Advances in Observational Studies of Nearby Luminous Infrared Galaxies (Postprint)

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Abstract

(Ultra)luminous infrared galaxies ((U)LIRGs) play an important role in galaxy evolution. They are primarily formed through mergers of gas-rich spiral galaxies, accompanied by intense star formation activity and possible active galactic nucleus (AGN) activity. The re-radiation by dust heated by starbursts and AGN in the infrared band endows these galaxies with extremely high infrared luminosity. With the deployment of various advanced astronomical observational facilities, observational studies of (U)LIRGs in the nearby universe have achieved many important advances. This paper first introduces the multi-wavelength observational characteristics of nearby (U)LIRGs obtained from recent studies, then presents the research hotspots related to nearby (U)LIRGs, and finally discusses future research plans.

Full Text

Preamble

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Progress in Observational Studies of Local Luminous Infrared Galaxies

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Abstract

(Ultra) Luminous Infrared Galaxies ((U)LIRGs, with infrared luminosities $L_{8\ 1000}$ m $> 10^{11}(^{12})$L) represent a brief yet crucial phase in galaxy evolution. These systems primarily form through mergers of gas-rich spiral galaxies, triggering intense starburst activity and potential active galactic nucleus (AGN) accretion. The re-emission from dust heated by starbursts and/or AGNs produces their extreme infrared luminosities. Recent advances in observational facilities have yielded significant progress in studying (U)LIRGs in the local universe. This review first presents the multi-wavelength observational characteristics of nearby (U)LIRGs based on the latest research, then discusses key research topics related to these systems, and concludes with future observational prospects.

Keywords: galaxy evolution; (ultra)luminous infrared galaxies; star formation; active galactic nuclei
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1 Introduction

(Ultra) Luminous Infrared Galaxies ((U)LIRGs, $L_{8\ 1000}$ m $> 10^{11}(^{12})$L) [Figure 1: see original paper] constitute a transient but important stage in galaxy evolution. Their study began with the Infrared Astronomical Satellite (IRAS), which discovered 629 local galaxies with 60 m flux densities ≥ 5.24 Jy [1]. The finding of objects whose infrared emission dominates their total energy output sparked intense interest in understanding their power sources. Observations reveal that (U)LIRGs primarily originate from mergers of gas-rich spiral galaxies, spanning all merger stages and containing abundant molecular gas and dust [2]. These mergers drive substantial gas and dust into the central regions, fueling violent starbursts and rapid supermassive black hole (SMBH) growth, potentially triggering AGN activity. Compared to non-merging galaxies, (U)LIRGs exhibit higher star formation rates (SFRs of 10–100 M yr^{-1}) and a larger AGN fraction [2]. Their infrared emission arises from dust heated by both starbursts and AGNs. Brighter ULIRGs are typically late-stage mergers with higher SFRs and AGN fractions, sharing properties with high-redshift star-forming galaxies [3,4]. They are considered transitional objects preceding quasar (QSO) and massive elliptical galaxy formation [5,6,7]. Infrared Space Observatory (ISO) and Spitzer Space Telescope observations show that (U)LIRGs dominate cosmic star formation at $z > 1$, contributing over 50% of the infrared energy density [8,9,10].

Recent advances in adaptive optics and radio interferometry have enabled high-resolution studies of astrophysical phenomena in nearby (U)LIRGs, including star formation, SMBH accretion, and outflows. These studies serve two key purposes: (1) investigating local, low-redshift (U)LIRGs allows inference about the physical properties of their high-redshift counterparts, clarifying their role in galaxy evolution; and (2) in the era of multi-messenger astronomy, studying SMBH environments in merging galaxies aids understanding of gravitational wave electromagnetic counterparts.

The Great Observatories All-sky LIRG Survey (GOALS) [13] has compiled high-resolution multi-wavelength data for 21 ULIRGs and 180 LIRGs at $z < 0.088$ using state-of-the-art facilities including NuSTAR, Chandra, GALEX, HST, Spitzer, Herschel, Keck, ALMA, and VLA. This review summarizes recent observational progress on (U)LIRGs based on GOALS results, building upon earlier reviews of IRAS/ISO-era multi-wavelength properties [2,14] and wavelength-specific surveys [15,16,17]. Compared to previous work, we incorporate more recent Spitzer and Herschel far-infrared results and emphasize advances from the past decade across X-ray to radio wavelengths. Section 2 presents multi-wavelength observational characteristics, Section 3 discusses key research topics, and we conclude with future prospects.

2 Multi-Wavelength Observational Characteristics

This section addresses the central question of whether AGN exist in (U)LIRG nuclei, summarizing observations from X-ray to radio wavelengths and discussing astrophysical processes such as shocks and gas cooling. Many morphological and spectral features support the evolutionary sequence from LIRGs to ULIRGs to QSOs. We also describe methods for studying high-redshift galaxies using local (U)LIRGs and important caveats.

