Close Major-merger Pairs at z = 0: Star-forming Galaxies with Pseudobulges (Postprint)

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We present a study of star-forming galaxies (SFGs) with pseudobulges (bulges with Sérsic index $n < 2$) in a local close major-merger galaxy pair sample (H-KPAIR). With data from new aperture photometries in the optical and near-infrared bands (aperture size of 7 kpc) and from the literature, we find that the mean Age of central stellar populations in Spirals with pseudobulges is consistent with that of disky galaxies and is nearly constant against the bulge-to-total ratio (B/T). Paired Spirals have a slightly lower fraction of pure disk galaxies ($B/T \leq 0.1$) than their counterparts in the control sample. Compared to SFGs with classical bulges, those with pseudobulges have a higher ($>2\sigma$) mean of specific star formation rate (sSFR) enhancement (sSFRenh = 0.33 ± 0.07 versus sSFRenh = 0.12 ± 0.06) and broader scatter (by 1 dex). The eight SFGs that have the highest sSFRenh in the sample all have pseudobulges. A majority (69%) of paired SFGs with strong enhancement (having sSFR more than 5 times the median of the control galaxies) have pseudobulges. The Spitzer data show that the pseudobulges in these galaxies are tightly linked to nuclear/circum-nuclear starbursts. Pseudobulge SFGs in S+S and in S+E pairs have significantly ($>3\sigma$) different sSFR enhancement, with the means of sSFRenh = 0.45 ± 0.08 and -0.04 ± 0.11, respectively. We find a decrease in the sSFR enhancements with the density of the environment for SFGs with pseudobulges. Since a high fraction (5/11) of pseudobulge SFGs in S+E pairs are in rich groups/clusters (local density $N_{1Mpc} \geq 7$), the dense environment might be the cause for their low sSFRenh.

Full Text

Preamble

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Abstract

We present a study of star-forming galaxies (SFGs) with pseudobulges (bulges with Sérsic index $n < 2$) in a local close major-merger galaxy pair sample (H-KPAIR). Using new aperture photometry in the optical and near-infrared bands (aperture size of 7 kpc) combined with data from the literature, we find that the mean age of central stellar populations in spirals with pseudobulges is consistent with that of disky galaxies and remains nearly constant against the bulge-to-total ratio (B/T). Paired spirals have a slightly lower fraction of pure disk galaxies ($B/T \leq 0.1$) than their counterparts in the control sample. Compared to SFGs with classical bulges, those with pseudobulges exhibit a higher specific star formation rate enhancement (sSFR $= 0.33 \pm 0.07$ versus sSFR $= 0.12 \pm 0.06$) and broader scatter (by 1 dex). The eight SFGs with the highest sSFR in the sample all have pseudobulges. A majority (69%) of paired SFGs with strong enhancement (having sSFR more than 5 times the median of the control galaxies) have pseudobulges. Spitzer data show that the pseudobulges in these galaxies are tightly linked to nuclear/circum-nuclear starbursts. Pseudobulge SFGs in S+S and S+E pairs have significantly ($>3\sigma$) different sSFR enhancement, with mean values of sSFR $= 0.45 \pm 0.08$ and -0.04 ± 0.11, respectively. We find a decrease in sSFR enhancement with environmental density for SFGs with pseudobulges. Since a high fraction (5/11) of pseudobulge SFGs in S+E pairs reside in rich groups/clusters (local density $N_1 \geq 7$), the dense environment may be responsible for their low sSFR .

Key words: galaxies: evolution – galaxies: interactions – galaxies: star formation – galaxies: structure – galaxies: bulges – galaxies: photometry

