ISM & Star Formation in Extreme Environments

Brent Groves
ICRAR-UWA
Why Extreme?

• Most star formation in Universe appears to follow simple rules
• However in extreme environments, these rules are either altered or harder to determine
• Star formation in these environments therefore give clues on the underlying physics of star formation
• At their core, it is the physics of the ISM diving these differences

• DISCLAIMER!! - this is a rapid view with biases, there is much more out there!
Extreme Environments?

- What are extreme environments?
- Environments outside the norm
- ULIRGs
- Starbursts
- AGN
- Kinematically disturbed regimes
Overview

- ULIRGs (a historical perspective & recent update)
- Starbursts
- Kennicutt-Schmidt relation
- The ISM of Starbursts/ULIRGS
- AGN & their ISM
- Outflows
- Star formation & ISM in kinematically disturbed regions
ULIRGS
Since the advent of IR, some galaxies found to emit more in IR than optical (Riecke & Lebofsky 1979)

Some were known quasars or clear AGN

Others were found to host a remarkable amount of star-formation activity

These are the first “Starbursts”
ULIRGS

• Ultra Luminous InfraRed Galaxies (ULIRGs): $L_{\text{IR}} > 10^{12} L_\odot$ (LIRGS $> 10^{11} L_\odot$, HyLIRGS $> 10^{13} L_\odot$, SMGs…)

• Locally found earlier (Riecke & Lebofsky 1979) but many found with advent of IRAS (Houck et al. 1985)

• Most Luminous (non-transient) sources in Universe

• See early review of ULIRGs Sanders & Mirabel (1996)

Markarian 231

Credit: NASA, ESA, the Hubble Heritage (STScI/AURA)-ESA/Hubble Collaboration, and A. Evans (University of Virginia, Charlottesville/NRAO/Stony Brook University)
Physics of ULIRGs

IR/1.4 GHz

Sanders \& Mirabel+1996
ULIRGs

• Locally most ULIRGs are mergers or interactions
• At higher z, evolution of typical SFR means some non-merger ULIRGs found
• Strong evolution with redshift ($L_{\text{IR}} \sim (1+z)^4$), but linked to evolution of star formation rate
• While bright, they are rare; only $\sim 3\%$ of total energy density (6% IR energy density; Lonsdale, Farrah & Smith 2006)
• At high z see review Casey, Narayanan, Cooray, 2014.
ULIRGs

- Locally most ULIRGs are mergers or interactions
- At higher $z$, evolution of typical SFR means some non-merger ULIRGs found
- Issues are optical depth
- UV originates different sites
- ID heating mechanism hard

Lonsdale, Farrah, Smith (2006)
Heating the monsters

- Most ULIRGs heating can be identified with optical/NIR lines.
- All have significant SFR, but AGN fraction high (> 25%) and increases with $L_{\text{IR}}$.
- AGN also have warmer mid-IR colours.
- However some ULIRGs have $A_v > 60$.
- Can even be Thompson thick (x-rays).
- **GOALS** survey has overview of identifying ULIRGs (Armus+2009).
- Next PUMA: Physics of ULIRGS with MUSE & ALMA (Perna,Arribas+21).
Measuring SFR in ULIRGs

- SFRs in ULIRGs are easy & hard
- Basically perfect bolometers
- $L_{IR} \sim SFR$

Groves+2008

Main issue - what fraction of heating by stars or AGN?
Drivers?

• High gas masses and densities distinguish ULIRGs (mostly $\text{H}_2$)
• Mergers/interactions drive gas to centres
• Lead to AGN & high SFRs
• High gas/dust columns process light to IR $\rightarrow$ ULIRGs
• At high $z$, high SFRs at high mass can lead to ULIRGs, but not merger driven
Why ULIRGs?

- Extreme monsters
- High gas densities & High SFRs (> 1000 M\(\odot\)/yr!)
- Warm H\(_2\) (NIR lines observed)
- Shocks ([FeII] and H\(_2\) observed in NIR, strong gas flows)
- AGN
- Compact (high surface brightness)
- High optical depths (even to IR!)
- Luminosity means visible across cosmic time (plus negative k-correction)
Why not ULIRGs?

- Extreme monsters (limited number)
- Huge optical depths make diagnostics hard
- Shocks, high densities, AGN & obscuration mean Xco & densities uncertain
- Fractional contribution of AGN mean SFR uncertain
- How to study star formation when its hard to see?
Why not ULIRGs?

