The Astrophysical Journal, 627:L29–L32, 2005 July 1
© 2005. The American Astronomical Society. All rights reserved. Printed in U.S.A.

DISCOVERY OF AN EXTENDED ULTRAVIOLET DISK IN THE NEARBY GALAXY NGC 4625

A. Gil de Paz,[1] B. F. Madore,[1] S. Boissier,[1] R. Swaters,[2] C. C. Popescu,[3] R. J. Tuffs,[3] K. Sheth,[4] R. C. Kennicutt, Jr.,[5] L. Bianchi,[6] D. Thilker,[6] and D. C. Martin[7]

Received 2005 March 25; accepted 2005 May 20; published 2005 June 9

ABSTRACT

Recent far-UV (FUV) and near-UV (NUV) observations of the nearby galaxy NGC 4625 made by the *Galaxy Evolution Explorer* (*GALEX*) show the presence of an extended UV disk reaching to 4 times the optical radius of the galaxy. The UV-to-optical colors suggest that the bulk of the stars in the disk of NGC 4625 are currently being formed, providing a unique opportunity to study today the physics of star formation under conditions similar to those when the normal disks of spiral galaxies like the Milky Way first formed. In the case of NGC 4625, the star formation in the extended disk is likely to be triggered by interaction with NGC 4618 and possibly also with the newly discovered galaxy NGC 4625A. The positions of the FUV complexes in the extended disk coincide with peaks in the H I distribution. The masses of these complexes are in the range 10^3–10^4 $M_\odot$, with their Hα emission (when present) being dominated by ionization from single stars.

Subject headings: galaxies: formation — galaxies: individual (NGC 4625) — galaxies: star clusters — ultraviolet: galaxies

Online material: color figures

1. INTRODUCTION

The disks of spiral galaxies are thought to have formed stars more or less continuously over the last 5–10 Gyr, with their individual star formation histories being a function of the mass and angular momentum of the disk (Bell & de Jong 2000; Boissier et al. 2001). The current specific star formation rates in the disks of most spiral galaxies are as low as 0.1 Gyr^{-1} (Boissier et al. 2001). Therefore, the only way to learn about the properties of early spiral galaxies, including the physics of their star formation, was thought to be by looking at faint, poorly spatially resolved, high-redshift galaxies.

In this Letter we report the discovery of an extended UV (XUV) disk in the nearby galaxy NGC 4625 reaching to 4 times its optical radius at $\mu_B = 25$ mag arcsec^{-2} ($D25$ radius). Although Swaters & Balcells (2002) already showed the presence of an extended low surface brightness component in their optical surface brightness profiles of this galaxy, *Galaxy Evolution Explorer* (*GALEX*) observations show that the disk is even more extended at UV wavelengths, that it has a well-defined spiral morphology (so it is certainly a disk, not a halo), and that it seems to be forming most of its stars at the current epoch. Therefore, NGC 4625 may provide a rare opportunity to study locally the conditions governing the early formation of the disks of spiral galaxies. This object increases the small number of XUV disks reported to date and constitutes its most extreme example (Thilker et al. 2005; D. A. Thilker et al. 2005, in preparation).

NGC 4625 is a nearby (9.5 Mpc for $H_0 = 70$ km s^{-1} Mpc^{-1}; Kennicutt et al. 2003), low-luminosity ($M_B \sim -17.4$), one-armed Magellanic spiral galaxy thought to be interacting with the also single-armed spiral NGC 4618.[8] In spite of the interaction with NGC 4618, NGC 4625 shows a remarkably regular H I velocity field and a well-defined rotation curve (Bush & Wilcots 2004). To the southeast we report the discovery of a low surface brightness galaxy only ~4′ away from NGC 4625, which, if its association with NGC 4625 is confirmed, might also have played a role (along with NGC 4618) in the recent activation of the star formation in the XUV disk of NGC 4625.