2.1 X-ray Band

(U)LIRG X-ray emission comprises diffuse soft X-rays and compact hard X-ray nuclei. Ptak et al. and Franceschini et al. studied small (U)LIRG samples with Chandra and XMM-Newton, characterizing their X-ray spectra [18,19]. In the 0.5-2 keV soft band, interstellar medium heated by massive star winds and supernovae dominates, producing 0.3-0.7 keV thermal plasma continuum. Above 2 keV, (U)LIRGs show power-law spectra from massive X-ray binaries and AGN. In local star-forming galaxies with LIR $< 10^{11}$L , hard X-ray emission correlates with far-infrared radiation [20,21,22] because both trace SFR [23,24]. However, in (U)LIRGs with LIR $> 10^{11}.^{73}$L and no AGN, hard X-ray emission is weaker than predicted from the far-infrared correlation, especially in ULIRGs. One explanation is that central massive X-ray binaries are heavily obscured by high column density gas [25].

AGN-hosting (U)LIRGs show hard X-ray luminosities an order of magnitude higher ($L_{2\ 10}$keV $> 10^{35}$ W) than non-AGN systems and significantly exceed their soft X-ray emission. X-ray luminosity and hardness ratio (HR = $(H-S)/(H+S)$, where H and S are hard and soft band photon counts) help identify power sources. In some cases, nuclear gas is optically thick even to hard X-rays, dramatically reducing luminosity. The presence of AGN can then be diagnosed via the 6.4 keV Fe Kα line from gas heated by the accretion disk. Iwasawa et al. [26] analyzed Chandra data for 44 (U)LIRGs with LIR $> 10^{11}.^{73}$L , finding AGN signatures in 16 galaxies using HR > -0.3 and Fe Kα criteria. Twelve of these AGN were in the brighter (LIR $> 10^{12}$L) subsample; NGC 6240 hosts a dual AGN. These AGN contribute only ~10% to total infrared emission. Among 63 LIRGs with LIR = $10^{11}.^{0}$-$10^{11}.^{73}$L and Chandra data, 24 contain

AGN [27]. Including galaxies with mid-infrared but not X-ray AGN signatures, the AGN fraction is $(38\$\pm 7)^{\{11\}\cdot}\{73\}L \odot and(31\pm 5)^{\{11\}\cdot}\{0\}–10^{\{11\}\cdot}\{73\}\$$L , indicating the AGN fraction increases with infrared luminosity.

X-ray observations reveal heavily obscured AGN in merging galaxies, emphasizing the importance of multi-wavelength surveys for AGN identification in large samples. The methods described above—X-ray color analysis and Fe Kα line detection—provide robust AGN diagnostics.

2.2 Ultraviolet Band

UV emission in (U)LIRGs originates from young stars and AGN. Dust absorbs some UV radiation and re-emits it in the far-infrared, quantified by the infrared excess (IRX) and UV color β. IRX is defined as the ratio of 8-1000 m infrared to far-UV flux:

IRX = log(fIR/fFUV)

For GALEX, β is defined as: βGALEX = log(fFUV) − log(fNUV) − 0.182

where fFUV and fNUV are the average flux densities in the far-UV and near-UV bands [28]. GOALS includes 135 (U)LIRGs observed by GALEX in the far-UV (λeff = 1528 Å) and near-UV (λeff = 2271 Å). Howell et al. [29] selected 112 high-quality sources to construct the IRX-β relation using GALEX UV and Spitzer infrared data [Figure 2: see original paper]. The linear relationship is approximately:

$$\mathrm{IRX} = (0.46 \pm 0.06)\beta + (2.1 \pm 0.1)$$

In Figure 2, black points indicate LIR $< 10^{11}$L , red points 10^{11}L $<$ LIR $<$ $10^{11}.^{4}$L , green points $10^{11}.^{4}$L $<$ LIR $<$ $10^{11}.^{8}$L , and blue points LIR $>$ $10^{11}.^{8}$L . Most (U)LIRGs lie above the Meurer et al. [30] IRX-β relation for typical starbursts (solid line), with only ~15% below the trend. The Cortese et al. [31] fit for late-type galaxies (dashed line) clearly separates (U)LIRGs from LIR $<$ 10^{11}L galaxies. Overall, (U)LIRGs show larger IRX values at given β, with brighter systems having higher IRX and redder colors (larger β). Following Charlot & Fall' s [32] dust model, the IRX-β relation reflects dust optical depth, indicating that brighter (U)LIRGs contain more dust absorbing UV radiation from young stars and AGN. This aligns with the theoretical evolution from LIRGs to ULIRGs to QSOs, where gas and dust first accumulate in the nucleus, fueling intense starbursts, then are expelled by AGN and starburst winds in the final QSO phase.

In merging galaxies where GALEX and Spitzer resolve individual components, 32% show infrared and UV emission dominated by different sub-galaxies. This implies that observed properties of high-redshift mergers may differ significantly from their constituent galaxies.

2.3.1 Imaging Observations

Near-infrared observations suffer less dust extinction and achieve higher resolution than mid/far-infrared, enabling studies of AGN and starbursts in galactic nuclei. High-resolution near-infrared imaging reveals that while most ULIRGs are mergers, many LIRGs remain widely separated galaxy pairs or even non-merging systems [33]. Haan et al. [34] used HST/NICMOS H-band images to study morphologies of 73 (U)LIRGs, finding that a large fraction contain double (63%) or triple (6%) nuclei. The median nuclear separation is 6.7 kpc for LIRGs and 1.2 kpc for ULIRGs, indicating LIRGs represent early merger stages while ULIRGs correspond to late stages.

Half of the double-nucleus systems detected in H-band have nuclei completely obscured in B-band by dust. This requires corrections when counting multi-nucleus systems in high-redshift ($z > 2$) (U)LIRGs, where observed near-infrared emission corresponds to rest-frame B-band. Indeed, observed high-redshift (U)LIRGs show significantly lower merger fractions [35,36,37].