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• How to study star formation when it’s hard to see?

• ULIRGs are complex & rare
• While part of the next discussion I’ll split these into Starbursts and AGN, but remember that ULIRGs will be in both
Starbursts

- Starbursts are places with excessive star formation
- This can either be global or as density
- In nearby galaxies typically manifests as circumnuclear rings or starbursts
- But what’s “excessive”?

Credit: ESO (WFI & NACO)
Starbursts

- Most star-forming galaxies follow a relation between $M_\star$ and SFR ("Main-Sequence")

SDSS-DR4

Brinchmann+2004

D. Dale talk yesterday
Starbursts

- Most star-forming galaxies follow a relation between $M_★$ and SFR ("Main-Sequence")
- Many fall below this (Passive/Quenched)
- But some have much higher star formation
- These are Starbursts

Fraser-McKelvie+2021

D. Dale talk yesterday
Starbursts

- Simplistically, Starbursts have excessive SFR (either as a function of mass or $\Sigma_{M\star}$)
- A few % relative to MS galaxies
- Are gas rich & increased extinction
Variation in the main-sequence

- Given uncertainty with MS and dispersion exact definition of SBs malleable

GAMA/DEVILS sample Davies+2019
Variation in the main-sequence

GAMA/DEVILS sample

Davies+2022
Excess SFR varies with $z$

**Figure a**
- $N = 1,914$ SFGs, $\log(M_*) > 10$
- $\delta \log(M_{\text{mol/gas}}/M_*)$
- $\delta M_S$

**Figure b**
- $N = 2,044$ SFGs
- $\delta \log(M_{\text{mol/gas}}/M_*)$
- $\log(M_*/M_\odot)$

**Figure c**
- $N = 1,304$ SFGs, $\log(M_*) > 10$, $\delta M_S = \pm 0.6$
- $\log(M_{\text{mol/gas}}/M_*)_{\text{MS}}$
- Starbursts
- Green valley
- $|\delta M_S| \leq 0.6$

**Figure d**
- $\log(M_{\text{mol/gas}}/(M_{\text{mol/gas}} + M_*))$
- $\log(1 + z)$

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Variation of Gas over MS

- Globally we see $f_{\text{HI}} = \frac{M_{\text{HI}}}{M_\star}$ decrease with increasing $M_\star$
Variation of Gas over MS

- Globally we see \( f_{\text{HI}} = \frac{M_{\text{HI}}}{M_*} \) decrease with increasing \( M_* \)
- But \( f_{\text{H}_2} = \frac{M_{\text{H}_2}}{M_*} \) increasing with increasing SFR at same \( M_* \)
Resolved Main-Sequence

- The star forming main sequence also appears at resolved scales (~kpc)

CALIFA: Cano-Díaz+2020
Resolved Main-Sequence

- The star forming main sequence also appears at resolved scales (~kpc)
- However this appears mostly to be driven by the $\Sigma_{H_2}$-$\Sigma_*$ relation

ALMA/MaNGA:Baker+2022
We also start to see variation in these relations as a function of galactic environment.
Resolved Starbursts

- Note going forward:
- I tend to interchange global & resolved starbursts
- However generally global == local starburst
- But resolved != global
- For nearby galaxies, we’re limited by small number of global starbursts

Kennicutt & De Los Reyes (2021)
Resolved Starbursts

- ‘Resolved' Starbursts in nearby galaxies tend to be circumnuclear
- Located in barred or interacting galaxies
- Bars or interactions drive gas into centre (e.g. Sormani+2023 for NGC1097)
- Examples are NGC253, M82, NGC1365…
- Also associated with AGN (NGC1365, NGC1068, NGC1097…)

Credit: ESO (VIMOS & ERIS)
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Credit: ESO (VIMOS & ERIS)
Kennicutt-Schmidt Relation

OR

Depletion times & SF Efficiencies

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Kennicutt-Schmidt relation

- First put forward by Schmidt (1959) the relation between gas and stars has proven remarkably tight.
- Kennicutt (1998) put it together using nearby galaxies, including (nuclear) starbursts (squares)
- Depletion time $\tau_{\text{dep}} = \frac{\text{Gas}}{\text{SFR}}$
- SF Efficiency $= \frac{\text{SFR} \times \Delta t}{\text{Gas}}$
Kennicutt-Schmidt relation

- Heracles pushed this to kpc scales with Bigiel+2008,2011
- Finding a tight relation with constant depletion times of few $\times 10^9$ yr
- PHANGS (Sun+2023 has only confirmed this)
Kennicutt-Schmidt on kpc scales

