Evolution of Galaxies and the Star Formation Rate in the Infrared

Grant NAG5-10777

Annual Performance Report No. 4

For the Period 1 May 2004 through 30 April 2005

Principal Investigator:

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1. Summary of Research Project

A central goal of extragalactic observational astronomy is to understand how normal galaxies evolve with redshift, and particularly when galaxies formed their stars. While optical and rest-frame UV observations have begun to address these issues, the interpretation of such data is particularly challenging because of the sensitivity to dust obscuration (at optical and UV wavelengths). The absorbed light is re-radiated at IR wavelengths, hence the optimal indicators of the star-formation rate (SFR) is at a rest-frame wavelength of ~60 μm.

The Spitzer Space Telescope mission is revolutionizing the study of the global properties and evolution of galaxies. Spitzer reaches nearly two orders of magnitude more sensitivity than previous IR space missions. This research program is to study the SFR using statistical samples of galaxies in the local universe, at intermediate redshifts, and set the stage for continuing studies up to z=5.

The overall research program is divided into three main investigations:

- A Mid-IR Hubble Atlas and SFR estimators in the local universe,
- Evolution of the SFR at $0 < z < 1$ using pencil beam redshift surveys, and
- Galaxy formation and evolution at $1 < z < 5$.

The first papers from Spitzer were published during the last year, including ten refereed journal papers where the PI was first or co-author.

2. Work Performed During the Previous Year

- Co-author of ten refereed journal papers during last year.
- Press conference at the 2004 May-June meeting of the American Astronomical Society in Denver CO entitled, "Spitzer Reveals What Hubble Missed" (see http://cfa-www.harvard.edu/press/pr0419.html). This PR was covered by many media outlets, and the image mosaic (attached below) has been often reproduced as handouts for the greater Spitzer community.
- Submitted approximately a dozen proposals to HST and Spitzer for observations/research of nearby galaxies and the distant universe. Four of five of last year's Spitzer proposals, and one of one HST proposal (a large program, PI: S. Faber), were allocated observing time.
- Supervised summer undergraduate student (Krystal Tyler, Purdue) on research into the IR spectral energy distributions (SEDs) of active galactic nuclei (AGN). Work led to AAS poster presentation and journal paper in preparation. A follow-up proposal for observations with Spitzer was based on success of the method developed in her work.
- Results presented at a number of international meetings along with subsequent publication of conference proceedings papers.

Major New Results

- A new galaxy classification scheme based on the Interstellar Medium from IR images taken with Spitzer. This new scheme elucidates the traditional morphological sequence with more clarity than at any other wavelength. Classifications correlate well with bulge-to-disk-ratio and galaxy colors.
- Developed a new scheme to spatially remove the stellar emission from 5.8 and 8.0 μm images in order to spatially separate out the dust and active nucleus contributions.

- Discovery of the spatial distribution of dust emission in lenticular galaxies: In at least three cases, the warm dust is in spiral arm structures! This has profound implications for the evolutionary history of this sub-class of early-type galaxies.
- Characterization of IR SEDs of AGN, which shows clear separation of LINER, Seyfert, and Starburst nuclear classes based on 3.6-70μm flux ratios.
- Detection of z=3 galaxies at 3.6 to 8.0 μm. This demonstrates that the Spitzer Space Telescope can probe both galaxy evolution and formation.

Other Professional Activities

- HST Cycles 13 and 14 Time Allocation Committee, Extragalactic Panel.
- Spitzer Cycle 2 Time Allocation Committee, Extragalactic Panel.
- CfA Time Allocation Committee (optical/IR telescopes).

Public Education / Outreach

- Press conference at AAS Meeting on 2004 May 31 [see above].
- Public lecture in 2004 October for the Smithsonian Associates in Washington DC titled, "The Hidden Universe . . . Revealed!"
- Preparing a manuscript (with co-author Tom Megeath) for *Sky & Telescope* on the major new science results from the first year of the Spitzer Space Telescope.

3. Work Planned for Upcoming Year

- Publish methodology of measuring the global star-formation rate using the PAH emission at 6.2 and 7.7 μm for galaxies at $z<0.5$. This will be the first time this approach is used to study the cosmic star-formation history.
- Compare mid- and far-IR images for galaxies of all morphological types from the IRAC GTO program.
- Publish "Spitzer's Hubble Atlas of Galaxies" based on 3.6-8.0 μm images for a broad sample of 100 galaxies (already in hand).
- Work on various kinds of photometric redshift predictors using combined HST and Spitzer datasets. This will be important for creating large statistical samples of galaxies at high redshift. A Harvard graduate student (Vit Hradecky) has chosen to pursue this research (as a tool to find distant clusters of galaxies) for his dissertation.
- Other research projects:
  - Compare Spitzer (PAH emission) and HST (dust obscuration) abilities to detect dust in elliptical galaxies (with T. Lauer and S. Faber)
  - Study IR properties of irregular galaxies (with D. Hunter)
  - Compare UV, Hα (both from HST), PAH, and far-IR (from Spitzer) estimators of the star formation rate in late-type, star-forming galaxies (with R. Windhorst and R. Jansen)
  - Analyze merging cluster at z=0.2 ("The Bullet") to determine if the cluster shows signs of enhanced star formation due to the merger (with C. Jones, W. Forman, and A. Gonzalez)
  - Compare CXO X-ray and Spitzer IR SEDs of AGN in early-type galaxies (with C. Jones)