2. OBSERVATIONS AND ANALYSIS

The NGC 4618/4625 system was simultaneously observed in the far-UV (FUV) and near-UV (NUV) bands by *GALEX* on 2004 April 5 for 3268 s split across two orbits. Images were reduced using the *GALEX* pipeline (Martin et al. 2005). The spatial resolution achieved was FWHM ≃ 4″.5 and 5″.0 in the FUV and NUV channels, respectively.

Deep ground-based optical imaging data in the *B* and *R* bands were obtained previously with the prime-focus camera of the 2.5 m Isaac Newton Telescope (La Palma, Spain) on 1995 May 28 (see Swaters & Balcells 2002 for details). On 2004 August 20, we obtained an Hα image at the Palomar Observatory 5 m telescope using COSMIC and a 6563/20 narrowband filter. The total exposure time was 800 s. The seeing on all three optical images was in the range 1″.2–1″.4. Neutral hydrogen observations in the 21 cm line of the NGC 4618/4625 system were obtained with the Westerbork Synthesis Radio Telescope as part of the WHISP survey (Kamphuis et al. 1996; Swaters et al. 2002).

We have derived surface photometry for NGC 4625 in the FUV, NUV, *B*, and *R* bands, Hα, and H I using circular annuli centered on R.A. = 12^{h}41^{m}52^s.6, decl. = +41°16′21″.5 (J2000.0). Circular apertures provide a very clear separation between the optical disk (with approximately circular isophotes) and the XUV disk. Almost identical results (both qualitatively and quantitatively) were obtained when elliptical apertures matching the light distri-

[1] Observatories of the Carnegie Institution of Washington, 813 Santa Barbara Street, Pasadena, CA 91101.

[2] Department of Astronomy, University of Maryland, College Park, MD 20742-2421.

[3] Max-Planck-Institut für Kernphysik, Saupfercheckweg 1, 69117 Heidelberg, Germany.

[4] *Spitzer* Science Center, California Institute of Technology, MC 220-6, 1200 East California Boulevard, Pasadena, CA 91125.

[5] Steward Observatory, University of Arizona, 933 North Cherry Avenue, Tucson, AZ 85721.

[6] Center for Astrophysical Sciences, Johns Hopkins University, 3400 North Charles Street, Baltimore, MD 21218.

[7] California Institute of Technology, MC 405-47, 1200 East California Boulevard, Pasadena, CA 91125.

[8] Note that Odewahn (1991) estimated a rather closer distance for this system of 6.0 Mpc.