Power law fits:
- Fiducial
- FUV+W4 SFR
- Av-corr Hα SFR
- MW $\alpha_{CO}$
- B13 $\alpha_{CO}$
- G20 $\alpha_{CO}$

Contours+limits:
- Fiducial only

Fiducial
- $2.0^{+1.7}_{-1.0}$
- FUV+W4 SFR
- $2.0^{+1.4}_{-1.0}$
- Av-corr Hα SFR
- $1.7^{+1.5}_{-0.8}$
- MW $\alpha_{CO}$
- $2.1^{+1.9}_{-1.1}$
- B13 $\alpha_{CO}$
- $1.9^{+1.5}_{-1.0}$
- G20 $\alpha_{CO}$
- $1.4^{+1.2}_{-0.7}$

$\Sigma_{SFR}$ [M$_{\odot}$ yr$^{-1}$ kpc$^{-2}$]

$\Sigma_{mol}$ [M$_{\odot}$ pc$^{-2}$]

$t_{dep}$ [Gyr]

Sun+ (2023)
Kennicutt-Schmidt on kpc scales

- Heracles pushed this to kpc scales with Bigiel+2008,2011
- Finding a tight relation with constant depletion times of few $\times 10^9$ yr
- PHANGS (Sun+ has only confirmed this)
- BUT…

Bigiel+ (2011)
Kennicutt-Schmidt on kpc scales

Bigiel+ (2008)
Kennicutt-Schmidt on kpc scales

Bigiel+ (2008)
Kennicutt-Schmidt on kpc scales

Bigiel+ (2008)

HI

“Normal”
Kennicutt-Schmidt on kpc scales

Bigiel+ (2008)
Kennicutt-Schmidt on kpc scales

Wilson+ (2019)
Kennicutt-Schmidt on kpc scales

Local Sample

Unweighted: $y = (1.50^{+0.02}_{-0.02})x - 3.87^{+0.04}_{-0.04}$

95% confidence interval

Linmix: $y = (1.54^{+0.02}_{-0.02})x - 3.95^{+0.04}_{-0.04}$, $\sigma = 0.27$

Kennicutt & De Los Reyes (2021)
Kennicutt-Schmidt on kpc scales

local+high-z

Daddi+ (2010)
Kennicutt-Schmidt on kpc scales

local+high-z

log$_{10}$ \( \Sigma_{\text{SFR}} \) [M$_\odot$ yr$^{-1}$ kpc$^{-2}$]

log$_{10}$ \( \Sigma_{\text{Gas}} \) [M$_\odot$ pc$^{-2}$]

Daddi+ (2010)
Kennicutt-Schmidt & starbursts

- Kennicutt-Schmit relation: more gas = more stars
- Similar efficiency across normal galaxy disks
- Yet starbursts offset? Steeper relation?

- SFRs are fairly robust in ULIRGs given most comes out in IR (and AGN removed) but still matching normal and burst hard
  - IMF concerns?
- But Gas densities?
- What about Sizes? (Not all are “resolved”)
- Kennicutt & De Los Reyes (2021) very good discussion on these issues
Varying $\alpha_{\text{CO}}$

- It’s been accepted for a while that relation between CO intensity and H2 column varies in Starbursts.
- Must be lower than MW conversion.
- See Bolatto+13 for discussion.

Also J. Roman-Duval talk
Dust-based evidence of $\alpha_{\text{CO}}$

Sandstrom+ (2013)

Teng+ (2023)
Varying $\alpha_{\text{CO}}$

Kennicutt & De Los Reyes (2021)
Varying $\alpha_{\text{CO}}$

Kennicutt & De Los Reyes (2021)
Resolving the regions

Kennicutt & De Los Reyes (2021)
All evidence suggests ULIRGs more efficient at Star formation

Kennicutt & De Los Reyes (2021)
Even using dust offset seen

- Clear evidence that $\alpha_{\text{CO}}$ varies within and between galaxies
- $\alpha_{\text{CO}}$ lower in starbursts
- Offset with $\Sigma_{\text{gas}}$ likely due to HI $\rightarrow$ H$_2$ differences
- Evidence that SF more efficient in ULIRGs ($\tau_{\text{dep}}$(H$_2$) lower)

- Why?
  see M. Chevance Talk

Kennicutt & De Los Reyes (2021)
Even in ‘normal’ galaxies, offsets seen

PHANGS: Pessa+ (2022)

\[
\log \Sigma_{SFR} - \langle \log \Sigma_{SFR} \rangle = C_\star \Delta \log \Sigma_\star + C_{mol} \Delta \log \Sigma_{mol}
\]

- Variation seen within galaxies
- SB rings offset high (as seen)
- BUT Bars offset low?
Even in ‘normal’ galaxies, offsets seen

- Variation seen within galaxies

- SB rings offset high (as seen)
- BUT Bars offset low?