4. Publications

During the Past Year (Submitted, Revised, and/or Published):

Refereed Journals

Helou, G., and 21 colleagues 2004. The Anatomy of Star Formation in NGC 300. *Astrophysical Journal Supplement Series* 154, 253-258.

Pahre, M.A., Ashby, M.L.N., Fazio, G.G., Willner, S.P. 2004. Mid-Infrared Galaxy Morphology along the Hubble Sequence. *Astrophysical Journal Supplement Series* 154, 235-241.

Pahre, M.A., Ashby, M.L.N., Fazio, G.G., Willner, S.P. 2004. Spatial Distribution of Warm Dust in Early-Type Galaxies. *Astrophysical Journal Supplement Series* 154, 229-234.

Willner, S.P., and 17 colleagues 2004. Infrared Array Camera (IRAC) Observations of M81. *Astrophysical Journal Supplement Series* 154, 222-228.

Wang, Z., Fazio, G.G., Ashby, M.L.N., Huang, J.-S., Pahre, M.A., Smith, H.A., Willner, S.P., Forrest, W.J., Pipher, J.L., Surace, J.A. 2004. The Off-Nuclear Starbursts in NGC 4038/4039 (The Antennae Galaxies). *Astrophysical Journal Supplement Series* 154, 193-198.

Barmby, P., and 17 colleagues 2004. Deep Mid-Infrared Observations of Lyman Break Galaxies. *Astrophysical Journal Supplement Series* 154, 97-102.

Eisenhardt, P.R., and 26 colleagues 2004. The Infrared Array Camera (IRAC) Shallow Survey. *Astrophysical Journal Supplement Series* 154, 48-53.

Fazio, G.G., and 14 colleagues 2004. Number Counts at 3 μm < lambda < 10 μm from the Spitzer Space Telescope. *Astrophysical Journal Supplement Series* 154, 39-43.

Fazio, G.G., and 64 colleagues 2004. The Infrared Array Camera (IRAC) for the Spitzer Space Telescope. *Astrophysical Journal Supplement Series* 154, 10-17.

Stern, D., and 14 colleagues 2005. Mid-Infrared Selection of Active Galaxies. *Astrophysical Journal (Letters)*, submitted.

Conference Proceedings / Abstracts

Polomski, E., and 18 colleagues 2004. The Spitzer Space Telescope M33 Project: First Epoch Images. American Astronomical Society Meeting Abstracts 204.

Wang, Z., Fazio, G.G., Ashby, M.L.N., Huang, J.-S., Pahre, M.A., Smith, H.A., Willner, S.P., Forrest, W.J., Pipher, J.L., Surace, J.A. 2004. Spitzer Space Telescope Observations of the Antennae Galaxies. American Astronomical Society Meeting Abstracts 204.

Pahre, M.A., and 18 colleagues 2004. IRAC Extragalactic GTO Program: From Nearby Galaxies to the High Redshift Universe. American Astronomical Society Meeting Abstracts 204.

Fazio, G.G., and 37 colleagues 2004. In-Flight Performance of the Infrared Array Camera (IRAC) for the Spitzer Space Telescope. American Astronomical Society Meeting Abstracts 204.

Wang, Z., and 10 colleagues 2004. Imaging Observations of Interacting and Starburst Galaxies with Spitzer. American Astronomical Society Meeting Abstracts 205.

Gorjian, V., and 17 colleagues 2004. Spitzer Infrared Array Camera (IRAC) Properties of Chandra Sources in the Nine Square Degree Bootes Field. American Astronomical Society Meeting Abstracts 205.

Tyler, K.D., Pahre, M.A., Fazio, G.G., Ashby, M.L.N. 2004. Mid-Infrared Flux from AGN in Nearby Galaxies. American Astronomical Society Meeting Abstracts 205.

Smith, H.A., Wang, Z., Fazio, G.G., Ashby, M.L.N., Huang, J.-S., Pahre, M.A., Willner, S.P., Forrest, W.J., Pipher, J.L., Surace, J.A. 2004. Interacting Galaxies as Seen by Spitzer-IRAC. The Dusty and Molecular Universe: A Prelude to Herschel and ALMA 74.

