Remarkable Disk and Off-Nuclear Starburst Activity in the Tadpole Galaxy as Revealed by the Spitzer Space Telescope

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The Tadpole

• Designation: UGC 10214 = VV 29 = Arp 188
• $z = 0.0310$
• Distance = 129 Mpc ($H_0=72 \text{ km s}^{-1} \text{ Mpc}^{-1}$)
• Gas rich main disk and tidal tail
• HST ACS images show newly forming, massive clusters in the spiral arms.
  – Some are SSC ‘Super star clusters’
    • Total masses and stellar densities that rival globular clusters and dwarf galaxies ($M > 10^5 \, M_\odot$)
A Note on Mergers

• Boost level of star formation in disk galaxies
• Distortion of spiral arms
  – Violent star formation
    • Large-scale alterations to the underlying gas and stellar populations
    • ISM can collapse and form giant molecular clouds, spots for massive star formation
• Outer spiral arms
  – Atomic hydrogen stretched into filamentary tails
  – Will either dissipate into IGM or collapse back on merger remnant
    • Forms streams or ring-like structures
• But:
  – Not all tidally interacting galaxies show this remarkable star formation
The Data

• Optical Images
  – U-band (0.358 um), g’-band (0.485 um), r’-band (0.624 um), and i’-band (0.774 um)
  – Gathered using the Issac Newton Telescope of the La Palma Observatory
  – Also employ HST ACS g-band (F475W) and V (F606W)
The Data II

- Optical Spectroscopy
  - Tadpole Nucleus
  - The brightest tidal tail SSC – J160616.85+552640.6
    - Using the COSMIC camera on the Hale 200 inch (5m) at the Palomar Observatory

- NIR Images
  - J-band (1.2 um) and $K_s$-band (2.2 um)
The Data III

• Mid Infrared (MIR) – Spitzer Space Telescope
  – Four IRAC Bands
    • 3.6, 4.5, 5.8, 8.0 \( \mu \)m
  – Two MIPS Bands
    • 24, 70 \( \mu \)m

• Resolution
  – All IRAC, NIR, and Optical data were reprojected and resampled onto a common grid and were Gaussian-convolved to match the 8 \( \mu \)m image resolution
SED Templates

- SEDs from Tadpole are compared to representative galaxy types
  - 13 Gyr elliptical galaxies
    - The underlying (old) stellar components, dust free
  - S0/Sa Galaxies
    - Early-type disk galaxies
  - Sc disk galaxies
    - More active disk galaxies
  - IR-bright galaxies
    - Prototype starburst galaxy M82, with steeply rising SED from dust emission
  - Active, dust-absorbed nuclei
    - Seyfert 2 template
### TABLE 1

UGC 10214 Global Flux Density and Luminosity per Filter

<table>
<thead>
<tr>
<th>Band</th>
<th>$\lambda_0$ ((\mu\m))</th>
<th>$\Delta \lambda$ ((\mu\m))</th>
<th>$F_\nu$ (mJy) (^a)</th>
<th>$\nu F_\nu$ (10(^8) L(_\odot)) (^b)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$U$</td>
<td>0.3580</td>
<td>0.0638</td>
<td>2.132</td>
<td>8.89</td>
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<tr>
<td>$g'$</td>
<td>0.4846</td>
<td>0.1285</td>
<td>9.035</td>
<td>27.8</td>
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<tr>
<td>$r'$</td>
<td>0.6240</td>
<td>0.1347</td>
<td>15.292</td>
<td>36.6</td>
</tr>
<tr>
<td>$z'$</td>
<td>0.7743</td>
<td>0.1519</td>
<td>19.848</td>
<td>38.3</td>
</tr>
<tr>
<td>$J$</td>
<td>1.250</td>
<td>0.162</td>
<td>47.181</td>
<td>56.4</td>
</tr>
<tr>
<td>$K_s$</td>
<td>2.150</td>
<td>0.397</td>
<td>43.020</td>
<td>29.9</td>
</tr>
<tr>
<td>IRAC-1</td>
<td>3.600</td>
<td>0.750</td>
<td>23.674</td>
<td>10.2</td>
</tr>
<tr>
<td>IRAC-2</td>
<td>4.500</td>
<td>1.020</td>
<td>13.816</td>
<td>4.58</td>
</tr>
<tr>
<td>IRAC-3</td>
<td>5.800</td>
<td>1.414</td>
<td>15.762</td>
<td>4.06</td>
</tr>
<tr>
<td>IRAC-4</td>
<td>8.000</td>
<td>2.974</td>
<td>28.253</td>
<td>5.27</td>
</tr>
<tr>
<td>MIPS-24</td>
<td>24.00</td>
<td>5.35</td>
<td>27.093</td>
<td>1.69</td>
</tr>
<tr>
<td>MIPS-70</td>
<td>71</td>
<td>19</td>
<td>207.5</td>
<td>4.36</td>
</tr>
</tbody>
</table>

\(^a\) No reddening corrections are applied here; flux uncertainties are \(\sim 5\%\) for the optical and NIR measurements and \(\sim 10\% - 20\%\) for the IRAC and MIPS measurements.