1. Introduction

Extensive research has demonstrated that galaxy interactions can induce star formation enhancement (Toomre & Toomre 1972; Larson & Tinsley 1978; Kennicutt et al. 1987; Xu & Sulentic 1991; Sanders & Mirabel 1996). Both simulations and observations indicate that the existence and intensity of such enhancement are influenced by many pair properties, including separation distance (Alonso et al. 2004; Nikolic et al. 2004), mass ratio (Cox et al. 2008), environment (Ellison et al. 2010), interaction phase (Scudder et al. 2012), and orbital parameters (Patton et al. 2013). Meanwhile, intrinsic properties of the paired galaxies, such as stellar mass (Madau & Dickinson 2014) and morphology (Kennicutt 1998), also affect star formation behavior. On the other hand, various quenching mechanisms have been reported, including mass (Peng et al. 2010), environment (Peng et al. 2012), AGN feedback (Kormendy & Ho 2013), and bulge-to-total ratios (B/T; Martig et al. 2009; Bluck et al. 2014). The combined effect of many factors, particularly when studying a large sample spanning a wide parameter range, may obscure potential results or even cause statistical bias. This motivates us to investigate the fundamental mechanisms of interaction-induced star formation.

For instance, by analyzing kinematic asymmetry using recent integral field spectrograph (IFS) techniques, Feng et al. (2020) revealed that the strength of ongoing tidal effects during certain merging phases is a more fundamental indicator for understanding intermittent star formation enhancement in galaxy pairs than projected separations. Additionally, the star formation rate (SFR) level is influenced by both the quantity of gas and its efficiency in forming stars. Lisenfeld et al. (2019) found that mergers in earlier stages (i.e., pairs) can lead in converting atomic gas to molecular gas, resulting in higher star formation efficiency (SFE) when calculating total gas. However, no significant SFE enhancement was found in their pair sample when calculating molecular gas alone. In contrast, later-stage mergers, which often appear as ULIRGs with strong star formation activity, can accumulate large amounts of molecular gas (e.g., Sargent & Scoville 1991; Scoville et al. 1991). By controlling for total gas content, Li et al. (2023) found no significant SFE enhancement in paired galaxies compared to isolated galaxies. In conclusion, whether and how galaxy interactions induce star formation enhancement remains controversial. To obtain solid evidence, one must carefully select samples and controls, and perform detailed classifications.

Far-infrared (FIR) observations by Spitzer (Xu et al. 2010) and Herschel (Cao et al. 2016) of a complete, unbiased close major-merger pair sample selected from Ks-band (Domingue et al. 2009) suggest that only star-forming galaxies (SFGs) in spiral-spiral (hereafter S+S) pairs have significantly enhanced specific star formation rate (sSFR = SFR/M), but not those in spiral-elliptical (hereafter S+E) pairs. This pattern also appears in Park & Choi (2009), Hwang et al. (2010), Xu et al. (2010), and Moon et al. (2019). He et al. (2022) studied the dependence of interaction-induced specific star formation rate enhancement (sSFR = log sSFR − log sSFR , , where "pg" stands for paired galaxy and "med,ctrl" for the median of their control galaxies) on the bulge-to-total ratio (B/T). They found a negative dependence of sSFR on B/T and significant (>5σ) enhancement only in paired SFGs with B/T $<$ 0.3. This aligns with theoretical simulations predicting that massive bulges can stabilize disks and suppress SFR during and after close encounters (Mihos & Hernquist 1996; Cox et al. 2008; Di Matteo et al. 2008). However, SFGs with low B/T ratios, particularly disky galaxies (B/T $\leq$ 0.1), show very diversified sSFR spanning 2.5 orders of magnitude, with some even exhibiting sSFR deficits.

In their analysis, He et al. (2022) separated pseudobulges (Sérsic index n $<$ 2) from classical bulges (n $\geq$ 2) and assigned B/T = 0 to galaxies with pseudobulges. This is because many pseudobulges identified in two-component (bulge and disk) models are misidentified bars, nuclear disks, and nuclear rings (Kormendy & Kennicutt 2004) that may themselves be triggered by interactions (Chown et al. 2019; Erwin et al. 2021). Meanwhile, pseudobulges are mostly found in late-type spirals with relatively low B/T ratios (Kim et al. 2016), and assigning them to disky galaxies should not introduce strong bias. However, bars and nuclear rings often have intermittent star formation activity and, when observed in an "off" phase, may appear SFR-quenched (Fraser-McKelvie et al. 2020). Additionally, some massive early-type spirals (such as S0 and Sa galaxies) with pseudobulges unrelated to nuclear star formation and with low gas content and low SFR may host large bars (Herrera-Endoqui et al. 2017).

