Multiwavelength Observations of Tidally Induced Star Formation in the M81 Group

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Abstract
We combine optical, infrared, and millimeter/submillimeter-wave observations to study a small clump of recently formed stars and the interstellar environment between the galaxies of M81 and NGC 3077. This clump is coincident with an H I emission knot in the Southern Tidal Arm of the M81 system, and is known to have formed stars as recently as 30-70 Myr ago; long after the interactions that created the Hi arm. This object is about 1 kpc in extent, and is considered a tidal dwarf (TD) candidate. To better characterize its star forming environment, we place limits on the molecular gas and dust content of this potential TD object, and compare its properties to well-studied star forming regions. The infrared observations were obtained as part of the Spitzer Space Telescope Research Program for Teachers and Students, so these data are also being used for educational purposes by teachers and students across the US.

Introduction & Background
Between 220 and 280 million years ago, tidal encounters between M81, M82, and NGC 3077 scattered stars of the Southern Tidal Arm from their original location within the M81 galaxy system. The scattered stars are known to have formed stars as recently as 30-70 Myr ago; long after the interactions that created the Hi arm. These streams appear as a network of Hi bridges dotted by small dwarf galaxies (Karachentsev et al. 1995, Karachentsev et al. 1985). Since some of these dwarfes contain stars that are significantly younger than the interaction age of the system, it is possible that they formed from material stripped from galactic outskirts (Malhotra et al. 2002). Here we present preliminary multiwavelength observations (including broadband optical images, H α observations, IR Spitzer (IRAC 8 μm) data, and molecular line (CO) observations) of two previously undiscovered tidal dwarf candidates in the M81 Group and attempt to characterize the nature of their stellar and molecular environments. The proximity of the M81 Group, and the relative isolation of TD1, makes this object an ideal laboratory for the study of the tidal dwarf galaxy phenomenon.

Optical Imaging & CFHT Results

Left: Color-Magnitude Diagram of stars in the TD1 region. Solid lines denote 2-5 (red) isochrones with ages 25, 50, 100 and 500 Myr; from bottom to top, from Griselli et al. (2002), and dotted lines represent the same models with 2-0.08 (m-M) = 28, 29 and 30 respectively. Hα and CO (J=2-1) have been applied to both sets of lines. Dashed lines denote the 50% completeness level for the CFHT photometry.

Right: Color image of TD1 from the CFHT data (DeC尺度 et al. 2004). Image is 2.6 x 2.6 arcmin 2 or ~1 kpc at the distance of M81 (3.25 kpc, Tamman & Sandage 1968).

- CFHT (CH2K camera) survey data show "blue" (A and F-type) supergiant scattered through the group (DeC尺度 et al. 2003, see also Durrell et al. 2004).
- Southeast of M81 are two isolated blue clumps (TD1 & TD2); They are part of the Aig Iod (Arp 1982), the Garland (Karachentsev et al. 1985) or a previously cataloged feature.
- The clumps are ~ 2 kpc in extent, and coincident with dense Hi knots.
- A CMD of the stars in TD1 (~10’20”) shows that they are anywhere from ~25 to ~50 Myr old.
- Last tidal encounter between M81 and NGC 3077 occurred ~250 Myr ago (Yun, Ho, & Lo 1994; Yun 1999). This is likely in situ in intergalactic environment.

Hα and CO (J=2-1) & (J=1-0) Observations

We have used the ARO 10m (HHT) and 12m telescopes and the VATT 1.8 m telescopes on Mt. Graham & Kitt Peak, AZ to probe the cold warm (~5 – 15 K) molecular and hot, ionized environments. Images (~1 hr total exposure) were made with a CCD camera and narrowband Hα filter at the VATT. Spectral line observations of CO (J=2-1) and (J=1-0) were made at the HHT and 12m telescopes, respectively. A summary of the observational results are presented.