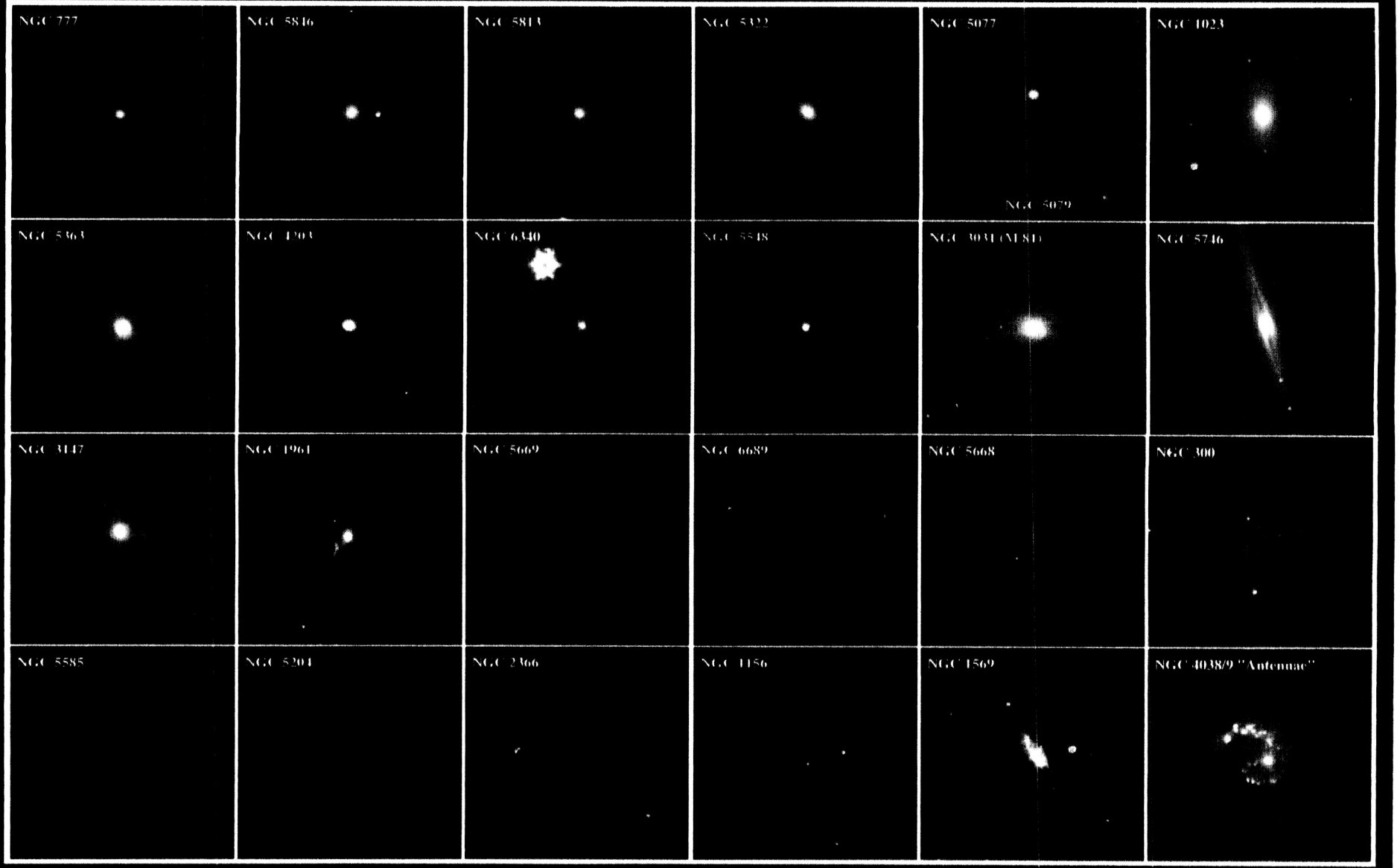
Fazio, G.G., Pahre, M.A., Ashby, M.L.N., Willner, S.P. 2005. Recent Results from the Spitzer Space Telescope: A New View of Galaxy Morphology and Classification. In *The Hubble Tuning Fork Hits a New Note* (ed. D. Block).

5. Annual Patents Rights/New Technology Statement

There have been no reportable patents/new technology made under this grant.

Figure Caption

Mosaic of nearby galaxies imaged with the Spitzer Space Telescope at 3.6-8.0 μm. Galaxies are sorted according to "traditional" Hubble morphological type, from the elliptical galaxies (top), to spiral galaxies (middle), and the irregular galaxies (bottom). The work from this project has demonstrated the systematic trends in the IR spectral energy distributions ranging from starlight (blue, top row), to mixed starlight and dust (blue and red, middle row), to mostly dust-dominated (red, bottom row).



Infrared Mosaic of Nearby Galaxies

Spitzer Space Telescope • IRAC

M. A. Pahre & G. G. Fazio (SAO) / NASA / JPL-Caltech

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