PHANGS: Querejeta+ (2021)
And Stretch!
The ISM of Starbursts/ULIRGs

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ISM of starbursts & ULIRGs

- A lot of it (high $M_{\text{H}_2}/M_\star$)
- Warm (high $T$, $\sigma_{\text{gas}}$)
- Dense (high $\Sigma_{\text{gas}}$, $n_{\text{gas}}$)
- With high luminosity and molecular abundance, ULIRGs show a suite of easily accessible molecular lines

Meijerink+2013
ISM of starbursts & ULIRGs

Greve+2009

Meijerink+2013
The Warm ISM - CO ladders

- ULIRGs & AGN show high J CO transitions (c.f. Milky Way)
- AGN high, but even starburst (e.g. M82)

Mashian+2015

See J. Roman-Duval talk
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Daddi+ (2015)
Mashian+2015

See J. Roman-Duval talk
Likely impacted by optical depth

- HCN/CO ratio suggests much denser & warmer gas than CO SLED alone
- High-J transitions obscured!
- Xco difficult in ULIRGs

Papdopolous+2010
Underlying physics of $^{12}\text{C}^{16}\text{O}$

Narayan & Krumholz (2014)
Underlying physics of \( \alpha_{\text{CO}} \)

Narayan & Krumholz (2014)
Dense gas

- See more linear correlations with dense gas tracers HCN, HCO⁺
- But HCN/HCO⁺ impacted by shocks, X-rays (Meijerink+2007,2011)
Dense gas

Leroy+ (2015)
Dense gas

- See more linear correlations with dense gas tracers HCN, HCO⁺
- This gives a constant $\tau_{\text{dep}}(\text{dense})$ with $\sim 0.5$ dex scatter
- However scatter may be related to cloud properties...
Dense gas

$log_{10} \langle W_{CO(2-1)} \rangle [K \text{ km s}^{-1}]$ vs $log_{10} \langle \Sigma_{mol} \rangle [M_{\odot} \text{ pc}^{-2}]$

$log_{10} \langle \sigma_{mol}^2 / \Sigma_{mol} \rangle [(\text{km s}^{-1})^2 / (M_{\odot} \text{ pc}^{-2})]$ vs $log_{10} \langle \alpha_{vir} \rangle$
Dense Gas

NGC3627

$F_{\text{H}_2}/[L_\odot/(K\text{km}\cdot\text{s}^{-1}/\text{pc}^2)] \propto SFE_{\text{dense}}$

$L_{\text{HCN}} / L_{\text{CO}(2-1)} \propto f_{\text{dense}}$
Other molecular lines

- Brightness of ULIRGs allow measurement of transitions of multiple molecules
- Density & Heating in AGN allow for high level transitions (not just in CO)

IRAS 13120–5453
Privon+ (2017)
ISM of ULIRGs

- ULIRGS & Starburst have higher $\Sigma_{\text{gas}}$, high $f(H_2)$
- Clear evidence of high dense gas fraction ($f_{\text{dense}} \sim HCN/CO$)
- At high density $T_K \sim T_{\text{dust}}$ (& warm dust in ULIRGs)
- BUT extra heating sources
  - X-rays (AGN)
  - Cosmic rays
  - shocks (winds & turbulence/high $\sigma_{\text{gas}}$)
Cloud scales

- With ALMA we’re now reaching cloud scales in nearby galaxies
- PHANGS show us where typical star-forming galaxies lie
- But even in ‘normal’, see high values and dispersion in barred galaxy centres

Sun+ (2020)
Cloud scales

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• Observations of mergers/Starburst show similar/higher than barred centres

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Observations: Brunetti+ (2020,22)
Simulations: He,Bottrell+ (2023)
With ALMA we’re now reaching cloud scales in nearby galaxies.

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But even in ‘normal’, see high values and dispersion in barred galaxy centres.

Observations of mergers/Starburst show similar/higher than barred centres.