Optical bands are heavily obscured by dust, making it difficult to observe AGN and star clusters in (U)LIRG cores. However, HST’ s Advanced Camera for Surveys (ACS) provides large fields (202 × 202) and high spatial resolution (~0.05), enabling detailed studies of large-scale structures such as bulges, bars, disks, and tidal tails. The HST GOALS program obtained B- and I-band ACS data for all (U)LIRGs with LIR $> 10^{11}.^{4}$L . Kim et al. [38] used GALFIT [39] to fit surface brightness profiles of 85 galaxies (64 LIRGs and 21 ULIRGs) from I-band images [Figure 3: see original paper]. The model comprises a point-spread function for the nuclear point source and a Sérsic model [40] for the bulge and disk:

$$I(r) = Ie\ \exp\{-b[(r/re)^{1}/^{n} - 1]\}$$

where Ie and re are effective surface brightness and radius, $n = 1$ corresponds to a disk, and $n = 4$ to a bulge.

The results show pure disks in 32.1%, disk+bulge systems in 48.9%, and ellipticals in 19% of the sample. LIRGs have a higher disk fraction (34.5%), while ULIRGs contain more ellipticals (33.3%). Systems with both components dominate both populations (50% of LIRGs, 45% of ULIRGs), with bulge-to-disk ratios < 1 in 60% of these cases–meaning disks dominate most (U)LIRG structures. Early-stage mergers with widely separated nuclei (30–70 kpc) show bars in 57% of galaxies, similar to local spirals (48–55%) [41], while late-stage mergers with unresolved nuclei have only 6.3% bars, indicating bar disruption during final merger phases. Based on sub-galaxy luminosities and assuming constant mass-to-light ratios, most GOALS mergers are major mergers (mass ratios $>$ 1/4), with only ~7% being minor mergers. The average mass ratio is 0.55 ± 0.23, showing no significant difference between ULIRGs and LIRGs.

2.3.2 Spectroscopic Observations

Optical spectra of (U)LIRGs include various classifications: Seyfert types I/II, starbursts, and LINERs. The AGN fraction increases with infrared luminosity, with >50% of ULIRGs showing AGN features in optical spectra [42]. Rich et al. [43] used integral field spectroscopy on small (U)LIRG samples, finding shock-ionized gas regions in many systems. Shocks arise from gas collisions during mergers, tidal effects, and outflows driven by AGN or starbursts, producing velocity dispersions of 100–200 km s^{-1} [44,45]. In BPT diagrams [46,47,48], shock excitation resembles LINERs, showing stronger low-ionization lines ([S II] λ\$ \$6717,6731 Å and [O I] λ\$ $6300, 6364)andhigher[SII]/H$ \$ and [O I]/Hα ratios than H II regions photoionized by hot stars [45]. Spatially, shocks create LINER-like emission in outer regions while nuclei show H II region characteristics [44,45]—the opposite trend of AGN-dominated galaxies where line ratios decrease outward. Figure 4 [Figure 4: see original paper] shows [S II]/Hα distributions and BPT positions for three galaxies: IRAS F17222-5953 (H II-dominated), IRAS F21453-3511 (AGN-hosting) [49], and IRAS F01053-1746 (shock-excited) [45]. This study found that shock contributions to emission lines increase with merger progression, with >50% of Hα emission produced by shocks in seven late-stage mergers, while early mergers show predominantly H II region emission.

The spectral energy distribution of (U)LIRGs peaks at 0.3–2 m from stellar thermal emission, typically 1.2 mag fainter than the far-infrared dust peak in ULIRGs and 0.7 mag fainter in LIRGs [50]. Near-infrared spectra include hydrogen recombination lines, hot H_2 ro-vibrational lines, and metal emission lines. While optical Hα and Hβ lines commonly trace star formation, they suffer heavy dust extinction in (U)LIRG nuclei (A 3 mag for LIRGs [33]; A > 10 mag for ULIRGs [51]). In contrast, infrared hydrogen recombination lines like Paα are less affected (A 0.1A [52]), making them better star formation tracers, though space telescopes are required for nearby (U)LIRGs due to atmospheric opacity.

Similar to optical BPT diagrams, near-infrared [Fe II] 1.26 m/Paβ and H_2 2.12 m/Brγ line ratios distinguish excitation sources. Shock-ionized LINER-like emission shows the highest ratios, 2× higher than AGN and >5× higher than starbursts [53]. AGN presence also produces broad Paα emission and [Si VI] 1.963 m lines [54,55]. Combining optical and infrared integral field spectroscopy, Medling et al. [56] identified two shock components in IRAS F17207-0014: (1) merger-driven ISM collisions affecting the entire nuclear region (H_2/Brγ 0.6–4), and (2) starburst-driven outflows extending ~400 pc (H_2/Brγ 4–8), with optical spectra confirming large-scale outflows. This study pioneered the combination of small-scale, high-resolution spectroscopy with large-scale observations to investigate emission mechanisms across scales and provide new insights into star formation–AGN interactions.

2.4 Mid-Infrared Band

Spitzer observations (3.6–160 m) have extensively studied (U)LIRGs in the mid-infrared. Most mid-infrared emission is extended, with LIRGs being 2–3× more extended than ULIRGs. At 13.2 m, ULIRG nuclei are only ~1.5 kpc in size. Overall, late-stage mergers with higher AGN contributions are more compact

[57].