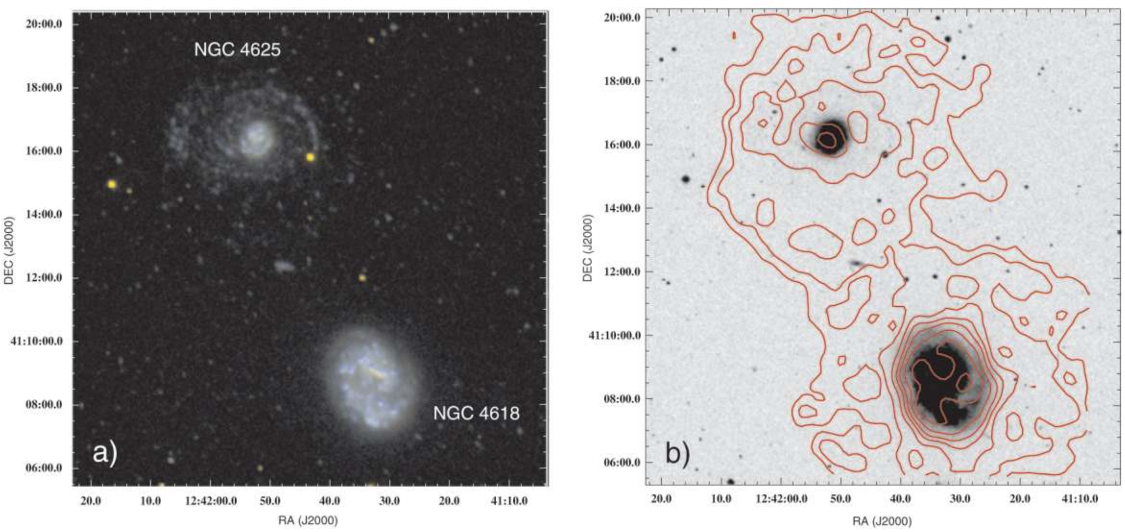

FIG. 1.—(*a*) *GALEX* false-color RGB composite image (R = NUV; $G = 0.2 \times$ FUV + $0.8 \times$ NUV; B = FUV) of the NGC 4618/4625 system with an arcsinh stretch (Lupton et al. 2004). (*b*) POSS II blue-plate Digitized Sky Survey image of the same region with 21 cm H I contours superposed (1, 2, 4, 6, 8, 11, 15, and 20×10^{20} cm^{-2}). The H I contours were obtained from our 30″ resolution convolved map. The 3 σ level of this H I map is at 1.5×10^{20} cm^{-2}. The morphology of the XUV disk is remarkably similar to that of the H I disk.

bution of the XUV disk were used. Individual region photometry was computed using elliptical apertures as defined in the FUV image by SExtractor (Bertin & Arnouts 1996). A few FUV sources missed by SExtractor were added by hand to the source catalog.

3. DISCUSSION

3.1. *XUV Disk Morphology and Stellar Populations*

Figure 1 shows that the XUV emission in NGC 4625 (almost invisible in shallow optical images from the ground) covers a significant fraction of the area detected in 21 cm, with some correspondence between the position of the brightest UV complexes and peaks in the neutral-gas distribution. The XUV disk is made up of several fragmented spiral arms in the inner regions and possibly a large faint arm in the outermost regions (Fig. 2*a*). Deep ground-based images show a similar morphology at optical wavelengths and also reveal the presence of a newly discovered, faint, red, low surface brightness companion (NGC 4625A; R.A. = $12^{h}42^{m}11^{s}.1$, decl. = $+41°15'10''$ [J2000.0]) seen ∼4′ to the southeast of NGC 4625 (see Fig. 2*b*). Deep optical spectroscopy will be required to establish whether NGC 4625A is physically associated with NGC 4625; chance projection of such a rare type of object is, however, unlikely.

The surface photometry of NGC 4625 (Fig. 3) shows very blue UV colors for the innermost regions of the galaxy [(FUV − NUV) ≃ 0.5 mag, typical of Magellanic spirals like NGC 4625; Bell et al. 2002], followed by a distinctly redder zone falling in the annulus 25″–50″ in radius and coincident with a steep exponential decline in surface brightness. Dust is not likely to be responsible for this reddening because (1) the dust content in NGC 4625 is relatively low overall [$E(B-V)$ = 0.1 mag],[9] and (2) the radial profiles of reddening-free color indices, such as the (FUV − NUV) color (Bianchi et al. 2005), show a clear change in color at the same position as well. If we now consider the fact that the profile at this position is very smooth and is not associated with any H II region or bright UV cluster, we then identify this transition region with an underlying, evolved (intrinsically red) Population II component.[10] The sharply declining surface brightness profile of NGC 4625 in this region (between 25″ and 50″) suggests that the (extrapolated) contribution of this population to the even more distant XUV emission is negligible. Finally, we note that the XUV disk shows very blue colors, especially in (FUV − NUV) and (NUV − B), with a rather flat profile in (FUV − NUV) and ($B - R$) but a clear bluing in the (NUV − B) profile. These colors suggest the presence of a young stellar population (<1 Gyr) dominating the UV and optical emission (and probably also the mass) of the XUV disk of NGC 4625. However, although it seems unlikely (based on the light distribution of its Population II component), we cannot rule out the presence of a faint several Gyr old stellar population partly contributing to the observed colors and stellar mass of the XUV disk. Deep near-infrared photometry from the ground or a single-star photometry color-magnitude diagram with the *Hubble Space Telescope* should provide fundamental clues for answering this question.