Could the broad scatter of sSFR among disky SFGs be due to the diversity of galaxies with pseudobulges? The primary scientific goal of this paper is to answer this question and investigate the roles of pseudobulge SFGs in sSFR enhancement in paired galaxies. Unlike He et al. (2022), we use the original B/T values for galaxies with pseudobulges instead of assigning B/T = 0. We introduce our SFG sample in Section 2, present a study of optical color–color diagrams measured in the inner regions of paired galaxies (particularly for pseudobulges to separate bars, nuclear disks, and nuclear rings from normal pseudobulges with n $<$ 2) in Section 3, and present our scientific analyses and results in Section 4. We discuss our findings in Section 5 and conclude in Section 6. Throughout this paper, we adopt a ΛCDM cosmology with Ω = 0.3, Ω_Λ = 0.7, and $H_0 = 70$ km s^{-1} Mpc^{-1}.

2. The Sample

The sample used in this paper is identical to that in He et al. (2022), which is the local close major-merger sample H-KPAIR (Cao et al. 2016). H-KPAIR is a subsample of KPAIR, a complete and unbiased Ks-band (Two Micron All Sky Survey, 2MASS) selected pair sample (Domingue et al. 2009). H-KPAIR includes 44 Spiral+Spiral (S+S) pairs and 44 Spiral+Elliptical (S+E) pairs, all with spectroscopic redshifts in the range $0.0067 < z < 0.1$, projected separations of 5 h^{-1} kpc $\leq$ s(p) $\leq$ 20 h^{-1} kpc, radial relative velocities δ(V_z) $<$ 500 km s^{-1}, and Ks-band magnitude differences within 1 mag (corresponding to a mass ratio no greater than 2.5). The strict selection criteria of H-KPAIR gather the most enhanced close major-merger pairs, making it ideal for exploring interaction effects. All galaxies have Herschel imaging observations in six bands (70, 110, 160, 250, 350, and 500 m), with SFRs derived from Herschel data (Cao et al. 2016). Seventy pairs have GBT 21 cm HI observations (Zuo et al. 2018), and 78 spiral galaxies were observed by the IRAM 30 m telescope for CO emissions (Lisenfeld et al. 2019). B/T ratios are taken from He et al. (2022), based on 2D decompositions using SDSS r-band images. Stellar masses are also from He et al. (2022), who updated the formalism of Cao et al. (2016) by including a (g − r) color correction when estimating mass from Ks-band luminosity. We focus on two subsamples: (1) all spiral galaxies (Sections 3 and 4.1) and (2) all star-forming galaxies (SFGs; Sections 4.2 and 4.3). Following Cao et al. (2016) and He et al. (2022), SFGs are defined by log sSFR $>$ -11.0 yr^{-1}. There are 98 SFGs out of 132 spirals in H-KPAIR (Table 1).

3. Galaxy Central Colors

We perform aperture photometry for all H-KPAIR galaxies using a consistent circular aperture in SDSS u, r, i and 2MASS Ks-band images. The u, r, i images are generated using the SDSS SAS mosaic tool, which stitches together sky-subtracted, calibrated frames to form coherent images using SWarp (Bertin et al. 2002). For the Ks-band, 2MASS images are resampled to the same pixel scale as SDSS images (0.396 pixel^{-1}), and backgrounds are subtracted with SWarp. The median full-width at half-maximum (FWHM) of the point-spread function is 1.53 , 1.32 , 1.26 , and 2.9 in the four bands, respectively.

For each galaxy, we use the same aperture in all four bands, corresponding to a projected diameter of 7 kpc centered on its SDSS coordinates. This avoids overlap between member galaxies in a pair, given the minimum separation of 5 h^{-1} kpc (7 kpc for $H_0 = 70$ km s^{-1} Mpc^{-1}). Aperture diameters range from 4.2 to 53 , with most galaxies (141/176) having diameters larger than twice the worst resolution (2 × 2.9 for Ks-band), so no aperture correction is needed.

Photometric errors for SDSS bands combine Poissonian source flux error, background rms, and calibration error. Given the high S/N in optical bands, errors are dominated by calibration error (1% for r and i, 2% for u). For 2MASS Ks-band, we also include coadd noise from resampling and smoothing in Atlas Images. The spiral galaxies have a median bulge size of $2 \times R = 3.6$ kpc (R : effective radius), with 26% having $2 \times R \geq 7$ kpc. For these, colors probe bulge stellar populations; for others, the 7 kpc aperture includes both bulge and inner disk contributions, with relative importance depending on B/T.

