has the second-highest SFR among galaxies in $S+S$ pairs (see Table 2). Interestingly, the SFE in Arp 142 is ~30 times lower than that in Arp 238-E (Lisenfeld et al. 2019). With the NOEMA observations, we aim to probe the cause of the strong difference between the SFEs of the two pairs, which may also shed light on the physical mechanism for the SFE difference between S+E and S+S pairs in general.

2. Observations

The CO(1–0) was observed with the NOEMA of the IRAM in the C and D arrays with 10 antennas (project W19BL). The observations were carried out under good weather conditions. For each object, we made a small mosaic consisting of two overlapping regions. The receiver covers two sidebands, each with a width of 7.744 GHz. The autocorrelator PolyFix was used, which has a channel width of 2 MHz (corresponding to 5.3 km s$^{-1}$ at the frequency of our observations). The line frequency was tuned in the upper sideband (USB). Some basic parameters of the observations are listed in Table 1.

We reduced the data following standard procedures using the GILDAS software. The data were calibrated using the IRAM package Continuum and Line Interferometer Calibration (CLIC). The standard pipeline reduction and calibration was followed to a large extent, but some poor data scans were flagged, and the use of the standard flux calibrator had to be enforced in one observing run. From the resulting $uv$ tables, a continuum table was produced combining all non-line channels in both sidebands with the tasks $uv_{\text{cont}}$ and $uv_{\text{merge}}$. For the line data, a constant baseline was subtracted from the calibrated $uv$ tables in the USB. We then reduced the table size by extracting only the channels with line emission and channels nearby. Finally, we produced $uv$ tables with four different frequency resolutions using the task $uv_{\text{compress}}$: the original 2 MHz resolution, 4 MHz (corresponding to 10.6 km s$^{-1}$), 8 MHz (corresponding to 21.3 km s$^{-1}$), and 12 MHz (corresponding to 31.9 km s$^{-1}$).

Table 1
Summary of the CO(1–0) Observations and Properties of the Final Data Cube

|              | Arp 142 | Arp 238 |
|--------------|---------|---------|
| Dates        | 2020 April 12–15 | 2020 May 8–24 |
| Total observing time | 4.4 hr | 3.7 hr |
| Center position of mosaic | R.A.: 09:37:43.90, decl.: 02:45:26.0 | R.A.: 13:15:32.77, decl.: 62:07:37.6 |
| Offsets of mosaic pointings (R.A., decl.) | ($7^\circ 5, 8^\circ 0$) | ($10^\circ 0, –5^\circ 0$) |
| Observed central frequency | 112.644262 GHz | 111.82685 GHz |
| Flux calibrator | LKHA 101 | MW 349 |
| Bandpass calibrator | J0930+0034, J0909+0121 | J1302+5748, J1302+6902 |
| Phase calibrator | J0930+0034, J0909+0121 | J1302+5748, J1302+6902 |
| Mean noise of cleaned image (frequency resolution of 12 MHz) | 1.14 mJy beam$^{-1}$ | 0.73 mJy beam$^{-1}$ |

We imaged the data with natural weighting to maximize the sensitivity. We tested different tapers in order to search for faint extended emission but found no evidence for it. We will therefore use the untapered data (for the beam sizes, see Table 1). We tested different cleaning procedures: the robust algorithm CLEAN introduced by Högbom (1974), the variant developed by Clark (1980), and the method proposed by Steer et al. (1984, hereafter SDI), which represents a cleaning algorithm that is better adapted to extended structures. We finally selected the data cube cleaned with Högbom for the compact source Arp 238 (although no major difference was found when using the Clark algorithm) and the cube cleaned with SDI, which was able to best deal with the extended emission in Arp 142 without producing artifacts. For both objects, we used the recommended loop gain of 0.2 and truncation threshold of 0.2 of the primary beam sensitivity. The velocities in this paper are calculated using the optical convention and are relative to the local standard of rest reference frame.

