The 2^{nd} Spitzer Conference: Infrared Diagnostics of Galaxy Evolution
ASP Conference Series, Vol. 381,
Ranga-Ram Chary, Harry I. Teplitz, Kartik Sheth, eds.

Remarkable Disk and Off-nuclear Starburst Activity in the *Tadpole Galaxy*, UGC10214

T. H. Jarrett and the SWIRE Team

SSC/Caltech, 100-22 IPAC, Pasadena, CA 91125

Abstract. We present ground-based optical and *Spitzer* infrared imaging observations of the interacting galaxy UGC 10214, the "Tadpole Galaxy" (z = 0.0310), focusing on the star formation activity in the nuclear, disk, spiral arms and tidal tail regions. The major findings of this study are that the Tadpole is actively forming stars in the main disk outside of the nucleus and in the tidal plume, with an estimated mean star formation rate of 2 to 4 $M_{\odot}$/yr. The most prominent sites of mid-infrared emission define a ring morphology that, combined with the overall morphology of the system, suggest the interaction may belong to the rare class of off-center collisional ring systems that form both shock-induced rings of star formation and tidal plumes. The nuclear emission is solely powered by older stars, with little evidence for ongoing star formation at the center of the Tadpole. Extra-nuclear star formation accounts for greater than 50% of the total star formation in the disk and spiral arms, featuring infrared-bright "hot spots" that exhibit strong PAH emission, whose band strength is comparable to that of late-type star-forming disk galaxies. The tidal tail, which extends ∼2 arcmin (∼75 kpc) into the intergalactic medium, is populated by super massive star clusters, likely triggered by the galaxy-galaxy interaction that has distorted UGC 10214 into its current "tadpole" shape.

1. Introduction

The Tadpole Galaxy (UGC10214 = VV 29 = Arp 188) is the result of a close gravitational interaction with a smaller galaxy some time (∼100-200 Myr) in the past (Briggs et al. 2001; de Grijs et al. 2003). Tidal forces have separated a major spiral arm from its main body, creating a long plume of gas and stars that extends over ∼2 arcmin into the surrounding intergalactic medium, whose optical morphology is akin to the Toomre & Toomre (1972) classic weak galaxy-galaxy interaction tails. Galaxy-galaxy collisions and weaker tidal interactions, such as those inferred for the Tadpole, can boost the level of star formation activity within disk galaxies, in doing so transform the subsequent evolution of the merging system (Kennicutt et al. 1987; Lambas et al. 2003; Xilouris et al. 2004). Distortion of spiral arms and violent star formation episodes lead to large-scale alterations in the underlying gas and stellar populations. Under this intense compression, the interstellar medium (ISM) can rapidly coalesce with cloud-cloud collisions, accreting to form giant molecular clouds, creating the conditions for deeply embedded massive star formation (Olson & Kwan 1990; Scoville et al. 1991; Mihos & Hernquist 1996).

To properly understand the evolution of interacting galaxies, one must study the interaction between the underlying (old star) mass distribution, dust distribution, neutral atomic gas, cold molecular gas and newly forming (energetic) stars. Consequently, this sets a premium on building complete data sets that span the radio-ultraviolet electromagnetic spectrum. A rich data set was recently made available by the Spitzer Wide-field Infrared Extragalactic Survey (SWIRE; Lonsdale et al. 2003). This work combines the optical and infrared data sets to investigate the large-scale morphology of the disk and tidal tail, properties of the embedded star formation regions, and the super massive star clusters in the tail and spiral arms.

2. Physical Content of Optical-IR Imaging

Spanning a sizeable portion of the electromagnetic spectrum, the SWIRE imaging, Fig. 1, provides lucid contrast between stellar populations and the nebular ISM that comprise the bulk of the Tadpole emission. The optical imaging separates the youngest, hottest stellar populations from the moderate aged (type A-F) stars. The NIR imaging illuminates the oldest, most numerous stellar populations that form the backbone of the disk and halo structures. The MIR, with < 5 μm combines the old (evolved) stellar population with a hot dust component originating from the ISM. The MIR, with > 6 μm, measures the warm