As shown in Figure 1, bulge size correlates significantly with B/T (Spearman's rank coefficient $r = 0.55$, $p = 5.6 \times 10^{-12}$).

To interpret colors, we calculate broadband flux predictions using the Simple Stellar Population (SSP) model of Bruzual & Charlot (2003), with free parameters τ (time after instantaneous burst, i.e., stellar age) and attenuation A . The model uses Padova (1994) tracks, Chabrier (2003) IMF (0.1–100 M), and solar metallicity ($Z = 0.02$). Extinctions follow Cardelli et al. (1989) for standard diffuse ISM. While the SSP model may oversimplify real stellar populations and has large uncertainties, it provides a framework linking colors to physical properties, allowing investigation of differences between pseudobulge and classical bulge galaxies via color–color diagrams. Aperture photometry and model fits are listed in Table 2.

4.1. Difference Between Pseudobulges and Classical Bulges

Figures 2 and 3 present u–r versus i–K color–color diagrams, with false-color scales representing B/T ratio and sSFR , respectively. The red-contoured region (labeled "E") in the upper-left corner marks where elliptical galaxies (not plotted) reside. Most spirals in this region have large classical bulges and low sSFR . The mesh grid shows fixed τ and A values from the SSP model. According to the model, galaxies in region "E" have old central stellar populations (Age $>$ 1 Gyr). Most remaining galaxies have central ages of 0.1–1 Gyr, with very few young ages (0.01–0.1 Gyr) likely associated with nuclear/circumnuclear starbursts. A ranges 0–3 mag, with most galaxies having $1 <$ A < 2.5 mag.

We estimate Age and A for each galaxy by interpolating among adjacent model predictions. Galaxies with Age $>$ 13 Gyr are set to 13 Gyr; those with A $<$ 0 are set to 0. Figure 4 shows a strong anti-correlation between A and Age, as younger populations typically have stronger star formation and higher dust attenuation, while older populations have less star formation and dust. Several galaxies with large classical bulges have high A , explained by two factors: (1) they have relatively high sSFR and thus high attenuation, though their controls have low sSFR; (2) our u–r–i–K colors probe the central region, not the whole galaxy, and dust concentration in bulges of old galaxies is reasonable.

To investigate interaction effects on bulge properties, we select a new control sample (control-sample-2). Selection matches He et al. (2022, Section 4) except without B/T matching. The criteria are:

1. Identified as spiral in Galaxy Zoo (Lintott et al. 2008)
2. Not in any interacting system: no neighbor galaxy in SDSS within 100 kpc projected distance and 1000 km s^{-1} redshift difference
3. Has reliable B/T ratio: $^2/$ < 2 and no bad flag (flag bit 20 = 0) in Meert et al. (2015)
4. Local density match: we use N_1 , counting galaxies brighter than M = -19.5 with redshift differences $<$ 1000 km s^{-1} within 1 Mpc radius (including the target if it meets the brightness criterion). Galaxies are classified into four environments: field (N_1 ≤ 3), small group ($4 \leq N_1$ ≤ 6), large group ($7 \leq N_1$ ≤ 10), and cluster (N_1 > 10). Controls

match the paired galaxy's environment.

5. Among qualified candidates, has the closest redshift to the paired galaxy.

In Figure 5 we compare Age and B/T for paired galaxies separated into pseudobulge and classical bulge subsamples, plotting mean Ages in five B/T bins: (1) $B/T \leq 0.1$, (2) $0.1 < B/T \leq 0.3$, (3) $0.3 < B/T \leq 0.5$, (4) $0.5 < B/T \leq 0.7$, (5) $B/T > 0.7$. The mean Age of central stellar populations for classical bulge galaxies increases with B/T, as expected because bulge dominance in central colors grows with B/T and classical bulge populations are generally older than disks (Driver et al. 2006; Kim et al. 2016). In contrast, pseudobulge galaxies show flat Age versus B/T, with stellar populations similar to inner disks of disky galaxies (B/T 0). This confirms that pseudobulges differ from classical bulges and are dominated by "disk phenomena" like bars and nuclear disks/rings, as assumed in He et al. (2022).