3. Results

For both Arp 142 and Arp 238, we present integrated CO(1–0) maps, compared to Spitzer-IRAC (Xu et al. 2010) and Hubble Space Telescope (HST) images, in Figure 1. The total integrated CO fluxes, together with other physical parameters, are presented in Table 2. As shown in Figure 1, the CO in Arp 142 is widely distributed within a highly distorted disk of NGC 2936. While the CO traces quite well the star formation region 2 in Figure 1(b), which also coincide with the dust lanes in the Hubble images, there is no CO concentration in the nucleus (region 2 in Figure 1(b)). The total CO flux measured in the NOEMA map of Arp 142 (Table 2) is a factor of 1.35 higher than that detected by the IRAM 30 m (175.3 ± 2.8 Jy km s$^{-1}$; Lisenfeld et al. 2019), because the NOEMA measurement covers a significantly larger area than the IRAM beam (FWHM = 22″). Assuming the standard conversion factor $\alpha_{\text{CO}} = 3.2 M_\odot K^{-1} \text{km s}^{-1} \text{pc}^{2}$ (Bolatto et al. 2013), the total molecular gas mass of Arp 142 is

8 IRAM is supported by INSU/CNRS (France), MPG (Germany), and IGN (Spain).
9 http://www.iram.fr/IRAMFR/GILDAS

10 The HST data are based on observations made with the NASA/ESA Hubble Space Telescope and obtained from the Hubble Legacy Archive, which is a collaboration between the Space Telescope Science Institute (STScI/NASA), the Space Telescope European Coordinating Facility (ST-ECF/ESA), and the Canadian Astronomy Data Centre (CAD/NRC/CSA).
$M_{\text{mol}} = 10^{10.29 \pm 0.02} M_\odot$. This is about a factor of 2 higher than that of Bothwell et al. (2014) based on a CO$(2-1)$ observation of APEX, which has a beam ($27''$) significantly smaller than the size of the CO emission (Figure 1(a)). On the other hand, the $M_{\text{mol}}$ is 0.39 dex lower than that estimated by Lisenfeld et al. (2019), suggesting that the large aperture correction ($f_{\text{aper}} = 3.16$) adopted by Lisenfeld et al. (2019) might have been overestimated.

