Starburst, AGN and Mergers

Many galaxies have emission that has nothing to do with just passive evolution of a simple stellar population as we have already learned.

-- many Local Group galaxies have complex star formation histories

-- galaxies interact and merge which can change their characters dramatically

The nuclei often appear to be home to a variety of energetic events, sometimes merger-driven, sometimes as the result of other circumstances.
Mergers Cause Starbursts

Tidal torques and enhanced probabilities for cloud-cloud collisions make interactions and mergers a likely driver for starbursts.

Observations support this idea.

Starburst Galaxy Modes of Star Formation

-- even for modest luminosity starbursts, interactions appear to be a significant driver (M82, NGC1614, Arp 299 all show clear signs of interaction)

Arp 299 shows that a starburst may encompass a variety of types of vigorous star formation:

- IC694 (Component A) is a large spiral with an extended duration nuclear starburst accounting for $3 \times 10^{11} L_\odot$
  (may include nuclear super star clusters)

- NGC3690 B1 and B2 representing another massive galaxy nucleus and a nearby region with a vigorous star formation episode representing about $1.5 \times 10^{11} L_\odot$

- Young and vigorous star formation at C,C' at the interface region between IC694 and NGC3690

- Numerous supergiant HII regions and stellar clusters both near the nuclear star formation regions and along spiral arms
NGC3690 = Components B1, B2, C, C'

0.6 \mu m

1.60 \mu m

1.10 \mu m

H_2 2.12 \mu m

P\alpha 1.875 \mu m

FeII 1.644 \mu m
IC694 = Component A

- H₂ 2.12 µm
- Paα 1.875 µm
- FeII 1.644 µm
Supergiant HII Regions and Stellar Clusters in Arp 299

19 HII regions with log \( L(P_{\alpha}) \geq 38.7 \text{ erg/s} \) *

26 clusters with \( M_H < -14 \) and deep CO bands

For comparison, the super star clusters in the Antennae have \( M_H = -11 \) to -16

* This is the \( P_{\alpha} \) luminosity of 30 Dor
NGC 1614: Nearly Face-on with $A_v \sim 5 = \text{Starburst Laboratory}$

Deep WFPC2 Image of NGC 1614

NGC 1614

H-K, dark = bigger $A_V$

300 pc
NGC1614 Has a Pα Ring

Ring diameter is $\sim 650$ pc.
Propagating Star Formation in NGC1614

- CO strongest on the nucleus
- $\text{P}_\alpha$ strongest in the ring
- $\text{H}_2$ extends beyond the $\text{P}_\alpha$ ring

$\Rightarrow$ star formation began in the center and is propagating outwards.

Modeling the Starburst in NGC1614

Best fit comes from using two bursts separated by $5 \times 10^6$ years. This fits use a total of $0.6 \, M_{\text{dynamical}} = 5.5 \times 10^8 M_\odot$ and use “IMF8”.

Double burst time scale implies a propagation speed of $\sim 60$ km/sec.
More on Thoughts on the Initial Mass Function:

NGC 1614 an ideal laboratory for studying starbursts:
-- relatively low extinction with $A_V \sim 5$
-- favorable inclination at $l=51^\circ$

But an uncomfortably large fraction of the maximum possible dynamical mass needs to be used in the burst to produce a good fit.

Is the IMF at fault?

Comparison of Percentages of High Mass Stars

<table>
<thead>
<tr>
<th>IMF</th>
<th>10-30$M_\odot$</th>
<th>30-100$M_\odot$</th>
</tr>
</thead>
<tbody>
<tr>
<td>IMF8</td>
<td>14%</td>
<td>5%</td>
</tr>
<tr>
<td>Modified Salpeter</td>
<td>13%</td>
<td>9%</td>
</tr>
<tr>
<td>Original Salpeter</td>
<td>7%</td>
<td>5%</td>
</tr>
<tr>
<td>Miller &amp; Scalo 1979</td>
<td>6.5%</td>
<td>3%</td>
</tr>
<tr>
<td>Scalo 1986</td>
<td>3%</td>
<td>1%</td>
</tr>
<tr>
<td>Basu &amp; Rana 1992</td>
<td>3%</td>
<td>3.5%</td>
</tr>
</tbody>
</table>

recall Salpeter has $\alpha = 2.35$ for all masses

To avoid using too much mass in the starburst, will have to appeal to even more top heavy IMF!
Conclusions from Starburst Modeling

- Star formation in spiral arms, not just nucleus, is extreme in a starburst
- Propagating star formation observed in several starbursts
- Super star clusters and HII regions more luminous than 30 Dor are common
- CO/H$_2$ mass ratio needs revision for starbursts
- Formation of stars with M $< \sim 3M_\odot$ must be suppressed
- [FeII] is an SN indicator but most emission is diffuse and not correlated exactly one for one with radio SNR
IR-Luminous Galaxies as a Class