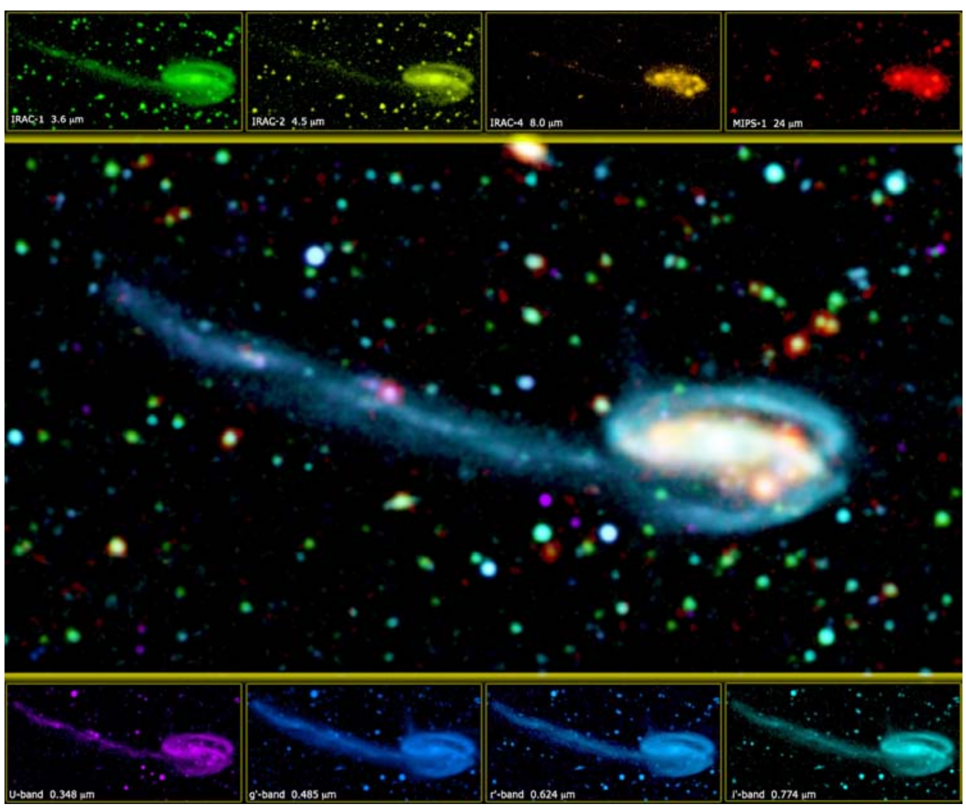

Figure 1. Optical-infrared panchromatic view of the Tadpole Galaxy (UGC10214). The center image is a composite combination of eight bands (from blue to red colors): U-band (0.348 μm), g'-band (0.485 μm), r'-band (0.624 μm), i'-band (0.774 μm), *Spitzer* IRAC-1 (3.6 μm), IRAC-2 (4.5 μm), IRAC-4 (8.0 μm) and MIPS-1 (24 μm).

dust continuum and molecular aromatic features (e.g., Leger & Puget 1984) that arise from the diffuse ISM and dense star formation regions. Fig. 1 encapsulates the full informational content of the data set, assigning a separate color scale (from blue to red) to each band, optical to IR, respectively, to form the color composite. The combined colors provide clues into the past and current state of the Tadpole, and combined with dynamical models, into the future evolution of the system.

The most striking features seen in Fig. 1 include: (a) the "blue" spiral arms and tidal tail that are prominent in the bands that are sensitive to the youngest, most massive stars that are unobscured by dust, (b) IR-bright "hot spots" in a ring-like structure that dominates the disk emission, indicative of embedded dusty star-formation regions, and (c) the prominent 24 μm "hot spots" in the tidal plume that are spatially coincident with the brightest "super star clusters" resolved by *HST* (e.g., Tran et al. 2003; De Grijs et al. 2003). Dark dust lanes coincide with bright 8 μm emission most notably along the eastern side of the Tadpole. Fainter structures be discerned from the background, including a western plume, extending beyond the figure boundary, and a polar stream of stars that wraps under the disk before exiting northward along the eastern edge of the disk. The tidal interaction with the intruder galaxy, VV29c (note the faint fuzzy object hiding behind the western edge of the disk, at the extreme end of the "bar") has not catastrophically disrupted the parent galaxy. The disk and tidal tail show evidence for recent starburst activity, both deeply embedded within dense molecular clouds (IR markers) and unobscured sites that are fully open to the disk and intergalactic medium.