Compared with the distribution of the UV emission, the azimuthally averaged Hα emission in the XUV disk is much fainter than that of the innermost regions of the galaxy (see Figs. 2*b* and 3). On the other hand, the H I emission is clearly more extended still than the UV. Beam smearing is unlikely to be responsible for the apparent flattening of the neutral-gas profile, considering the relatively good spatial resolution of our H I map (FWHM ≃ 15″). A more detailed analysis of the star formation history of NGC 4625 and of the implications of these results on the star formation law will be presented in a forthcoming paper (A. Gil de Paz et al. 2005, in preparation).

3.2. *Stellar Complexes*

Inspection of our deep, arcsecond-resolution, optical images of NGC 4625 shows that the FUV-bright complexes in the XUV disk are made up of one or several stellar clusters in which some bright individual stars can be resolved (Sandage & Bedke 1994). Aperture photometry on a sample of 74 FUV-

[9] This is derived from the global infrared-to-UV ratio [log (TIR/FUV) = 0.23] assuming the relationship between (TIR/FUV) and A_{FUV} given by Buat et al. (2005) and a Galactic extinction law. If the effects of scattering are considered, $E(B-V)$ could be as low as 0.04 mag (Tuffs et al. 2004).

[10] A similar smooth red envelope is also seen in the outer parts of NGC 4618 (see Fig. 1*a*).

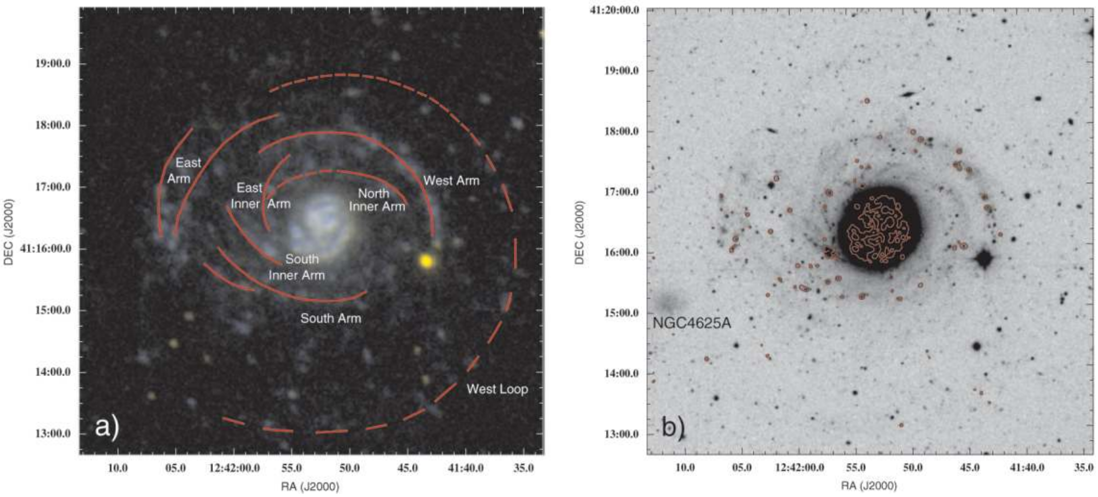

FIG. 2.—(*a*) *GALEX* false-color image of NGC 4625 (color scheme as in Fig. 1). A sketch of the spiral morphology of the XUV disk is also shown. Long-dashed lines show the position of the West Loop. Short-dashed lines represent tentative extensions of some of the structures identified in the UV images. (*b*) Deep, ground-based, *B*-band image of the same region. We have labeled the newly discovered companion of NGC 4625 as NGC 4625A. Contours of the continuum-subtracted Hα emission are overplotted.