For Arp 238, CO is detected only in two compact sources at the centers of the two galaxies. Both sources can be fitted well with elliptical 2D Gaussian functions of FWHM $= 4.4'' \times 3.3''$ with P.A. $= 80^\circ$ (Arp 238-E) and FWHM $= 4.4'' \times 3.3''$ with P.A. $= 90^\circ$ (Arp 238-W). Neglecting the small difference between the P.A. of each source and that of the beam (P.A. $= 88^\circ$; Table 1), the intrinsic sizes of these sources after the deconvolution are
2\,\textquotedblright\times\,2\,\textquotedblright\times\,3\,\textquotedblright\times\,3\,\textquotedblright\times\,3\,\textquotedblright\times\,3\,\textquotedblright\times\,3\,\textquotedblright\times\,3\,\textquotedblright\times\,3\,\textquotedblright\times\,3\,\textquotedblright\times\,3\,\textquotedblright\times\,3\,\textquotedblright\times\,3\,\textquotedblright\times\,3\,\textquotedblright\times\,3\,\textquotedblright\times\,3\,\textquotedblright\times\,3\,\textquotedblright\times\,3\,\textquotedblright\times\,3\,\textquotedblright\times\,3\,\textquotedblright\times\,3\,\textquotedblright\times\,3\,\textquotedblright\times\,3\,\textquotedblright\times\,3\,\textquotedblright\times\,3\,\textquotedblright\times\,3\,\textquotedblright\times\,3\,\textquotedblright\times\,3\,\textquotedblright\times\,3\,\textquotedblright\times\,3\,\textquotedblright\times\,3\,\textquotedblright\times\,3\,\textquotedblright\times\,3\,\textquotedblright\times\,3\,\textquotedblright\times\,3\,\textquotedblright\times\,3\,\textquotedblright\times\,3\,\textquotedblright\times\,3\,\textquotedblright\times\,3\,\textquotedblright\times\,3\,\textquotedblright\times\,3\,\textquotedblright\times\,3\,\textquotedblright\times\,3\,\textquotedblright\times\,3\,\textquotedblright\times\,3\,\textquotedblright\times\,3\,\textquotedblright\times\,3\,\textquotedblright\times\,3\,\textquotedblright\times\,3\,\textquotedblright\times\,3\,\textquotedblright\times\,3\,\textquotedblright\times\,3\,\textquotedblright\times\,3\,\textquotedblright\times\,3\,\textquotedblright\times\,3\,\textquotedblright\times\,3\,\textquotedblright\times\,3\,\textquotedblright\times\,3\,\textquotedblright\times\,3\,\textquotedblright\times\,3\,\textquotedblright\times\,3\,\textquotedblright\times\,3\,\textquotedblright\times\,3\,\textquotedblright\times\,3\,\textquotedblright\times\,3\,\textquotedblright\times\,3\,\textquotedblright\times\,3\,\textquotedblright\times\,3\,\textquotedblright\times\,3\,\textquotedblright\times\,3\,\textquotedblright\times\,3\,\textquotedblright\times\,3\,\textquotedblright\times\,3\,\textquotedblright\times\,3\,\textquotedblright\times\,3\,\textquotedblright\times\,3\,\textquotedblright\times\,3\,\textquotedblright\times\,3\,\textquotedblright\times\,3\,\textquotedblright\times\,3\,\textquotedblright\times\,3\,\textquotedblright\times\,3\,\textquotedblright\times\,3\,\textquotedblright\times\,3\,\textquotedblright\times\,3\,\textquotedblright\times\,3\,\textquotedblright\times\,3\,\textquotedblright\times\,3\,\textquotedblright\times\,3\,\textquotedblright\times\,3\,\textquotedblright\times\,3\,\textquotedblright\times\,3\,\textquotedblright\times\,3\,\textquotedblright\times\,3\,\textquotedblright\times\,3\,\textquotedblright\times\,3\,\textquotedblright\times\,3\,\textquotedblright\times\,3\,\textquotedblright\times\,3\,\textquotedblright\times\,3\,\textquotedblright\times\,3\,\textquotedblright\times\,3\,\textquotedblright\times\,3\,\textquotedblright\times\,3\,\textquotedblright\times\,3\,\textquotedblright\times\,3\,\textquotedblright\times\,3\,\textquotedblright\times\,3\,\textquotedblright\times\,3\,\textquotedblright\times\,3\,\textquotedblright\times\,3\,\textquotedblright\times\,3\,\textquotedblright\times\,3\,\textquotedblright\times\,3\,\textquotedblright\times\,3\,\textquotedblright\times\,3\,\textquotedblright\times\,3\,\textquotedblright\times\,3\,\textquotedblright\times\,3\,\textquotedblright\times\,3\,\textquotedblright\times\,3\,\textquotedblright\times\,3\,\textquotedblright\times\,3\,\textquotedblright\times\,3\,\textquotedblright\times\,3\,\textquotedblright\times\,3\,\textquotedblright\times\,3\,\textquotedblright\times\,3\,\textquotedblright\times\,3\,\textquotedblright\times\,3\,\textquotedblright\times\,3\,\textquotedblright\times\,3\,\textquotedblright\times\,3\,\textquotedblright\times\,3\,\textquotedblright\times\,3\,\textquotedblright\times\,3\,\textquotedblright\times\,3\,\textquotedblright\times\,3\,\textquotedblright\times\,3\,\textquotedblright\times\,3\,\textquotedblright\times\,3\,\textquotedblright\times\,3\,\textquotedblright\times\,3\,\textquotedblright\times\,3\,\textquotedblr
observations of various SFR indicators in the radio continuum (Condon et al. 1991), 8 μm Spitzer-IRAC band (Xu et al. 2010), and Hα line emission (Hattori et al. 2004) all show the dominance of two nuclear sources over the entire pair. The high-resolution 8.44 GHz VLA maps (beam = 0″25) of Condon et al. (1991) show that the emission regions associated with Arp 238-E and Arp 238-W have sizes of ∼2″ and ∼1″, respectively. These are even smaller than the estimated intrinsic sizes of the CO emission regions (2″8 × 2″3 for Arp 238-E, 2″8 × 1″3 for Arp 238-W). Assuming that both CO and 8 μm emissions in Arp 238-E are from an elliptical region of size 2″8 × 2″3 and those in Arp 238-W from a region of size 2″8 × 1″3, we raise both the Σ_{SFR} and Σ_{mol} of Arp 238-E by a factor of 11.5 and the Σ_{SFR} and Σ_{mol} of Arp 238-W by a factor of 20.3. This moves the data points representing the two central regions to the upper right part of the K-S plot and, because of the nonlinearity of the K-S relation (power = 1.4), much closer to the line of the K-S relation.