3. Summary of Major Findings

The *Spitzer* Wide-area Infrared Extragalactic Survey (SWIRE) observed the interacting galaxy UGC10214 with deep ground-based optical and NIR imaging in support of the Spitzer IR imaging. The major results of this study are:

- The IR morphology is broadly separated by: nucleus, disk with star formation "hot spots", spiral arms, plume and tidal tail structures; there is no evidence for a large-scale bar.

- Active star formation is observed in the disk, spiral arms, and tidal tail, with an estimated cumulative SFR (IR) equal to ∼2 to 4 $M_{\odot}$/yr.

- The nucleus is powered by starlight from the old stellar population; there is no evidence of active star formation; the deduced average foreground extinction is $A_v < 1$.

- IR-bright "hot spots" in the disk exhibit strong PAH emission bands, tracing the locations where gas has merged to form massive star formation regions; the level of star formation activity is comparable to that of late-type spiral galaxies, with SFR ∼0.5 $M_{\odot}$/yr in the eastern cluster representing ∼17% of the total star formation in the Tadpole; the combined disk SFR (MIR) is estimated to be $> 50\%$ of the total in the system.

- The inner spiral arm or ring-like structure exhibits bright IR emission, indicative of embedded massive star formation; the ring may be the result of an off-center collision with a lower-mass companion galaxy.
- The outer spiral arm is very blue, dominated by starlight from intermediate age and massive stars; the arm distorts into a long tidal tail that extends ∼2 arcmin (∼75 kpc) into the intergalactic medium.
- The tidal tail is very blue, dominated by starlight, lined with super massive star clusters; two of these clusters are detected with *Spitzer* in the MIR .
- The low metallicity, IR-bright tidal tail super star cluster, J160616.85+552640.6, exhibits many remarkable IR properties, including exceptionally strong 24 μm emission relative to all other optical-IR components; PAH emission is suppressed, suggesting grain destruction from the hard UV radiation field; the SFR $\sim 0.2 - 0.4\ M_{\odot}$/yr, or 10% of the total in the Tadpole system.
- The mass of the super star cluster is $\sim 1.4 - 1.6 \times 10^6\ M_{\odot}$ based on the g'-band (0.5 μm) and NIR (2.2 μm) flux measured in a 4.5 arcsec aperture centered on the cluster; the mass is comparable to the largest globular cluster found in the Milky Way and to the so-called tidal dwarf galaxies.

Three outstanding results from this study are: (1) even though the system has matured ∼100 to 200 Myr since the interaction, the nucleus is not undergoing a starburst or even modest star formation phase, unusual for galaxy-galaxy systems, (2) the main disk is actively forming stars in a distorted spiral arm or ring-like structure, and (3) within the tidal tail, far from the main disk, a massive cluster of newly formed stars appears to have formed only a few Myr ago from a large reservoir of metal-poor gas and dust detected by the *Spitzer Space Telescope*. Details of this study may be found in Jarrett et al. 2006.

4. References

Briggs , F., et al. 2001, A&A, 380, 418
De Grijs, R. 2003, A&G, 44, 5
Jarrett, T.H., et al. 2006 AJ, 131, 261
Kennicutt, R. C., et al., 1987, AJ, 93, 1011
Lambas, D. G., et al. 2003, MNRAS, 346, 1189
Leger, A. & Puget , J.L. 1984, A&A, 137, L5
Lonsdale, C., et al. 2003, PASP, 115, 897
Mihos, C.J. & Hernquist, L. 1996, ApJ, 464, 641
Olson, K. & Kwan, J. 1990, ApJ, 349, 480
Scoville, N.Z., et al. 1991, ApJ, 366, L5
Toomre, A. & Toomre, J. 1972, ApJ, 178, 623
Tran, H.D. et al. 2003, ApJ, 585, 750
Xilouris, E. M., et al. 2004, MNRAS, 355, 57