First identified as a class of galaxies by Rieke and Low, 1972.
### 10-μ Observations of Ultrahigh-Luminosity Galaxies

<table>
<thead>
<tr>
<th>Object</th>
<th>10-μ Flux ((10^{-26} \text{ W m}^{-2} \text{ Hz}^{-1}))</th>
<th>Distance (Mpc)</th>
<th>7.9-13.3-μ Luminosity ((10^{32} \text{ W}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Markarian 231</td>
<td>1.42±0.11</td>
<td>230</td>
<td>1.3×10^6</td>
</tr>
<tr>
<td>I Zw 1</td>
<td>0.40±0.04</td>
<td>340</td>
<td>8.0×10^5</td>
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<tr>
<td>Cyg A</td>
<td>0.18±0.03</td>
<td>310</td>
<td>3.0×10^6</td>
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<tr>
<td>NGC 1614=II Zw 15</td>
<td>0.92±0.05</td>
<td>130</td>
<td>2.7×10^6</td>
</tr>
</tbody>
</table>

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![Diagram of galaxy classification](image)

- **Normal Galaxies**
- **Seyfert and Related Galaxies**
- **Ultra-High Luminosity Galaxies**
- **Quasi-Stellar Objects**

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*Rieke and Low 1972 ApJ L 176 95*
IRAS Yielded Statistical Samples

Nomenclature: LIRG = Luminous Infrared galaxy $1 \times 10^{11} L_\odot - 1 \times 10^{12} L_\odot$

ULIRG = Ultraluminous Infrared galaxy $1 \times 10^{12} L_\odot - 1 \times 10^{13} L_\odot$

HyperLIRG = Hyper Luminous Infrared galaxy $> 1 \times 10^{13} L_\odot$
Many High Luminosity IR Galaxies are Merging/Interacting

Scoville et al. 2000 AJ 119 991

NICMOS Imaging
As luminosity increases, larger fractions of the sample show merging and AGN characteristics.

Sanders & Mirabel 1996 ARAA 34 749

<table>
<thead>
<tr>
<th>No. of objects&lt;sup&gt;a&lt;/sup&gt;</th>
<th>10.5–10.99</th>
<th>11.0–11.49</th>
<th>11.5–11.99</th>
<th>12.0–12.50</th>
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<tbody>
<tr>
<td>Morphology</td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>merger</td>
<td>50</td>
<td>50</td>
<td>30</td>
<td>40</td>
</tr>
<tr>
<td>close pair</td>
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<td>32%</td>
<td>66%</td>
<td>95%</td>
</tr>
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<td>single (?)</td>
<td>21%</td>
<td>36%</td>
<td>14%</td>
<td>0%</td>
</tr>
<tr>
<td>Separation&lt;sup&gt;b&lt;/sup&gt;</td>
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<td></td>
<td></td>
<td></td>
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<td>[kpc]</td>
<td>36</td>
<td>27</td>
<td>6.4</td>
<td>1.2</td>
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<td>Opt Spectra</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Seyfert 1 or 2</td>
<td>7%</td>
<td>10%</td>
<td>17%</td>
<td>34%</td>
</tr>
<tr>
<td>LINER</td>
<td>28%</td>
<td>32%</td>
<td>34%</td>
<td>38%</td>
</tr>
<tr>
<td>H II</td>
<td>65%</td>
<td>58%</td>
<td>49%</td>
<td>28%</td>
</tr>
<tr>
<td>$L/L_B$&lt;sup&gt;c&lt;/sup&gt;</td>
<td>1</td>
<td>5</td>
<td>13</td>
<td>25</td>
</tr>
<tr>
<td>$L/L_{CO}$&lt;sup&gt;c&lt;/sup&gt;</td>
<td>[37]</td>
<td>[78]</td>
<td>[122]</td>
<td>[230]</td>
</tr>
</tbody>
</table>

<sup>a</sup>Objects in the IRAS BGS plus additional ULIGs from Kim & Sanders (1996).
<sup>b</sup>Mean projected separation of nuclei for mergers and close pairs only.
<sup>c</sup>Mean values.
Black Holes in Galaxy Nuclei

\[
\log(\nu L_\nu) \quad [\text{ergs s}^{-1} \text{ cm}^{-2}]
\]

\[
\log(\nu) \quad [\text{Hz}]
\]

- radio
- infrared
- optical
- X-ray

\[ f_\nu \propto \nu^\alpha \]

- RQ
- RL
Humason (1932) noted that the galaxy NGC1275 has a very star-like nucleus. He also mentioned that galaxies with star-like nuclei usually have emission lines.