There is a large uncertainty for the conversion factor α_{CO}, in particular for (U)LIRGs (Bolatto et al. 2013; Downes & Solomon 1998). We compare the molecular gas mass estimated using the adopted α_{CO} with the H I (Zuo et al. 2018) and dust (Cao et al. 2016) mass for Arp 142 and Arp 238 in order to constrain the effect of this uncertainty to our results. As shown Table 2, the dust-to-gas ratios of the two pairs are 0.0095 ± 0.0024 and 0.0076 ± 0.0017, both consistent with the value (∼0.007) of Draine et al. (2007).
other hand, the two interacting systems have diagonally different orbital orientations; while the interaction is coplanar for both galaxies in Arp 238, it is nearly perpendicular for the spiral galaxy in Arp 142. Also, the radial velocity difference between the two galaxies in Arp 142 is 201 km s\(^{-1}\), significantly higher than that of Arp 238, which is only 6 km s\(^{-1}\). Mora et al. (2019) found a best-match model for Arp 142 in the suite of more sophisticated Galmer SPH simulations (DiMatteo et al. 2008; Chilingarian et al. 2010), which agrees very well with that of Holincheck et al. (2016), with \(r_{\text{min}} = 8\) kpc, \(v_{\text{min}} = 300\) km s\(^{-1}\), \(t_{\text{min}} = 52 \pm 25\) Myr, and the disk of the spiral galaxy perpendicular to the orbit plane.

Thus, simulation results indicate that Arp 142 and Arp 238 have gone through very different types of interactions: the former a high-speed (~300 km s\(^{-1}\)) head-on collision between the disk and the elliptical companion and the latter a low-speed coplanar interaction between two spiral galaxies. Both observations and simulations (Theys & Spiegel 1977; Appleton & Struck-Marcell 1987, 1996) have shown that off-center, high-speed, head-on collision produces ringlike density waves expanding through both stellar and gaseous disks and pushing gas in the central region to the outer disk. This scenario is consistent with the NOEMA data of Arp 142. Meanwhile, shocks and turbulence associated with the ring can either compress gas clouds and trigger starbursts similar to that in Arp 142 (Gao et al. 1997; Lamb et al. 1998; Higdon et al. 2011; Renaud et al. 2018) or inject kinetic energy into clouds and stabilize them against collapse (Guillard et al. 2012; Alatalo et al. 2014). Whether this can explain the large variation of the SFE in Arp 142 will be the subject of a follow-up study of the kinematics and its relation to SFE in Arp 142 via a high-resolution hydrodynamic simulation (F. Renaud et al., in preparation).

On the other hand, the very high SFEs of Arp 238-E and Arp 238-W are apparently related to the compactness of the starbursts in their nuclei, which have \(\Sigma_{\text{mol}}\) approaching those of ULIRGs (Scoville et al. 1991). This can be explained by the simulations of Barnes & Hernquist (1996) and Hopkins et al. (2009), which predicted that gravitational tidal torques in low-speed coplanar interactions can trigger strong gas inflows that lead to nuclear gas concentrations and nuclear starbursts.