Mid-infrared spectra show dust thermal continuum plus atomic emission lines from ionized gas ([O IV], [Ne II], [Ne III], [S III]), H_2 rotational lines, and polycyclic aromatic hydrocarbon (PAH) features [Figure 5: see original paper]. PAH emission, heated by UV photons and common in star-forming galaxies, can comprise $ $10% of total infrared emission [58,59] and traces photodissociation regions (PDRs). AGN affect PAHs by destroying molecules via X-ray radiation, reducing PAH equivalent widths relative to dust continuum [60,61]. GOALS LIRGs show larger average PAH 6.2 m line widths (0.55 m) than ULIRGs (0.30 m) [62].

Mid-infrared spectroscopy effectively probes (U)LIRG nuclei because it penetrates dust obscuration. High-ionization lines like [Ne V] [64] and broad PAH features [65,66] indicate AGN. Many galaxies not optically classified as AGN show mid-infrared AGN signatures [67,68]. Petric et al. [69] found that $ $18% of GOALS nuclei host AGN based on [Ne V], with AGN-dominated systems comprising only 10% of the sample and contributing ~12% to total infrared emission —confirming starbursts as the primary energy source. For ULIRGs alone, AGN contribute 30–40% to infrared emission, ranging from <10% to ~100% per object [70]. The prevalence of mixed AGN–starburst systems in ULIRGs suggests coevolution of SMBHs and galaxies during mergers.

Mid-infrared spectra also probe interstellar medium properties. H_2 rotational lines indicate warm molecular gas ($T > 200$ K) with masses of 10^8-10^9 M in bright ULIRGs [63,71]. This warm H_2 results from energy injection by young massive stars and AGN, with ~10% of (U)LIRGs showing H_2 emission exceeding single-energy-source models, indirectly evidencing AGN feedback [72]. AGN-affected H_2 shows higher temperatures and broader line profiles.

Silicate absorption features at 9.7 m and 18 m constrain dust optical depth and chemistry. Both the silicate strength $S_{9\cdot7}$ m and mid-infrared spectral slope F (30 m)/F (15 m) increase with merger stage and infrared luminosity [62]. ULIRGs show stronger silicate absorption (mean $S_{9\cdot7}$ m $= -1.5$) and steeper mid-infrared slopes (median F (30 m)/F (15 m) = 12.54) than LIRGs ($S_{9\cdot7}$ m = −0.25, slope = 7.11), indicating increasing dust accumulation in nuclei, greater obscuration, and higher dust temperatures during mergers.

2.5 Far-Infrared Band

Over 50% of (U)LIRG emission lies in the far-infrared. Dust absorbs high-energy photons and re-emits at far-infrared wavelengths, peaking at 50–100 m. The extreme far-infrared emission reflects very high SFRs.

Gas heating in (U)LIRGs occurs via radiation fields (UV from young stars, X-rays from AGN), cosmic rays, turbulence, winds, and outflows, while fine-structure lines provide major cooling channels. Herschel' s far-infrared to submillimeter capabilities have enabled studies of lines such as [O I] 63 m, [O III] 88 m, [N II] 122 m, [C II] 158 m, and [N II] 205 m. The [C II] 158 m line is the primary interstellar medium coolant in star-forming galaxies, contributing up to ~1% of total infrared emission [73,74], originating mainly from PDRs where UV-heated PAHs eject photoelectrons that collisionally excite C^+ [74]. Díaz-Santos et al. [75] found that the [C II]/FIR ratio in GOALS (U)LIRGs drops sharply from ~10^{-2} to 10^{-4} with increasing dust temperature Tdust and infrared surface density ΣIR, indicating [C II] is a poor SFR tracer.

This "fine-structure line deficit" also affects [O I] 63 m, [N II] 122 m, and [N II] 205 m [76]. In dense starbursts, strong radiation fields enhance dust cooling efficiency; dust near PDRs in H II regions absorbs more stellar energy, heating to higher temperatures and boosting far-infrared emission [76]. The difference between ULIRGs and LIRGs in [C II]/FIR (medians of 6.3\$×10^{-4}\$ vs. 2.8\$×10$^{\{-3\})reflectsmoreviolentstarburstactivityinULIRGs.Notably,70}$\{-3\}, *similartopurestarbursts*(*average*4×10^{-3}\$), and the deficit persists after removing AGN, demonstrating that AGN contribute secondarily to far-infrared continuum [75].

The [O I] 63 m line becomes increasingly important for interstellar medium cooling at higher gas temperatures and densities, sometimes exceeding [C II] in extreme starbursts. In (U)LIRGs, [O I] and [C II] contribute 30.1% and 33.6% to neutral gas cooling, respectively [78]. Most [O I] emission arises from PDRs near [C II]-emitting regions; in the optically thin limit, their ratio correlates with dust temperature, allowing gas temperature constraints when assuming PDR gas-dust temperature coupling [76].