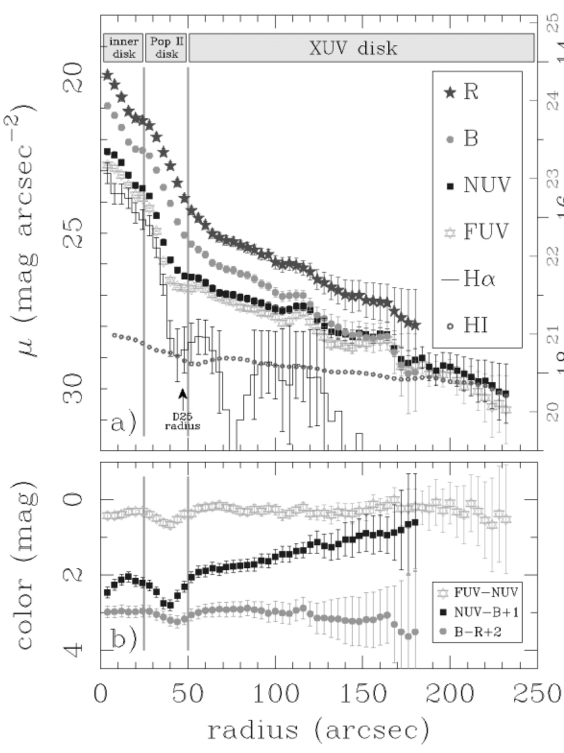

FIG. 3.—(*a*) Surface-brightness profiles of NGC 4625. Error bars do not include calibration uncertainties. Error bars in the Hα profile larger than 1 dex have been removed for the sake of clarity. The UV emission clearly extends beyond 4 times the *D*25 radius (47″). UV magnitudes are in AB scale, while optical photometry is in the Johnson/Cousins system. (*b*) Observed (FUV − NUV), (NUV − *B*), and (*B* − *R*) color profiles. The (FUV − NUV) and (*B* − *R*) color profiles are remarkably flat except at the position where the (red) Population II component dominates the emission. On the other hand, the (NUV − *B*) profile gets systematically bluer toward the outer parts of the XUV disk. Note that the (NUV − *B*) and (*B* − *R*) color profiles are offset by 1 and 2 mag, respectively, for clarity of presentation on a single plot. [*See the electronic edition of the Journal for a color version of this figure*.]

selected complexes in the XUV disk yields UV luminosities in the range $10^{23.0}$–$10^{24.5}$ ergs s^{-1} Hz^{-1} (Fig. 4, *circles and diamonds*). If we assume that their stars formed instantaneously, the corresponding stellar masses would be in the range

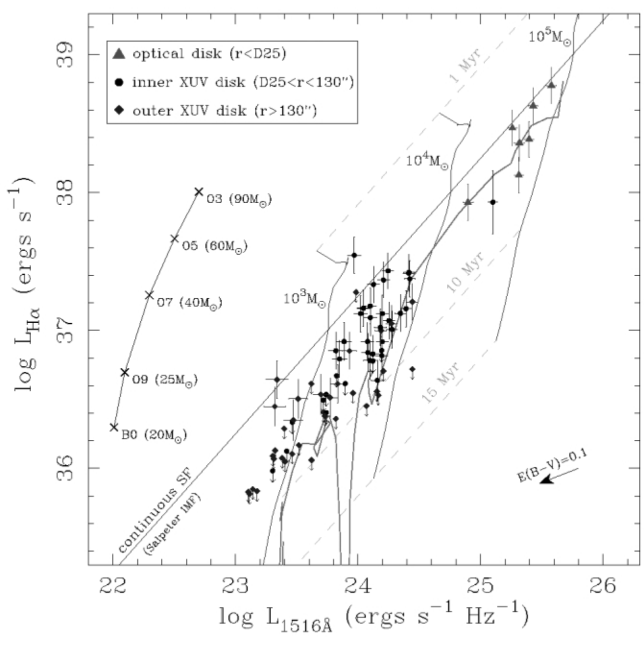

FIG. 4.—Hα vs. FUV luminosity of FUV-selected complexes inside *D*25 (*triangles*), in the inner XUV disk (*circles*), and in the outer XUV disk (*diamonds*). We also show the model predictions for the luminosities of single massive stars (Vacca et al. 1996; Sternberg et al. 2003) and instantaneous bursts with different ages and masses for a Salpeter initial mass function with mass range 0.1–100 $M_\odot$ (Bruzual & Charlot 2003). Model curves are plotted without any reddening. The thick solid line represents the expected luminosity inside an average aperture of 7″ in radius and a surface-brightness given by the azimuthally averaged profiles shown in Fig. 3. A reddening vector of $E(B - V) = 0.1$ mag is also shown in the lower right corner. [*See the electronic edition of the Journal for a color version of this figure*.]