However, some individual pseudobulge galaxies have old central populations (Age > 1 Gyr) with low star formation enhancement (sSFR ≤ 0). They have relatively low B/T (most < 0.3, all < 0.5) and may resemble isolated late-type galaxies with small pseudobulges (Kim et al. 2016). A few galaxies with large classical bulges appear in the lower-right quadrant of Figure 5, indicating relatively young central populations. These may host starbursts or post-starbursts that outshine old populations and "blue" the bulges. An outstanding example is J13151726+4424255, with B/T = 0.94, Age = 0.11 Gyr, and sSFR = 0.70. Compared to controls, paired galaxies with large bulges, particularly in the fourth B/T bin ($0.5 < B/T \leq 0.7$), have higher Ages. Inspection shows most have elliptical companions (i.e., in S+E pairs), suggesting their star formation histories may be affected by the environment associated with ellipticals (see Section 5).

Figures 6 and 7 show the probability density functions of classical and pseudobulge spirals in H-KPAIR and control-sample-2, respectively. Paired spirals have a lower fraction of pure disk galaxies (bin 1, $B/T \leq 0.1$), which we attribute to some paired disky galaxies hosting nuclear/circum-nuclear starbursts that raise their B/T ratios. These galaxies have flat profiles and are identified as pseudobulge galaxies assigned B/T = 0 in He et al. (2022).

4.2. Paired SFGs with Strong Enhancement

In Section 2 we defined SFGs by log sSFR > -11.0 yr^{-1} (see also Cao et al. 2016; He et al. 2022). Most non-SFGs are SFR-undetected (marked by crosses in Figures 2, 4, and 5) and are early-type galaxies with large old classical bulges. Including them in sSFR analysis does not affect our results. We now focus on the SFG subsample.

Figure 8 plots sSFR versus B/T, similar to Figure 9 of He et al. (2022) but using original B/T values for pseudobulge galaxies (instead of B/T = 0), with the same five bins as Figure 5. Pseudobulge SFGs show broad scatter spanning 2 orders of magnitude (1 dex broader than classical bulge SFGs), demonstrating that the scatter for disky galaxies (B/T < 0.1) in He et al. (2022) arises from pseudobulge galaxies assigned B/T = 0. The mean sSFR for pseudobulge SFGs is constant against B/T, unlike classical bulge SFGs where it decreases with increasing B/T (Figure 8; see also He et al. 2022). The mean sSFR is higher for pseudobulge SFGs (0.33 ± 0.07) than classical bulge SFGs (0.12 ± 0.06) at the 2σ level. The eight SFGs with highest sSFR all have pseudobulges.

To study strongly enhanced galaxies in detail, we focus on those with sSFR > 0.7, corresponding to >5× enhancement relative to control medians. This yields 13 strongly enhanced SFGs: nine with pseudobulges and four with classical bulges (Figure 8 and Table 3). Figure 9 shows their central stellar populations all have ages younger than 200 Myr, dominated by recently formed stars. Excluding these, the remaining sample has mean sSFR $= 0.11 \pm 0.04$, only marginally significant at 2.8σ. Statistically, strongly enhanced SFGs represent 13% (13/98) of SFGs and 10% (13/132) of all spiral galaxies in H-KPAIR.

Seven of the 13 have Spitzer observations, providing 8 m flux densities for nuclear (aperture D = 4 kpc) and total emission (Xu et al. 2010). Figure 10 plots sSFR against C_8 (nuclear-to-total 8 m ratio), an indicator of nuclear star formation concentration. A significant linear correlation exists (Pearson's r $= 0.81$, p $= 0.03$). Among the seven, all five pseudobulge SFGs have high nuclear concentration ($C_8 \geq 0.49$), while the two classical bulge SFGs have star formation mostly outside the nucleus ($C_8 < 0.30$). Despite the small sample, this indicates pseudobulges in strongly enhanced galaxies are tightly linked to nuclear/circum-nuclear starbursts. Since most strongly enhanced galaxies have pseudobulges, nuclear/circum-nuclear starburst may be the dominant mode for strong tidally induced star formation in paired galaxies. For a minority (particularly classical bulge SFGs), tidally induced star formation may be widely distributed across the disk. These results agree with literature showing nuclear/circum-nuclear starbursts are common in strongly interacting pairs, while widespread enhancement is also observed in some cases (Keel et al. 1985; Kennicutt et al. 1987; Pan et al. 2019; Steffen et al. 2021).