The [N II] 205 m line correlates well with SFR, is easily excited [79], suffers minimal dust extinction, and is insensitive to metallicity. For high-redshift galaxies, it shifts into ALMA' s submillimeter bands, making it valuable for studying distant star formation. In LIRGs with $LIR < 10^{12}L$ and no AGN, the SFR-L[N II] relation is [80]:

$$\log \mathrm{SFR}(M\ \ \mathrm{yr}^{-1}) = (-5.31 \pm 0.32) + (0.95 \pm 0.05) \log \mathrm{LN\ II}$$

Subsequent work found this relation depends slightly on far-infrared color $C(60/100) = f_{60}/f_{100}$ (IRAS flux densities at 60 and 100 m). Applying color corrections reduces uncertainties when C(60/100) is known independently [101].

CO rotational lines provide additional gas cooling and trace star-forming molecular H_2 gas. The H_2 mass-CO intensity relation is parameterized by αCO = M(H_2)/LCO. In (U)LIRGs, αCO $1.8^{+1.3}{}_{0.8}$ M (K km s^{-1} $pc^2)^{-1}$, significantly lower than in normal spirals (~4 M (K km s^{-1} $pc^2)^{-1}$) [91]. ALMA observations reveal 10^9 M of cold H_2 within ~100 pc of (U)LIRG nuclei [92,93]. The molecular gas fraction (Mgas/(Mgas + Mstars)) evolves with merger stage: ~18% in early mergers, rising to 33% in intermediate stages, then falling to 22% in late mergers [94]. This suggests HI initially concentrates in the center, forming H_2, which is later consumed by star formation and black hole accretion or dissociated by AGN feedback. Submillimeter dust continuum can also estimate molecular gas mass [95].

Higher-J CO lines (e.g., CO(6–5)) trace warmer, denser gas (T 100 K, n > 10^4 cm^{-3}) more closely linked to ongoing star formation, with intensity distributions tightly correlated with star-forming regions [96,97,98]. ALMA observations of CO(6–5) have identified extremely efficient star-forming regions (ΣSFR > 100 M yr^{-1} kpc^{-2}) in nearby (U)LIRG nuclei [99,100]. Zhao et al. [101] found spatial offsets between CO(6–5) peaks and AGN-dominated radio continuum in NGC 7130, and Cao et al. [102] observed weak CO(6–5) at the AGN position in NGC 5135. These <100 pc resolution results confirm Herschel conclusions that CO(6–5) excitation is dominated by ongoing star formation, with negligible AGN contribution.

Lu et al. [82] analyzed CO spectral line energy distributions (SLEDs) from J = 4-13 in 65 (U)LIRGs, finding that SLED peak position depends not on LIR but on C(60/100), indicating radiation field strength controls the shape. As C(60/100) increases from \$ \$0.6 to >1.0, the peak shifts from J < 5 to 5 < J < 10. The CO(6–5) and (7–6) to LIR ratios are independent of C(60/100), suggesting two components: a warm component (5 < J < 10) linked to star formation and a cold component (J < 4) of lower density, unrelated to current star formation. As C(60/100) increases, the warm component dominates, enhancing 5 < J < 10 emission.

Investigating the ratio of 5 < J < 10 CO emission to LIR (log RmidCO) versus C(60/100), Lu et al. found that starburst-dominated galaxies show nearly constant log RmidCO −4.13 with small scatter, confirming star formation dominates mid-J CO excitation. Galaxies with strong shocks (e.g., NGC 6240) have higher log RmidCO, while AGN-dominated systems (e.g., Mrk 231, NGC 1068) have lower values because AGN X-rays heat CO to J > 10. Lu et al. [83] confirmed these results in a larger sample: AGN heating appears at J > 10, while 5 < J < 10 emission is AGN-independent. After correcting for C(60/100), starburst- and AGN-dominated galaxies show similar SLEDs in this range, though AGN-dominated systems have lower CO-to-infrared ratios. Thus, mid-J lines like CO(7–6) trace SFR, showing tight correlations with LIR independent of C(60/100) [84]. In AGN-free systems, the [N II] 205 m/CO(7–6) ratio also correlates with C(60/100), enabling dust temperature constraints.

The [C I] 370 m and 609 m lines have critical densities similar to CO(1–0). Their ratio depends only on the excitation temperature between the $^3P_2$ and $^3P_1$ levels, providing gas temperature constraints under local thermodynamic equilibrium. In classical PDR models, [C I] emits in the transition zone between C^+ and CO, linking it to CO emission. Lu et al. [83] found that [C I]/CO ratios become less C(60/100)-dependent at lower J, indicating [C I] originates mainly in the dominant cold, low-density molecular gas component. Jiao et al. [85] confirmed linear relationships between both [C I] lines and CO(1–0), suggesting [C I] is more useful than CO(1–0) for studying cold molecular gas in high-redshift galaxies due to its stronger emission.

Most H_2O molecules exist as ice on dust grains, existing as vapor only in warm molecular gas. As the second most abundant oxygen-bearing molecule after

CO, H_2O is detected via rotational emission or absorption against continuum. Shocks, cosmic rays, and strong X-ray fields can enhance H_2O abundance. Yang et al. [87] detected at least one H_2O rotational line in 45 nearby (U)LIRGs using Herschel/FTS, finding good linear correlations with LIR. This can be explained by infrared pumping: H_2O molecules absorb infrared photons and cascade to lower levels at a constant rate, making H_2O emission proportional to LIR [88]. AGN do not significantly alter H_2O detection rates or the LIR correlation, indicating AGN are not the primary H_2O excitation source. The H_2O-to-LIR ratio decreases with increasing f_{25}/f_{60} but not with f_{60}/f_{100}, suggesting ~50 K dust contributes more to H_2O excitation than ~100 K dust.