Observations: Brunetti+ (2020,22)
Simulations: He,Bottrell+ (2023)
Cloud scale differences

Brunetti & Wilson (2022)
Ionized ISM in ULIRGs

• Typical optical lines from Ionized ISM are heavily obscured in ULIRGs
• However, NIR-FIR lines will not be as obscured
• Can be used to estimate SFRs, ionization states or presence of shocks AGN

Inami+(2013)  
GOALS
Ionized ISM in ULIRGs

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- However, NIR-FIR lines will not be as obscured
- Can be used to estimate SFRs, ionization states or presence of shocks AGN

Inami+ (2013)
• IR lines show “IR-deficit”
• Likely comes from changing ISM physics & increasing ‘dust cooling’
• That is dust competing for ionising photons with gas and collisionally heat dust cooling
• Intense radiation fields and compact star forming regions (PDRs) dominate
The ISM & SF in AGN

Brent Groves  GISM2
AGN

- AGN: Active galactic Nuclei
- Ongoing accretion onto supermassive black hole
- Strong winds & Jets
- Hard ionising UV& X-ray emission
- Rapid movement of gas towards centre (Broad line region)
- Hot dusty region around nucleus ("torus")

Credit: NASA/ESA, Filipenko, Pagan
AGN

Beckmann & Shrader 2012
AGN

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NGC1068
AGN heating
Physics of ULIRGs

IR/1.4 GHz

Sanders & Mirabel 1996
Physics of ULIRGs

Radio loud AGN

IR/1.4 GHz

Sanders & Mirabel 1996
Emission line diagnostics

- Hard UV & X-ray spectra leads to very different line emission than star formation
- Ionised and molecular show differences

Groves+2006
Emission line diagnostics

• Hard UV & X-ray spectra leads to very different line emission than star formation
• Ionised and molecular show differences

Perna+2021

PUMA: MUSE ULIRGs
Emission line diagnostics

- Diagnostics extend to both UV (but high extinction)
- And NIR & MIR where extinction is less
- Classically used lines in spectral windows
- But with JWST…

Colina et al. (2015)
Mid IR selection

- Warm mid IR emission from torus clear identifier
- Only difficult at highest of Av

D. Dale talk yesterday

Donley+2012
**Mid IR selection**

- Warm mid IR emission from torus clear identifier
- Only difficult at highest of Av
- Also in the mid-IR is the [NeV] line - with an IP of 86eV it should only be strong in AGN

D. Dale talk yesterday
Mid IR selection

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ULIRGs in X-ray

• X-rays are a classic way to detect AGN

• Issues in ULIRGs are absorption and high SFR

Torres-Alba+2018  C-GOALS
ULIRGs in X-ray

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Torres-Alba+2018  C-GOALS
AGN in Radio

- AGN Radio arises from synchrotron emission
- Arising from jets and strong particle emission
- Jets (& outflows) drive material to large radii
- Jets drive shocks into surrounding ISM

M87

Image courtesy: NRAO/VLA
AGN in Radio

- Jet lead to shocks in galaxy (both the “drill” and perpendicular)
- However, heating of the larger scale diffuse ICM is key to many galaxy evolution models
- Also play a key role in polluting ICM/IGM with metals

Image courtesy: CHANDRA
High-energy from AGN
High-energy from AGN

- AGN with high energy coronae, strong magnetic fields are big sources of high energy emission
- NGC1068 brightest extragalactic source of neutrinos in northern hemisphere
- Cosmic rays can penetrate into & through the deepest molecular cloud

Ice cube collaboration (2022)
High-energy from AGN

- AGN with high energy coronae, strong magnetic fields are big sources of high energy emission.
- NGC1068 is the brightest extragalactic source of neutrinos in the northern hemisphere.
- Cosmic rays can penetrate and through the deepest molecular cloud.

Ice cube collaboration (2022)
AGN in MS & SB galaxies

- Measuring star formation in AGN is about separating AGN heating (spatially/spectrally).
- What we find in typical EL AGN is star formation suppressed in starbursts with AGN (Masoura+18).