Figures 11 and 12 show optical (u, g, r) color images from the Dark Energy Spectroscopic Instrument (DESI) for the nine pseudobulge and four classical bulge strongly enhanced galaxies, respectively. DESI images are deeper and higher resolution than SDSS, revealing diffuse features more clearly. Four pseudobulge galaxies (J07543194+1648214, J09155467+4419510, J09155552+4419580, J17045097+3449020) and two classical bulge galaxies (J10100079+5440198, J17045089+3448530) appear nearly coalesced, indicating late merging stages. This suggests 46% (6/13) of strongly enhanced galaxies are in late-stage mergers. We separate late-stage mergers (pairs with strong interaction signs and very close nuclei) from early-stage mergers (no strong signs or widely separated). Late-stage mergers are likely observed during or after the second close encounter, as developing interaction features takes >100 Myr after the first encounter. Generally, only a low fraction of optically/near-IR selected pairs (like H-KPAIR) are late-stage mergers because this stage is much shorter than preceding stages (Di Matteo et al. 2007). Additionally, H-KPAIR's separation criterion ($ 5*h*^{-1}$ kpc) excludes some coalesced late-stage mergers. Thus, the 46% fraction suggests most late-stage merger SFGs may harbor strong tidally induced star formation, while only a small fraction of early-stage merger SFGs do. For the latter, significant SFR enhancement may require strong tidal torques during or after the first close encounter (pericenter passage; Feng et al. 2020) in low-speed coplanar orbits (with good spin-orbit alignment; Moon et al. 2021), as argued by Xu et al. (2021).

The remaining seven strongly enhanced galaxies are in earlier-stage mergers with clearly separated components. Three (J01183417−0013416, J13153506+6207287, J16024254+4111499) likely have low-inclination, low-velocity orbits (all with δv < 70 km s^{-1}). J13153506+6207287 (Arp 238, δv = 6 km s^{-1}) has a confirmed coplanar orbit from Holincheck et al. (2016). Xu et al. (2021) found a very compact molecular gas concentration fueling a strong nuclear starburst, triggered by strong tidal torque predicted for low-speed coplanar interactions (Barnes & Hernquist 1996; Hopkins et al. 2009). This may also apply to J01183417−0013416 and J16024254+4111499. In contrast, J10332972+4404342, J14005783+4251203, and J14005879+4250427 may have high-inclination orbits; the latter two are in the same pair (KPAIR J1400+4251) with high relative velocity (δv = 234 km s^{-1}). These three pseudobulge galaxies may be barred, though resolution limits prevent certainty. If so, their central starbursts may be fueled by bars. Finally, J03381222+0110088 is the only S+E pair among the 13 strongly enhanced SFGs, but it appears to interact with another nearby SFG in the same group, forming a close SFG-dominated triplet. Thus, it is not a true S+E pair. It has very high total gas content (M $_2$/M = 0.56) but relatively low star formation efficiency (SFE = SFR/M $_2$ = 10^{-9}.^{10} yr^{-1}), below the H-KPAIR average (Lisenfeld et al. 2019). Its high sSFR appears mainly due to high gas content rather than tidal effects.

4.3. Pseudobulge Galaxies in S+S and S+E Pairs

He et al. (2022) found that in all B/T bins except the last (0.5 < B/T ≤ 1), SFGs in S+S pairs have higher mean sSFR than those in S+E pairs, with a difference of 0.4 ± 0.1 dex in the lowest bin (B/T ≤ 0.1). In that work, pseudobulge galaxies were assigned B/T = 0 and included in the B/T ≤ 0.1 bin. Do pseudobulge SFGs in S+S and S+E pairs have significantly different sSFR ?