Does the contrast between Arp 142 and Arp 238 represent a common difference between S+E and S+S pairs? Namely, do more S+E pairs have high-speed and high-inclination interactions, while low-speed coplanar interactions are more common in S+S pairs? A definite answer to this question can only be obtained through dynamic simulations of a complete pair sample, which is beyond the scope this paper. However, some hints can be found in the following statistics of the H-KPAIR sample (Cao et al. 2016). For S+E pairs in H-KPAIR, the average radial velocity difference between pair members is 215.7 ± 20.4 km s\(^{-1}\), higher than that for S+S, which is 165.9 ± 18.2 km s\(^{-1}\). Also, for S+E and S+S pairs, the means of the number of galaxies of \(M_r \leq -19.5\) found within a 1 Mpc projected radius from the pair center and with redshift differences (compared to that of the pair) <500 km s\(^{-1}\) are 5.14 ± 0.59 and 3.81 ± 0.35, respectively. This indicates that, compared to S+S pairs, S+E pairs are in a higher local density environment and therefore more likely found in groups or clusters. While isolated pairs formed in intergalactic medium (IGM) filaments may preferentially have coplanar orbits, pairs in groups/ clusters are likely to have significantly disturbed orbits that are more randomly oriented, as suggested by the results of

![Figure 3](image3.png)

**Figure 3.** The CO spectrum of the integrated emission of Arp 142 (within the white ellipse shown in Figure 1(a)).

![Figure 4](image4.png)

**Figure 4.** The CO spectra of the integrated emissions of two galaxies in Arp 238 (within the white circles shown in Figure 1(c)).

obtained for local spiral galaxies. This suggests that, globally, our results are not significantly affected by the uncertainty of \(\alpha_{\text{CO}}\). It is worth noting that Liseno1 et al. (2019) gave an in-depth discussion of the applicability of the standard conversion factor to a sample of close major-merger pairs, to which both Arp 142 and Arp 238 belong, and concluded that their results on molecular mass derived using \(\alpha_{\text{CO}} = 3.2\) \(M_\odot\) K\(^{-1}\) km\(^{-1}\) s pc\(^{-2}\) are robust. Nevertheless, conservatively, we put an error bar of a factor of 3 for \(\Sigma_{\text{mol}}\) (Renaud et al. 2019) in Figure 5, applicable to all data points in the plot. Also plotted is an error bar of a factor of 2 for \(\Sigma_{\text{SFR}}\) (dominated by systematic uncertainties in the \(L_{\text{firm,dust}}\)-to-SFR conversion).

4. Discussion

Given the peculiar optical morphology of Arp 142 and Arp 238, it is likely that both pairs have undergone strong interactions recently, and their very different molecular gas distributions and SFEs found in NOEMA observations are due to differences in their interactions. The dynamic histories of both Arp 142 and Arp 238 were simulated by Holincheck et al. (2016) using a simple three-body simulation code, and their best models found that both pairs have undergone close encounters recently. For Arp 142, the pericentric passage has \(r_{\text{min}} = 8.95 \pm 1.14\) kpc and occurred \(r_{\text{min}} = 78.0 \pm 6.3\) Myr ago, whereas for Arp 238, \(r_{\text{min}} = 12.54 \pm 2.95\) kpc and \(t_{\text{min}} = 58.9 \pm 13.1\) Myr. On the
that Elagali et al. (2018) found, in an investigation of results of EAGLE simulations, that ring galaxies triggered by recent high-inclination collisions are more likely found in massive groups, and they tend to have low SFEs. These results favor the hypothesis that S+E pairs are more likely to have high-speed and high-inclination interactions and S+S pairs low-speed coplanar interactions, which may result in a lower chance for S+E pairs to have high SFE nuclear starbursts compared to S+S pairs.

5. Summary and Conclusions

Previous observations of the SFR (Cao et al. 2016) and the molecular (Lisenfeld et al. 2019) and atomic (Zuo et al. 2018) gas content of the H-KPAIR sample have shown pronounced differences between S+E and S+S pairs. The sSFR is only enhanced in S+S pairs, and there is a significant difference between the SFEs of S+E and S+S pairs (Lisenfeld et al. 2019). In order to probe the physical mechanism for these differences, we carried out NOEMA imaging observations of CO(1−0) line emission in two representative pairs: the S+E pair Arp 142 and the S+S pair Arp 238. In the sample of Lisenfeld et al. (2019), the spiral component of Arp 142 has the highest SFR among galaxies in S+E pairs, and Arp 238-E (an LIRG) has the second-highest SFR among galaxies in S+S pairs, whereas the SFE of the former is about 30 times lower than that of the latter.