10^3–10^4 $M_{\odot}$. Figures 2*b* and 4 also show that most of the Hα emission in the XUV disk comes from very compact sources with $L_{H\alpha} < 10^{37.6}$ ergs s^{-1}. These Hα luminosities are compatible with being produced by single stars having masses less than 60 $M_{\odot}$ or by associations of a few less massive O stars.

One of the most puzzling properties of the XUV disks recently discovered by *GALEX* is the fact that even these galaxies seem to have a truncation radius in the distribution of the inner disk Hα emission (e.g., Thilker et al. 2005). Such truncation has been traditionally explained by a star formation threshold (Martin & Kennicutt 2001). While in NGC 4625 there is no sharp truncation (since faint Hα emission is detected very far out in the disk), the Hα emission does decline with radius much faster than the UV light (Fig. 3). In Figure 4 we compare the Hα and FUV luminosities of individual complexes in the optically bright disk of NGC 4625 (inside *D*25; *triangles*), in the inner regions of the XUV disk (between *D*25 and 130″ in radius; *circles*), and in the outer XUV disk (beyond 130″; *diamonds*). This figure shows that while regions inside *D*25 have Hα-to-UV ratios similar to those expected for continuous star formation models, those in the XUV disk have somewhat lower Hα-to-UV ratios, especially in the very outer parts of the XUV disk. FUV-selected complexes in the outer XUV disk (*diamonds*) are also fainter in the UV than those in the inner XUV disk (*circles*).

We note that the Hα-to-UV ratios derived for individual complexes in the XUV disk are systematically higher than those found for the azimuthally averaged surface brightness profiles (adopting an average 7″ radius aperture; Fig. 4, *thick solid line*). This can be explained by the presence of diffuse UV emission from stars of intermediate age (a few 10^8 yr) in the interarm region or by scattering from dust grains (Popescu et al. 2005). If the former case is true it would imply that the star formation in the XUV disk is triggered by gravitational instabilities in the form of low-order spiral density waves or tidal interactions, which have timescales of the order of the UV emission (and also comparable to the galaxy dynamical timescale) but much longer than that of Hα. In the central parts of the optical disk, on the other hand, the higher frequency and efficiency of the gravitational instabilities and the presence of sequential and turbulence triggering (e.g., Elmegreen 2001) would result in ubiquitous and rather continuous star formation, with the UV output being dominated by young, luminous regions that also emit in Hα.

Therefore, although the difference between the Hα and UV radial profiles might be partly due to a lack of massive stars in the clusters of the XUV disk or to a higher porosity of the interstellar medium to the ionizing photons (Meurer et al. 2004), especially in its outermost regions, the use of azimuthal averages computed over spatial scales with dynamical timescales that are much longer than the evolutionary timescale of the emission under study (as is the case of Hα) artificially leads to a dimming in the outer parts of the corresponding surface brightness profile.

3.3. *On the Origin of the XUV Emission*

As we mentioned above, NGC 4625 is not the only galaxy in which *GALEX* has found extended, UV-bright disks with no obvious or very faint optical counterparts. Other remarkable objects are M83, NGC 5055, and NGC 2841. Early results indicate that the presence of a large H I disk is a necessary but not sufficient condition for the XUV emission to be present (D. Thilker et al. 2005, in preparation).

In the case of NGC 4625 the star formation in the outer H I disk is probably due to gravitational instability associated with the interaction with NGC 4618 and possibly also with NGC 4625A. In this sense, Bush & Wilcots (2004) argue that NGC 4618 and NGC 4625 have only had one close passage and that the current interaction has been ongoing for ~0.5 Gyr. This, we note, is of the same order as the timescale of the UV emission. Since NGC 4618 does not show XUV emission despite having a relatively extended H I envelope itself, there must be additional factors regulating the formation of XUV disks.