Figure 13 compares pseudobulge SFGs in S+S versus S+E pairs, plotting sSFR against stellar mass M , with color indicating Age and symbol size showing B/T. Pseudobulge SFGs in S+E pairs tend to have older stellar populations and lower sSFR enhancements, with none showing strong enhancement (sSFR ≥ 0.7). Mean sSFR values are 0.45 ± 0.08 for S+S pairs and −0.04 ± 0.11 for S+E pairs, differing at >3σ. Most pseudobulge SFGs in S+E pairs (9/11) have relatively low stellar mass ($ 10$^{\{10\}\cdot}$\{6\}$ M).

Figure 14 compares pseudobulge SFGs in S+S and S+E pairs using sSFR versus local density indicator N_1 (defined in He et al. 2022 and Section 4.1). SFGs in high-density regions (N_1 ≥ 7) have significantly lower sSFR , and a higher fraction (5/11) of S+E pseudobulge SFGs reside in such regions. These SFGs are in rich groups/clusters where star formation may be quenched by galaxy harassment (Moore et al. 1998) and/or ram pressure stripping (Gunn et al. 1972; Giovanelli & Haynes 1983; Gavazzi et al. 2006). They also have low probability of coplanar orbits due to frequent disturbances, making nuclear starbursts less likely (Xu et al. 2021). Optical images show their pseudobulges often correspond to bars or inner rings with low star formation activity (e.g., J12191866+1201054 with sSFR $= -0.01$, Figure 15).

Mean H_2 gas mass fractions (Lisenfeld et al. 2019) and total gas masses from FIR dust mass (Cao et al. 2016) are plotted in two B/T bins in Figures 16 and 17: (1) disk-dominated ($B/T \leq 0.3$) and (2) bulge-dominated ($B/T > 0.3$). SFE calculated from them appears in Figures 18 and 19. Generally, both H_2 and total gas decrease with B/T. Pseudobulge SFGs in S+S pairs have the flattest slope and highest gas fractions in bulge-dominated galaxies. No clear trend appears in SFE versus B/T. Comparing subsamples, pseudobulge SFGs have higher SFE, and S+S pair SFGs lead in both SFE measures. Notably, pseudobulge galaxies in S+E pairs do not have as high SFE as classical bulge galaxies in S+S pairs.

5. Discussion

The significant sSFR enhancement in close major-merger pairs is mainly due to a small population (15% in our sample; Figure 8) of strongly enhanced SFGs. About half are in late-stage mergers, all in S+S pairs and none in S+E pairs. It is unlikely that any late-stage S+S mergers with strongly enhanced SFGs are misclassified S+E mergers, as none is dominated by a classical bulge (the largest classical bulge is in J17045089+3448530, Figure 12d, with $B/T = 0.48$).

Why do spirals in late-stage S+E mergers avoid strong starbursts? Four late-stage S+E mergers exist in H-KPAIR (Table 4), with members nearly coalesced within a common halo (Figure 20). They are massive pairs with primaries $>10^{11}$ M . All spiral members are quiescent, with only one (J16354293+2630494; Figure 20d) qualifying as an SFG (sSFR $= 10^{-11}.^{26}$ yr^{-1}). They are uniformly gas-poor (M_9 /M $< 4\%$), lower than 88% of H-KPAIR SFGs and significantly below the sample mean (M_9 /M $= 0.13 \pm 0.01$).

Three galaxies (J10514450+5101303, J13131470+3910382, J16354293+2630494) are in pairs containing the most massive galaxies of rich groups/clusters with >12 members (Yang et al. 2012). For these, the rich-group/cluster environment may be key to cold gas depletion and suppressed star formation, as ram pressure stripping and/or IGM hot gas evaporation can remove most ISM and tidal-tail cold gas. J11542299+4932509 (Figure 20b) appears isolated, but its companion is a very massive elliptical (M $= 10^{11}.^{35}$ M). The pair is ROSAT

X-ray detected ($f_{0\cdot2\ 2}$ = 8.22 ± 1.73 × 10^{-14} erg s^{-1} cm^{-2}), suggesting a hot gas halo that can strip/evaporate cold gas, explaining the low gas content (M_9 /M = 0.035) and low sSFR (<$10^{-11}.^{33}$ yr^{-1}) of J11542299+4932509.