Rodigheiro+ (2015)
ISM in AGN-hosts

- Strong line (high accretion) AGN correlate with higher central gas densities
- Star formation common in AGN-host galaxies
- AGN act to further heat ISM
  - Shocks
  - X-rays
  - Turbulence/winds
- But ONLY within zone of influence ionization/wind cones
- Rest of disk like normal galaxies/Starbursts
Outflows
Outflows

- Starbursts & AGN inject significant momentum (winds & radiation pressure) in a small area
- This drives outflows to large scale heights

Credit: X-ray: NASA/CXC/JHU/D.Strickland; Optical: NASA/ESA/STScI/AURA/The Hubble Heritage Team; IR: NASA/JPL-Caltech/Univ. of AZ/C. Engelbracht
Outflows

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- These outflows can drag molecules & dust with them
- Outflows pollute outer disks and even IGM

Bolatto+2013
Outflows

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- This drives outflows to large scale heights.
- The outflows can create shocks.
- These outflows can drag molecules & dust with them.
- Outflows pollute outer disks and even IGM.

Rupke+2019
Outflows

- Still open questions on:
  - drivers of outflows
  - On multiphase nature of outflows (how do molecules & dust last in outflows)?
  - Exact mass loading factors (how much material is removed)?
  - See review by Veilleux+2020

![Graph of Mrk 231 with lines indicating velocities v1 = -266 km/s and v2 = -575 km/s](image)

Rupke+2017
AGNJets

- Jets (\& outflows) drive material to large radii
- Jets drive shocks into surrounding ISM
- Some Radio Jets observed to Mpc scales!

Mukhajee + 2017
Outflows

- Stronger outflows seen in starburst galaxies
- Outflows remove gas locally, limiting further SF
- Most will eventually return, but some mix with CGM
- AGN can drive massive outflows, impacting CGM & IGM
- Outflows are key mechanism for metal removal/mixing and pollution of the IGM
ISM & star formation in dynamic regions

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Tidal Dwarfs

Lelli+ (2015)
Tidal Dwarfs

- Galaxy collisions can not only lead to ULIRGs but though off material
- This collisional debris can form stars and become tidal dwarf galaxies (TDGs)
- TDGs are interesting that mostly HI and, if rotating, suggest no dark matter.
Tidal Dwarfs

- TDGs can be enriched and form molecular gas
- as in other galaxies CO
- SFR traces CO

Querejeta+2019
Tidal Dwarfs

- TDGs can be enriched and form molecular gas
- as in other galaxies CO SFR traces CO

Image: HST F547M
Ellipses: GMCs
Contours: Hα flux

Deep optical + HI
Composite g + r
HST WFC3 F547M + Hα contours

Querejeta+2019
Jellyfish galaxies are galaxies falling into clusters.

- Ram pressure & tidal forces stripping gas

- This gas can be shocked but also can form stars!

GASP-MUSE

Poggianti+2019
Jellyfish

- Jellyfish galaxies are galaxies falling into clusters
- Ram pressure & tidal forces stripping gas
- This gas can be shocked but also can form stars!

Poggianti+2019
Central Molecular Zones

- Centre of Milky Way shows dense gas
- but SFR depressed
- Likely kinematically disturbed (Shear/turbulence)

Henshaw+23
Central Molecular Zones

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Henshaw+23
Central Molecular Zones

- Centre of Milky Way shows dense gas
- but SFR depressed
- Likely kinematically disturbed (Shear/turbulence)
- This is true even with dense gas and in other galaxies’ CMZs and kinematically disturbed regions

Literature:
- Murphy+15
- Viaene+18

Querejeta+2019
ISM & Star formation in Extreme Environments

- Rapid overview of starbursts, ULIRGs & AGN
- DEFINITELY missed topics and references
- UV lines, Cosmic Rays, Magnetic Fields, [CI], large scale HI, large scale structure & clusters, low-metallicity starbursts, and more…
ISM & Star formation in Extreme Environments

- ULIRGs locally are highly obscured, merger-driven galaxies, with huge star formation rates and commonly AGN.
- However, luminosity cut includes normal galaxies at high-z.
- Starburst galaxies are rare, though starburst regions can be found in some galaxies.
- Associated with high gas densities and potentially high star formation efficiencies.
- Differences are seen even at cloud scales with massive, dense and turbulent clouds.
- AGN affect all phases of ISM with strong winds, jets, magnetic fields & UV-γ-ray field.
- But AGN only affect within ionization cone.
Standard references

- Saintonge & Catinella (2022): “The Cold ISM of Galaxies in the local Universe”
- Tacconi, Genzel & Sternberg: “Evolution of star forming ISM across cosmic time”
- Casey, Narayanan, & Hooray (2014): “Dusty star-forming galaxies at high-z”
- Veilleux, Maiolino, Bolatto, & Aalto (2020): “Cool outflows in galaxies and their implications”