In this context, we note that NGC 4625 shows a very regular velocity field with differential rotation, while the kinematics of NGC 4618 is highly disturbed, with some features characteristic of a strongly warped disk. It is therefore possible that a relatively undisturbed gas disk is required for the stars responsible for the XUV emission to form. In the case of NGC 4625 the stability of the H I disk is thought to be a consequence of its small $M_{\rm disk}/M_{\rm halo}$ mass ratio (Dubinski et al. 1996).

In summary, NGC 4625 provides a unique opportunity to study the physics of star formation in the early stages of the formation of disks in spiral galaxies. It is worth noting that although the star formation in the XUV disk of NGC 4625 is believed to be due to the presence of a nearby companion (NGC 4618 and/or NGC 4625A), this system should not necessarily be viewed as an anomaly, since frequent interactions are also thought to be a fundamental ingredient in the initial growth of disks of spiral galaxies at high redshift.

GALEX is a NASA Small Explorer launched in 2003 April. We gratefully acknowledge NASA's support for construction, operation, and scientific analysis of the *GALEX* mission. We thank Judith Cohen for kindly providing her Hα filter for COSMIC. R. C. K. is partially financed by NASA grant NAG5-8426.

REFERENCES

Bell, E. F., & de Jong, R. S. 2000, MNRAS, 312, 497
Bell, E. F., Gordon, K. D., Kennicutt, R. C., Jr., & Zaritsky, D. 2002, ApJ, 565, 994
Bertin, E., & Arnouts, S. 1996, A&AS, 117, 393
Bianchi, L., et al. 2005, ApJ, 619, L71
Boissier, S., Boselli, A., Prantzos, N., & Gavazzi, G. 2001, MNRAS, 321, 733
Bruzual, G., & Charlot, S. 2003, MNRAS, 344, 1000
Buat, V., et al. 2005, ApJ, 619, L51
Bush, S. J., & Wilcots, E. M. 2004, AJ, 128, 2789
Dubinsky, J., Mihos, J. C., & Hernquist, L. 1996, ApJ, 462, 576
Elmegreen, B. G. 2001, in ASP Conf. Ser. 249, The Central Kiloparsec of Starbursts and AGN: The La Palma Connection, ed. J. H. Knapen et al. (San Francisco: ASP), 492
Kamphuis, J. J., Sijbring, D., & van Albada, T. S. 1996, A&AS, 116, 15
Kennicutt, R. C., Jr., et al. 2003, PASP, 115, 928
Lupton, R., Blanton, M. R., Fekete, G., Hogg, D. W., O'Mullane, W., Szalay, A., & Wherry, N. 2004, PASP, 116, 133
Martin, C. L., & Kennicutt, R. C., Jr. 2001, ApJ, 555, 301
Martin, D. C., et al. 2005, ApJ, 619, L1
Meurer, G. R., Thilker, D., Bianchi, L., Ferguson, A., Madore, B. F., & Gil de Paz, A. 2004, BAAS, 205, 42.03
Odewahn, S. C. 1991, AJ, 101, 829
Popescu, C. C., et al. 2005, ApJ, 619, L75
Sandage, A., & Bedke, J. 1994, The Carnegie Atlas of Galaxies, Vol. 1 (Washington, DC: Carnegie Inst.)
Sternberg, A., Hoffmann, T. L., & Pauldrach, A. W. A. 2003, ApJ, 599, 1333
Swaters, R. A., & Balcells, M. 2002, A&A, 390, 863
Swaters, R. A., van Albada, T. S., van der Hulst, J. M., & Sancisi, R. 2002, A&A, 390, 829
Thilker, D. A., et al. 2005, ApJ, 619, L79
Tuffs, R. J., Popescu, C. C., Völk, H. J., Kylafis, N. D., & Dopita, M. A. 2004, A&A, 419, 821
Vacca, W. D., Garmany, C. D., & Shull, J. M. 1996, ApJ, 460, 914