Seyfert (1943) observed about a dozen galaxies with star-like nuclei and found that all have strong and broad emission lines. He noted that some of these lines are very high excitation lines not seen in HII regions.
Some radio galaxies display spectra which are very similar to giant ellipticals. Others exhibit emission lines – some are narrow-lined like Sey2s while others are broad-lined like Sey1s.
Reverberation Mapping

- A Seyfert nucleus will be seen to brighten at x-ray wavelengths.
- A few days later, UV HeII lines will brighten
- After another few days, visible wavelength HeII lines brighten
- After a couple of weeks, H\(\beta\) is observed to brighten
- And so on from high excitation lines to low excitation lines

Time for brightening relative to the original pulse measures the physical scale of the emitting region.

Measuring the velocity dispersion in the emission line then leads to a determination of the back hole mass.

This technique has been most successful for Seyferts; QSO timescales reach into the years so it becomes difficult to take the required variability data.

\[ r = \tau \times c \]

\[ \text{Mass}_{\text{BH}} = \frac{3fr\sigma^2}{G} \quad f=\text{factor } \sim 1 \text{ to account for geometry} \]

Example: NGC 5548

\[ \tau_{\text{HeII}\lambda 1640} = 3.8 \text{ days} \rightarrow r_{\text{HeII}\lambda 1640} = 9.8 \times 10^{10} \text{ km} \]
\[ \tau_{\text{HeII}\lambda 4686} = 7.8 \text{ days} \rightarrow r_{\text{HeII}\lambda 4686} = 2.0 \times 10^{11} \text{ km} \]
\[ \tau_{\text{H}\beta} = 18.6 \text{ days} \rightarrow r_{\text{H}\beta} = 4.7 \times 10^{11} \text{ km} \]

\[ \sigma_{\text{HeII}\lambda 1640} = 9800 \text{ km/sec} \quad \sigma_{\text{HeII}\lambda 4686} = 73400 \text{ km/sec} \quad \sigma_{\text{H}\beta} = 4660 \text{ km/sec} \]

\[ M_{\text{HeII}\lambda 1640} = 5.2 \times 10^7 M_\odot \quad M_{\text{HeII}\lambda 4686} = 6.0 \times 10^7 M_\odot \quad M_{\text{H}\beta} = 5.7 \times 10^7 M_\odot \]

assuming \( f=1 \).
Reverberation Results

Careful work can yield black hole masses good to at least a factor of 3 – know the BH mass better than the bulge mass for most AGNs.

Not surprisingly, AGNs typically are radiating at 10% of the Eddington limit with QSOs on the higher power side.

Peterson et al. 2004 ApJ 613 682
When broad line regions were discovered in polarized light from Seyfert 2s (Antonucci & Miller 1985), a model was proposed where the difference between Sey1 and Sey2 is just due to the viewing angle.

This model has been very useful and appears to be broadly correct, but there are variations in the accretion disk and torus structures that make AGN more complicated than the unified model implies.
Looking for the Torus
NGC 5728
Hubble Space Telescope
Wide Field / Planetary Camera

Ground View

HST View
Unification Across the Board

Seyfert 1s – BLRG – QSOs
Observing angle is within the cone angle of the torus.

Seyfert 2s – NLRG
Observing angle intercepts the torus

BL Lacs – OVV
Observing angle lies along the jet so relativistic effects are important.

BH is the ultimate power source in all of these objects.
AGN – Starburst Connection

A causal connection between star formation and AGN activity has not been proven definitively. Since most radio-quiet Seyferts are in spiral hosts, it is not surprising that star formation is observed. Galaxies with a mixture of behaviors are common.

One line of thought is that perhaps a circumnuclear starburst could provide enough kinetic energy to overcome angular momentum and drive material to the nucleus to feed the black hole.

Dale et al. 2006 ApJ 646 161
QSOs: Very Luminous AGN

The name QSO is a holdover from the photographic days. QSOs have spectra that are very similar to Seyferts, can be highly variable, and are strong x-ray sources. Remarkably, the properties of z~6 QSOs are extremely similar to z~1-2 QSOs.


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QSO SEDs

Few objects display a pure power law spectrum as would be expected from a synchrotron source.

Spectra tend to be complicated with the host galaxy evident at some wavelengths and hot gas and/or accretion disks being important at some wavelengths.
Detecting the host galaxies of QSOs was an essential step in tying QSOs to Seyferts. Note that many QSO hosts appear to be merging or interacting.
The number density of QSOs peaked around $z\sim2$, same era as when star formation was high. Numbers imply that a significant fraction of galaxies now should have massive black holes (and they are being found as we have seen).
Local Black Hole Mass Function

Local BHMF matches that extrapolated from AGN.