2.7 Radio Band

Ground-based interferometric radio observations penetrate dust with excellent resolution, making them ideal for locating compact nuclear sources and studying their properties.

The infrared-radio correlation is universal across galaxy types, quantified by the constant ratio q = log[(FIR(8-1000 m)/3.75$×10^{-12}$ W m^{-2})/($S_{1·4}$GHz/W m^{-2} s^{-1})] [114,115,116]. This arises because infrared emission comes from dust heated by young stars, while radio emission consists of thermal bremsstrahlung and non-thermal synchrotron from supernova remnants [117]. Deviations may indicate AGN radio emission [118,119,120]. VLA observations of 35 (U)LIRGs yield q = 2.75 ± 0.27, consistent with larger galaxy samples (2.64 ± 0.26) [121].

Radio spectral shape is described by the spectral index α (S $^{-\alpha}$). Under optically thin conditions, star-forming galaxies show α 0.8 at low frequencies (e.g., VLA L-band, 1-2 GHz) where synchrotron dominates, flattening to α 0.1 at high frequencies (e.g., Ka-band, 26.5-40 GHz) where thermal bremsstrahlung contributes [117]. Spatial α distributions distinguish nuclear power sources. AGN jets produce steep spectra (large α) in regions far from the center where plasma has cooled [122], creating radial α gradients. Compact starbursts produce flat spectra at low frequencies due to optically thick free-free absorption [118,123]; denser starbursts show flatter spectra. AGN also exhibit prominent radio jets [124] and high brightness temperatures (Tb 10^5-10^6 K) [118,125], while star-forming regions appear more extended with Tb $\leq 10^4$.^{5} K [118].

Using VLA 1.49 GHz and 8.44 GHz observations [118,126], Vardoulaki et al. [121] analyzed 35 (U)LIRGs containing 46 sub-galaxies, identifying 21 radio AGN, 9 starbursts, and 16 composites.

VLA' s high resolution enables precise measurements of nuclear source sizes, allowing calculation of radiation surface densities, star formation surface densities, and gas densities. Barcos-Muñoz et al. [127] used 33 GHz data to derive ΣSFR = 10^0.^{6}-10^4.^{1} M yr^{-1} kpc^{-2} and ΣIR = 10^{10}.^{5}-10^{14}.^{1} L kpc^{-2} in 22 (U)LIRGs, with maxima exceeding values measured in any other galaxy type.

Very Long Baseline Interferometry (VLBI) achieves pc-scale resolution for locating AGN and measuring SFRs. Herrero-Illana et al. [128] used the European

VLBI Network (EVN) to observe the LIRG NGC 1614, finding no compact radio sources within 200 pc of the nucleus at C-band (5.0 GHz) and X-band (8.4 GHz). This excludes an AGN, confirming NGC 1614 as a pure starburst.

3 Key Research Topics in (U)LIRGs

Adaptive optics on large ground-based telescopes and interferometers like ALMA and JVLA have dramatically improved resolution, enabling small-scale studies of star clusters, gas clumps, and nuclear SMBHs in nearby galaxies. Local (U)LIRGs provide excellent laboratories for such studies. This section summarizes high-resolution observational results on small-scale structures in nearby (U)LIRGs, focusing on three areas: star formation, gas outflows, and SMBH evolution.

3.1 Star Formation

Star formation plays a crucial role in galaxy evolution. Mergers elevate (U)LIRG SFRs to 10–100 M yr^{-1} for LIRGs and >100 M yr^{-1} for ULIRGs [2]. Submillimeter observations show higher star formation efficiencies in (U)LIRGs than normal galaxies, increasing with merger stage [98].

The key difference in local (U)LIRGs is nuclear starbursts. Mid-infrared spectroscopy indicates these starbursts are 1–4.5 Myr old with metallicities of 1–2 Z [129]. High-resolution studies reveal ring-like or compact nuclear star-forming regions with densities and SFRs 10× higher than typical star-forming regions. Xu et al. [99,100] used ALMA to observe CO(6-5) and dust continuum in NGC 34' s central 100 pc (ΣSFR $10^2.^9$ M yr^{-1} kpc^{-2}, Σgas $10^4.^4$ M pc^{-2}) and NGC 1614' s ring-like region at 100–350 pc radius (ΣSFR 10^0 M yr^{-1} kpc^{-2}, Σgas $10^3.^{54}$ M pc^{-2}). The morphological differences may arise from merger mass ratios: NGC 34' s 3:1–3:2 major merger drives gas to the center, while NGC 1614' s >4:1 minor merger provides insufficient torque. Alternatively, NGC 1614' s merger may not be complete.

Extranuclear star-forming regions in (U)LIRGs also differ from normal galaxies. Linden et al. [130] used VLA 3–33 GHz observations of 48 extranuclear regions in 25 (U)LIRGs, finding flatter radio spectra than nuclear regions, with thermal emission contributing 65% at 33 GHz—similar to normal star-forming galaxies [131]. These regions have SFRs of 0.05–7.5 M yr^{-1}, higher than analogous regions in broader galaxy samples (10^{-4}–10^{-1} M yr^{-1}) [132]. Similarly, Larson et al. [133] identified 810 star-forming clumps in 48 (U)LIRGs using HST narrowband Paα and Paβ imaging [Figure 6: see original paper], with radii of 90–900 pc and SFRs of 10^{-3}–10 M yr^{-1}. This range bridges normal galaxies and lensed high-redshift systems [134], suggesting extreme high-redshift star formation occurs in similar physical environments.