Results of Hα Image Analysis:
- Hα emission detected in the vicinity of young, blue star in TD1. The presence of H-alpha in TD1 provides a stronger case for a young population of stars in this region. Supports in situ formation hypothesis & results of the CFHT survey.
- Luminosity (Hα) = 8.0 x 10^7 L☉. The H-alpha luminosity of TD1 is smaller than various Hi regions measured in the tidal debris of major mergers (Hibbard 1995), but similar to lower luminosity regions in the Eastern tidal arm of minor merger NGC 2782 (Smith et al. 1999).
- Star Formation Rate = 6.3 x 10^4 M☉/yr
- Ionizing Photon Rate, Q(Φ) = 5.8 x 10^4 photons/sec

Results of CO Analysis:
- Using CO (J=1-0) and (J=2-1), limits were placed on the molecular mass within the telescope beam toward Tidal Dwarf candidates.
- Luminosity-density size relation of Galactic Giant Molecular Clouds. Assumptions: clouds are in virtual equilibrium, gravitationally bound, same metallicity, temperature and density as Milky-Way clouds; N(H2) [cm^-2] = 2.3 x 10^15 * (L/ L☉) (Strongly et al 1988) where L<☉ is the total CO integrated intensity.
- Molecular Gas Limit Toward TD1: < 1 x 10^4 M☉ Limit Peak of Hα emission: < 4.6 x 10^4 M☉
- Beam dilution may be a problem (size of 12m beam at 115 GHz ~ 1’ by 1’ and of SMT beam at 230 GHz ~ 3’). Observations with millimeter and submillimeter interferometers would shed new light (e.g., Walter, Martin, & Ott 2006).
- Comparing to other Tidal Environments: TD1 molecular mass limits are lower than the Western tidal tail of NGC 2782 taken with OVRO (< 6 x 10^4 M☉; Braine et al. 2001). Comparing to a tidal region near NGC 3077 (also within the M81 group), Walter, Martin, and Ott (2006) find 10^4 M☉ of molecular gas and order of magnitude increase in star formation rates.

Summary and Ongoing / Future Work

A CMD of the stars in TD1 clump shows they are anywhere from ~25 to ~100 Myr in age younger than last tidal encounter between M81 and NGC 3077. Stars have likely formed in situ in the intergalactic environment.
- Hα emission is coincident with 8 μm emission seen by IRAC – supports in situ star formation theory.
- Follow up Spitzer observations (IRAC & MIPS) would help strengthen this work.
- Absence of CO emission from Tidal Dwarf regions means that either the molecular gas has been completely disrupted into Hi or Hi OR that the molecular hydrogen still exists but the carbon is no longer CO, but instead C+ (see “Tapioca Pudding” model below).
- Follow-up observations with new mm and submm interferometers may help (e.g., CARMA, SMA).
- Ongoing analysis of PISCES narrowband infrared images (Boke Telescope) will provide a picture of the hot molecular gas component, searching for UV pumped 2.12 μm H2 emission at molecular cloud edges.
- Disrupted “tapioca” molecular clouds would be thin and granular, mostly H2 but with little or no CO (like a PDR). Our infrared H2 measurements can help constrain whether this ‘tapioca’ model really describes the environment.

Acknowledgements
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We would like to thank Min Yun for providing all Hi data presented in this work.

This project was funded by the Spitzer Space Telescope Research Program for Students and Teachers, a joint project of NASA and NOAO. We also acknowledge the NOAO Teacher Leaders in Research Based Science Education Project funded by the National Science Foundation under ESI 0101982, funded through the AURA/NSF Cooperative Agreement AST-9613615. NOAO is operated by the Association of Universities for Research in Astronomy (AURA), Inc. under cooperative agreement with the National Science Foundation.

Spitzer Observations and Results

Spitzer 8 μm Image: exposure time: ~144 sec, field of view = ~6’ x 6’, shows warm dust by tracing 8 μm PAH feature.

- IRAC 8 μm Image: exposure time: ~1 hour total
- Preliminary Results:
  - Hα emission coincides with 8 μm IRAC emission
  - Supports interpretation of in situ star formation in Tidal Dwarf candidates
  - More time with Spitzer (IRAC & MIPS) would help verify this result.