The NOEMA observations, with a linear resolution of about 2 kpc, gave the following results.

1. The CO emission in Arp 142 is widely distributed over a highly distorted disk of the spiral galaxy (NGC 2936) without any nuclear concentration, and an off-center ringlike structure is discovered in channel maps.
2. There is a significant variation of the SFE within Arp 142. The starburst region (region 1) near the eastern tip of the distorted disk has an SFE more than 0.7 dex higher than...
that of the CO peak region (region 3) and shows a moderate SFE enhancement (~0.3 dex) compared to the mean of the AMIGA control sample of isolated galaxies (Lisenfeld et al. 2019).

3. Only ~10% of the molecular gas in Arp 142 is found in the starburst region, whereas the majority of the remaining gas has relatively low SFE, as suggested by the result for the main disk (region 4), which has an SFE of 0.43 dex lower than the mean of the control sample.

4. In Arp 238, CO is detected only in two compact sources at the two galactic centers.

5. The two central regions in Arp 238 dominate the total $M_{\text{mol}}$ in Arp 238, and both have very high SFEs. Compared to the control sample, Arp 238-E shows an SFE enhancement of more than 1 dex, whereas Arp 238-W has an enhancement of ~0.7 dex.

The differences between these two merger pairs are most likely due to the different orbital parameters of the encounters. Simulations in the literature (Holíncheck et al. 2016; Mora et al. 2019) have found that Arp 142 has undergone a high-speed, off-center, head-on collision, while Arp 238 has gone through a low-speed coplanar interaction. The extended CO distribution and large SFE variation in Arp 142 are most likely related to the shocks and turbulence associated with an expanding large-scale ring triggered by the head-on collision. On the other hand, the very high SFEs of Arp 238-E and Arp 238-W are related to the compactness of the starbursts in their nuclei that have very high $\Sigma_{\text{mol}}$. As predicted by simulations (Barnes & Hernquist 1996; Hopkins et al. 2009), gravitational tidal torques in low-speed coplanar interactions can trigger strong gas inflows that lead to nuclear gas concentrations and starbursts.

These differences in orbits might be typical for S+S and S+E pairs in general. Statistics for the H-KPAIR sample indicate that, on average, S+E pairs have a higher radial velocity difference and are more likely found in groups or clusters compared to S+S pairs. Since isolated pairs formed in IGM filaments may preferentially have coplanar orbits (Dubois et al. 2014), and pairs in groups/clusters are expected to have significantly disturbed orbits that are more randomly oriented, we propose the following hypothesis in analog to the NOEMA results for Arp 142 and Arp 238: S+E pairs are more likely to have high-speed and high-inclination collisions and S+S pairs low-speed coplanar interactions, which may result in a lower chance for S+E pairs to have high SFE nuclear starbursts compared to S+S pairs.