Song et al. [135] studied ring-like star-forming regions in 5 normal galaxies and 4 LIRGs, finding rings contribute 49–60% of total SFR in LIRGs versus 7–40% in normal galaxies. Individual clumps in these rings reach SFRs of 1.7 M yr^{-1} and $\Sigma\text{SFR} = 400$ M yr^{-1} kpc^{-2} in LIRGs. This suggests star formation initially occurs in outer regions, with gas funneling to the center during mergers to create dense nuclear starbursts.

Despite enhanced star formation in mergers, massive star clusters have short lifetimes. Linden et al. [136] found a steep decline in massive cluster numbers with age using HST near-UV and optical data, indicating that strong tidal forces in mergers efficiently disrupt newly formed clusters.

Finally, Tan et al. [137] observed CO(1-0) in 8 ultraluminous infrared QSOs (IR QSOs), finding black hole accretion rates increase with SFR, a correlation persisting in high-redshift QSOs with 3 orders of magnitude higher SFRs. IR QSOs, as direct ULIRG-QSO transition objects with similar molecular gas masses and star formation efficiencies as ULIRGs, represent the most intense star-forming phase of mergers [138]. This result links star formation and AGN activity, consistent with the observed SMBH-galaxy coevolution since z 2 [139,140].

3.2 Gas Outflows

Merger-driven starbursts and AGN inject energy into the interstellar medium via outflows, affecting galaxy evolution by redistributing dust and metals and ejecting material into the intergalactic medium [141]. Outflows arise from black hole accretion disks [142], massive star winds, and supernovae [143], containing molecular, atomic, and ionized gas. Outflows are ubiquitous in (U)LIRGs, with late-stage ULIRGs hosting particularly powerful AGN-driven outflows capable of dispersing obscuring dust and gas, enabling the ULIRG-QSO transition [144]. Ionized gas outflows in NGC 6240 and Arp 220 were first detected by Heckman et al. [145,146]. Spitzer subsequently identified blueshifted high-ionization lines ([N III], [N V]) in some (U)LIRGs [147,148], with velocities too high for gravitational rotation, indicating AGN-driven outflows.

Blueshifted Na I λ\$ 5890, 5896*absorptiontracescoolHIgasinoutflows*, *observedongalacticscalesinmany*(*U*)*LI*
slitspectroscopy[149, 150, 151].*Integralfieldspectroscopybettermapsoutflowspatialdistributions*.*Rupke*&*Vei*
1}\$ outflow extending 2-3 kpc in the ULIRG Mrk 231—sufficient to escape into intergalactic space. The KOALA project used Keck/OSIRIS to observe 21 (U)LIRGs in K-band H_2 ro-vibrational and Brγ lines, identifying AGN outflows traced by shock-heated H_2 (H_2/Br$\gamma > 2$) in 5 ULIRGs and 1 LIRG [153] [Figure 7: see original paper]. Shock-heated H_2 is more common in ULIRGs, likely due to stronger starbursts and more AGN heating central gas, as evidenced by ULIRGs' median H_2/Brγ = 1.43, similar to Seyferts (1.41) [154].

Cold H_2 gas dominates outflow mass (up to 60%) [155], making outflows an effective mechanism for suppressing star formation in galactic centers. Herschel detected blueshifted OH 119 m absorption in ULIRGs, revealing molecular outflows with mass-loss rates of 100 M yr^{-1} [156,157,158,159]. ALMA observes cold H_2 outflows via molecular emission lines: Barcos-Muñoz et al. [160] detected >10^6 M of outflowing gas in Arp 220 via HCN(1-0), and Sakamoto et al. [111] identified outflows from both nuclei in NGC 3256 using CO(1-0), (2-1), and (3-2). Since (U)LIRGs are elliptical galaxy progenitors, massive molecular outflows provide evidence for star formation quenching. At high redshift, intense star formation and AGN activity are more common [161,162,163,164], making outflows particularly important for galaxy evolution.

3.3 Supermassive Black Hole Evolution

Observations reveal strong correlations between SMBH mass and host galaxy properties (bulge mass, luminosity, stellar velocity dispersion; the MBH-σ* relation) [165,166,167,168], explained by AGN feedback: when SMBHs reach critical masses, AGN activity expels surrounding gas, quenching both black hole accretion and star formation [169]. Simulations show galaxy mergers efficiently trigger AGN [170]. Merging galaxies host more AGN than isolated systems of similar stellar mass [171,172], with AGN fraction and luminosity increasing as nuclear separation decreases [173,174]. Moderate-luminosity X-ray AGN are found primarily in non-merging disk galaxies [175,176,177], while high-luminosity X-ray AGN reside mainly in mergers [178,179,180], demonstrating that mergers are important for the most luminous X-ray AGN.

Many SMBHs in merging galaxies are heavily obscured, with large fractions being Compton-thick (NH $> 10^{24}$ cm^{-2}) [181]. Compton-thick AGN absorb most <10 keV hard X-rays, showing flat hard X-ray spectra and scattered/reflected emission. Reflection produces broad Fe lines (>1 keV) and a prominent reflection hump at 20–30 keV [182], making >10 keV observations ideal.