\(^b\) Assuming a distance to UGC 10214 of 129 Mpc.
The Nucleus
Disk and Extranuclear Regions
Optical Spectra
Star Formation Rates

- Tracers of SF
  - Directly measure UV emission
    - Good only is there is no dust
  - FIR – Reprocessed starlight
    - Spatial Resolution of IRAS allows only for Global SFR
  - MIR – Kitchen sink
    - Starlight, ionized ISM, dust and PAHs, thermal radiation from dust grains, synchrotron radiation

<table>
<thead>
<tr>
<th>SFR Indicator$^a$</th>
<th>Global SFR$^b$ (M$_\odot$ yr$^{-1}$)</th>
<th>Disk Hot Spot SFR$^c$ (M$_\odot$ yr$^{-1}$)</th>
<th>Super Star Cluster SFR$^d$ (M$_\odot$ yr$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>FIR$^e$</td>
<td>2.37</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>MIPS 70 μm$^f$</td>
<td>4.5</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>MIPS 24 μm</td>
<td>3.26</td>
<td>0.51</td>
<td>0.11</td>
</tr>
<tr>
<td>Hα</td>
<td>...</td>
<td>...</td>
<td>0.23</td>
</tr>
<tr>
<td>[O iii] + Hβ</td>
<td>...</td>
<td>...</td>
<td>0.39</td>
</tr>
</tbody>
</table>

$^a$ For $M > 5$ M$_\odot$.
$^b$ Total area = 2.97 arcmin$^2$ (see § 3.1).
$^c$ J160605.90+552532.5.
$^d$ J160616.85+552640.6.
$^e$ Using IRAS 60 and 100 μm emission.
$^f$ Derived for $M > 0.1$ M$_\odot$. 
PAH Emission

• Prominent Bands
  – 6.2, 7.7, 11.2 um.
  – Weaker bands: 3.3 and 8.6 um

• Demonstrated to be effective tracers of ongoing star formation activity from early-type stars in dust-rich galaxies

• Spitzer IRAC bands are sensitive to this emission

• Comparing 5.8 and 8.0 um bands to optical or NIR produces contrast between star formation regions and starlight from older populations
PAH: Nucleus & IR-Bright Spot
PAH: SSCs

Need to uncover PAH bands:
  Remove all starlight from all bands
  Remove the dust continuum from IRAC 8 um
Quiescent or Active Star Formation

- Compare PAH strength to 24 um emission
  - $F_{8\text{um}}/F_{24\text{um}} = \text{const}$ for normal disk galaxies
  - Decreases when SF activity and FIR continuum increases
PAH Equivalent Width
Poised for Nuclear Starburst?

• Must remove angular momentum from gas in spiral arms
  – Tadpole nucleus shows little SF activity
  – Spitzer: No bar

• 100-200 Myr old

• N-body sims show that tidal tail regions reform with nucleus over Gyr timescales

• Don’t know: May be to early to tell.
  – Molecular gas may hold key
Off-Center Collision?

• Classic Spiral-Spiral Collision
  – Unwrapping of spiral arms (tidal tails)
  – Plumes
  – Counter-tails

• Tadpole has vigorous SF in disk. Ring?
  – Is this ring real? If so, could be formed by the merger
    • Off axis collision of 2 similar massed objects

  – Arguments for:
    – NIR & MIR
    – Ringlike structure of both old and new stars
    – Outer spiral arms
    – Distorted tidal tail
    – Companion that is directly behind the primary
    – Ring systems have little nuclear SF
Tidal Tail Stellar Cluster Masses

- **SSCs**
  - Emerging globular cluster systems?
  - Self-gravitating dwarf galaxies?
  - Do these remain bound or do they disperse
    - Must know: Mass, size, environment
      - IMF
    - Tran et al: (0.5-1.0)x10^6 M☉
      - Very high gas pressure and SF efficiency.
    - Compared to GCs SSCs cover much more area
      - Vulnerable to disruption
    - Mass estimates
      - g'-band: 5.0 x10^6 M☉ for 12” aperture
      - NIR: 7.0x10^6 M☉ for 12” aperture
      - g'-band: 1.4 x10^6 M☉ for 4.5” aperture
      - NIR: 1.6 x10^6 M☉ for 4.5” aperture
Summary

• IR Morphology
  – Nucleus, disk with SF hot spots, spiral arms, plumes, tidal tails. No large-scale bar

• Active SF
  – Disk, spiral arms, tidal tail.

• Nucleus
  – Old stellar population.
  – No SF

• IR Bright Spots
  – Strong PAH emission tracing locations where gas has merged into massive star forming regions

• Ring-like structure has bright IR emission → Massive SF.
  – Ring may be from off-center collision with lower mass companion
Summary II

- Outer Spiral arm is VERY blue.
- Tidal Tail
  - Very blue. Lined with supermassive star clusters
- SCC J160616.85+552640.6
  - IR bright Tidal tail SSC, low metallicity
  - Strong 24 um. Suppressed PAH. SF.
- Mass of SSC
  - 1.4-1.6 x M☉ based on g’ and NIR
    - Comparable to largest Globular Clusters in Milky Way or tidal dwarf galaxies
Outstanding Results

• Nucleus is not undergoing a starburst or even modest star formation
• Main disk is forming stars in a distorted spiral arm
• In the tidal tail, a massive cluster has formed after only a few megayears from a metal-poor gas reserve.
The End.

- Questions
- Comments