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References

Alatalo, K., Appleton, P. N., Lisenfeld, U., et al. 2014, ApJ, 795, 159
Appleton, P. N., & Struck-Marcell, C. 1987, ApJ, 318, 103
Appleton, P. N., & Struck-Marcell, C. 1996, FCPH, 16, 111
Barnes, J., & Hernquist, L. 1996, ApJ, 471, 115
Bergvall, N., Laurikainen, E., & Aalto, S. 2003, A&A, 405, 31
Bolatto, A. D., Wolfire, M., & Leroy, A. K. 2013, ARA&A, 51, 207
Bothwell, M. S., Wagg, J., Cicone, C., et al. 2014, MNRAS, 445, 2599
Cao, C., Xu, C. K., Domínguez, D., et al. 2016, ApJS, 222, 16
Chilingarian, I. V., Di Matteo, P., Combes, F., Melchior, A. L., & Semelin, B. 2010, A&A, 518, A61
Clark, B. G. 1980, A&A, 89, 377
Condon, J. J., Huang, Z.-P., Yin, Q.-F., & Thuan, T. 1991, ApJ, 378, 65
Dubois, P., Bournaud, F., Martin, M., et al. 2008, A&A, 492, 31
Domínguez, D. L., Xu, C. K., et al. 2009, ApJ, 695, 1559
Downes, D., & Solomon, P. M. 1998, ApJ, 507, 615
Draine, B. T., Dale, D. A., Bendo, G., et al. 2007, ApJ, 663, 866
Dubois, Y., Pichon, C., Welker, C., et al. 2014, MNRAS, 444, 1453
Elagali, A., Lagos, C. D. P., Wong, O. L. I., et al. 2018, MNRAS, 481, 2951
Ellison, S. L., Patton, D. R., Simard, L., et al. 2010, MNRAS, 407, 1514
Gao, Y., Solomon, P. M., Downes, D., & Radford, S. J. E. 1997, ApJL, 481, L55
Guillard, P., Boulanger, F., & Pineau des Forêts, G. 2012, ApJ, 749, 158
Hattori, T., Yoshida, M., Ohtani, H., et al. 2004, AJ, 127, 736
Helou, G., Roussel, H., Appleton, P., et al. 2004, ApJS, 154, 253
Higdon, J. L., Higdon, S. J. U., & Rand, R. J. 2011, ApJ, 739, 97
Höggbom, J. A. 1974, AAS, 15, 417
Holíncheck, A. J., Wallin, J. F., Borne, K., et al. 2016, MNRAS, 459, 720
Hopkins, P. F., Cox, T. J., Younger, J. D., & Hernquist, L. 2009, ApJ, 691, 1168
Horrellou, C., Booth, R. S., & Karlisson, B. 1999, Ap&SS, 269, 629
Huchtmeier, W. K., & Richter, O. G. 1989, A General Catalog of HI Observations of Galaxies. The Reference Catalog (Berlin: Springer)
Hwang, H. S., Elbaz, D., Dickinson, M., et al. 2011, A&A, 535, 60
Kennicutt, R. C. 1998, ApJL, 498, 541
Kennicutt, R. C., Keel, W., van der Hulst, J., et al. 1987, ApJ, 313, 1001
Knappen, J. H., & James, P. 2009, ApJ, 698, 1437
Lamb, S. A., Hearn, N. C., & Gao, Y. 1998, ApJL, 499, L153
Lisenfeld, U., Xu, C. K., Gao, Y., et al. 2019, A&A, 627, A107
Mora, M. D., Torres-Flores, S., Firpo, V., et al. 2019, MNRAS, 488, 830
Nicolici, B., Cullen, H., & Alexander, P. 2004, MNRAS, 355, 874
Park, C., & Choi, Y.-Y. 2009, ApJ, 691, 1828
Renaud, F., Athanassoula, E., Amram, P., et al. 2018, MNRAS, 473, 585
Renaud, F., Bournaud, F., Ageroz, O., et al. 2019, A&A, 625, A65
Sanders, D. B., & Mirabel, I. F. 1996, ARA&A, 34, 749
Scoville, N. Z., Sargent, A. I., Sanders, D. B., & Soifer, B. T. 1987, ApJL, 366, L55
Scaudder, J. M., Ellison, S. L., Torrey, P., et al. 2012, MNRAS, 426, 549
Shivaei, I., Reddy, N. A., Shapley, A. E., et al. 2017, ApJL, 837, 157
Steer, D. G., Dewdney, P. E., & Ito, M. R. 1984, A&A, 137, 159
Thys, J. C., & Spiegel, E. A. 1977, ApJL, 212, 616
Xu, C., & Salentijn, J. W. 1991, ApJ, 374, 407
Xu, C. K., Domínguez, D., Cheng, Y., et al. 2010, ApJL, 713, 330
Yang, X., Mo, H. J., van den Bosch, F. C., et al. 2007, ApJ, 671, 153
Zuo, P., Xu, C. K., Yun, M. S., et al. 2018, ApJS, 237, 2