Ricci et al. [183] used NuSTAR 10–24 keV and Chandra 2–10 keV data for 60 (U)LIRGs, detecting 35 X-ray AGN. The Compton-thick fraction is 46% ± 8%, higher than in local X-ray-selected AGN (27% ± 4%) [184]. In late-stage mergers, 69^{+9} $_{19}$% of AGN are Compton-thick versus 33% ± 12% in early mergers. The Compton-thick fraction and column density peak (NH $(1.6 \pm 0.5) \times 10^{24}$ cm^{-2}) occur at nuclear separations of 0.4-6 kpc. After absorption correction, Compton-thick AGN have higher intrinsic X-ray luminosities, perhaps due to abundant fuel or selection effects. These results suggest SMBHs are most active in late merger stages, with mass growth lagging intense star formation, making starbursts the primary (U)LIRG power source—consistent with gas requiring greater angular momentum loss to reach the black hole than to form stars.

However, some SMBHs begin growing earlier. U et al. [185] analyzed OSIRIS data for the ULIRG Mrk 273, discovering a rotating gas disk (radius ~0.3 = 240 pc) around the northern black hole. Using [Fe II] kinematics, they measured MBH $= (1.04 \pm 0.1) \times 10^9$ M , consistent with maser measurements [186]. Similar stellar/gas disk structures (50-800 pc radii, 10^8-10^{10} M) have been found in other (U)LIRGs, providing new methods for SMBH mass measurement [187]. OSIRIS K-band (1.965-2.381 m) observations are minimally affected by dust, and adaptive optics achieve <0.1 resolution for stellar and gas kinematics—unlike traditional methods that fail in heavily obscured, disturbed (U)LIRGs.

Using this approach, Medling et al. [188] measured dynamical masses of SMBHs within ~25 pc of nuclei in 9 (U)LIRGs via gas emission lines (Brγ) and stellar CO absorption. Keplerian disk and Jeans axisymmetric mass models (JAM) [189] provided lower and upper mass limits, respectively, yielding MBH = 10^7-10^9 M [Figure 8: see original paper]. Most (U)LIRGs lie above the MBH-σ* relation of McConnell & Ma [190]. If progenitors and remnants follow this relation, black hole growth during mergers must exceed host galaxy stellar formation, contradicting earlier conclusions.

However, dynamical masses include contributions from accretion disks and molecular gas. Medling et al. [191] analyzed ALMA 242 GHz data for NGC 6240, finding molecular gas masses of $(7.7 \pm 0.5) \times 10^8$ M (dust continuum) and $(1.2 \pm 0.7) \times 10^8$ M (CO(2-1)) within 30 pc of the southern black hole —6–89% of the original dynamical mass. For the northern black hole, gas contributes 5-11% of the dynamical mass. After correction, the southern black hole lies on the MBH-σ* relation, while the northern remains above. This demonstrates that molecular gas corrections are essential for accurate SMBH mass measurements, with the required correction varying between inactive and active black holes.

Future Prospects

On December 25, 2021, the James Webb Space Telescope (JWST) launched. Its 6.5 m primary mirror provides 50-100× Spitzer' s mid-infrared sensitivity and >10× better spatial resolution, enabling 100 pc-scale studies of atomic/molecular gas and dust physics in low-redshift galaxies. This will reveal how massive stars and black holes affect their environments and map gas kinematics in mergers.

The GOALS team was selected as a JWST Early Release Science (ERS) program to conduct initial observations and guide future studies. They selected four (U)LIRGs at different merger stages with diverse power sources and mid-infrared spectral features [Figure 9: see original paper]:

1. **II Zw 096** (LIR = $10^{11}.^{94}$L): An 8.4 kpc separation merger with both starburst and AGN. >80% of infrared emission originates from a third compact source (Σ 10^{14} L kpc^{-2}) [192], possibly a third nucleus with MBH 10^9 M from maser measurements [193], though its nature remains uncertain.

2. **VV 114** (LIR = $10^{11}.^{71}$L): An early-stage 6 kpc separation merger with tidal tails extending 25 kpc. The eastern and western galaxies dominate infrared and UV emission, respectively, with molecular outflow signatures suggesting an AGN in the eastern component.

3. **NGC 7469** (LIR = $10^{11}.^{65}$L): Hosts a Seyfert 1 AGN with a companion galaxy (IC 4283) 26 kpc to the north. A ring-like starburst surrounds the AGN at ~1.8 radius, with Brγ observations revealing nuclear outflows [153].

4. **NGC 3256** (LIR = $10^{11}.^{64}$L): A late-stage merger where the southern nucleus is heavily obscured and visible only in infrared. Both nuclei show

outflow signatures, with evidence for AGN-driven outflow from the southern nucleus [111]. Numerous star clusters exist within 20 of the nucleus.

GOALS will use NIRCam and MIRI for multi-band imaging and NIRSpec and MIRI' s integral field unit to obtain 0.5–28 m spectra, investigating power sources, outflow mechanisms, and AGN–starburst interactions to establish a foundation for future studies.

By 2030, the Next-generation Very Large Array (ngVLA) with 263 antennas will replace the VLA, offering 10× the sensitivity of current VLA and ALMA. These advanced facilities will enable detailed studies of star formation and black hole evolution in local and high-redshift (U)LIRGs, deepening our understanding of galaxy formation and evolution.

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