Thus, the lack of strong enhancement in late-stage S+E mergers may be due to cold gas removal by environmental hot gas (Park & Choi 2009; Hwang et al. 2011). Note that these quiescent spirals differ from SFGs studied by Cao et al. (2016) and Lisenfeld et al. (2019), who found no significant difference in M_9 /M between S+S and S+E pair SFGs, refuting the "cold-gas stripping" hypothesis for SFGs in S+E pairs. Most spirals in S+E pairs are SFGs (64% = 28/44 in H-KPAIR) and many are gas-rich (e.g., NGC 2936 in Arp 142; Xu et al. 2021). It remains unclear why they are absent in late-stage S+E mergers.

Interaction-induced star formation enhancement is affected by many factors. Some appear necessary (e.g., gas to fuel star formation), but none seems sufficient. For instance, the four most enhanced classical bulge SFGs (Figure 12) never reach ultra-enhanced levels (sSFR > 1, i.e., >10× enhancement) like their pseudobulge counterparts. However, as outstanding classical SFG cases, three have very low B/T. The other, J17045089+3448530 with B/T = 0.48, and the "blue" bulge-dominated galaxy J13151726+4424255 (sSFR 0.7, Figure 5's upper-right point and Figure 8's top-right data point) are both in low-density environments (N_1 = 4 and 3, respectively).

Although KPAIR (Domingue et al. 2009) is all-sky selected, strict criteria make it relatively small. Further refining classifications (S+S/S+E pairs, pseudo/classical bulges) sometimes yields subsamples too small for robust statistical analysis. Nevertheless, this study provides perspective on the complex mechanisms of interaction-induced star formation enhancement. Future surveys with deeper sensitivity and higher resolution (e.g., Euclid) will provide larger, better samples for more conclusive studies.

6. Conclusion

We present a study of SFGs with pseudobulges (Sérsic index $n < 2$) in the local close major-merger galaxy pair sample H-KPAIR. The sample is from He et al. (2022), who performed 2D GALFIT decompositions to study B/T dependence of star formation enhancement in paired SFGs. New aperture photometry in SDSS u, r, i and 2MASS Ks-bands probes central stellar populations (D = 7 kpc). With these and literature data, we find:

1. The mean age of central stellar populations in spiral galaxies with classical bulges increases with B/T. Conversely, the mean age in spirals with pseudobulges is nearly constant against B/T and consistent with that of disky galaxies (B/T 0). This confirms that pseudobulges in our sample are mainly associated with disk phenomena such as bars, nuclear rings, and bright nuclei.

2. Paired spirals have a modestly reduced fraction of pure disk galaxies

compared to isolated spirals, likely due to misidentifying nuclear/circum-nuclear starbursts as large pseudobulges.

3. Compared to classical bulge SFGs, pseudobulge SFGs have 2σ higher mean sSFR enhancement (sSFR $= 0.33 \pm 0.07$ vs. 0.12 ± 0.06) and much broader scatter (1 dex).
4. The eight SFGs with highest sSFR are all pseudobulge galaxies. A majority (69%) of paired SFGs with strong enhancement (>5× control median) have pseudobulges. Spitzer data show these pseudobulges are tightly linked to nuclear/circum-nuclear starbursts, suggesting this is the dominant mode for strong tidally induced star formation in paired galaxies.
5. Pseudobulge SFGs in S+S and S+E pairs have significantly different (3σ) sSFR enhancement: mean sSFR $= 0.45 \pm 0.08$ and -0.04 ± 0.11, respectively. A high fraction (5/11) of pseudobulge SFGs in S+E pairs reside in rich groups/clusters (local density $N_1 \geq 7$), where environment may hinder star formation enhancement.

In conclusion, paired SFGs with pseudobulges exhibit diverse central stellar populations and sSFR enhancements, including galaxies with bars, inner disks, rings, and strong nuclear/circum-nuclear starbursts. Strongly enhanced SFGs are dominated by pseudobulge galaxies with nuclear/circum-nuclear starbursts. Conversely, many pseudobulge SFGs, particularly in S+E pairs, are barred or ringed galaxies with old central populations and low sSFR enhancement, likely due to environmental effects.

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