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GALEX OBSERVATIONS OF THE ULTRAVIOLET HALOS OF NGC 253 AND M82

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ABSTRACT

We present *Galaxy Evolution Explorer* (*GALEX*) images of the prototypical edge-on starburst galaxies M82 and NGC 253. Our initial analysis is restricted to the complex of ultraviolet (UV) filaments in the starburst-driven outflows in the galaxy halos. The UV luminosities in the halo are too high to be provided by continuum and line emission from shock-heated or photoionized gas, except perhaps in the brightest filaments in M82, suggesting that most of the UV light is the stellar continuum of the starburst scattered into our line of sight by dust in the outflow. This interpretation agrees with previous results from optical imaging polarimetry in M82. The observed luminosity of the halo UV light is $\lesssim$0.1% of the bolometric luminosity of the starburst. The morphology of the UV filaments in both galaxies shows a high degree of spatial correlation with Hα and X-ray emission. This indicates that these outflows contain cold gas and dust, some of which may be vented into the intergalactic medium (IGM). UV light is seen in the "Hα cap" 11 kpc north of M82. If this cap is a result of the wind fluid running into a preexisting gas cloud, the gas cloud contains dust and is not primordial in nature, but was probably stripped from M82 or M81. If starburst winds efficiently expel dust into the IGM, this could have significant consequences for the observation of cosmologically distant objects.

Subject headings: galaxies: halos — galaxies: individual (M82, NGC 253) — galaxies: starburst — ISM: jets and outflows — ultraviolet: galaxies

1. INTRODUCTION

Many local starburst galaxies have galactic-scale outflows of metal-enriched gas, called starburst superwinds, that are driven by the stellar winds and supernovae of numerous massive stars (e.g., Heckman et al. 1990). These outflows contain a hot (10^7 K), metal-enriched wind fluid, in addition to entrained cooler gas and dust (Strickland & Stevens 2000). It is likely that the hot gas can escape from the potential well of the parent galaxy, enriching the intergalactic medium (IGM) with metals and energy (Heckman et al. 2000). It is not clear whether the colder gas can escape, and this is an important question, since it would mean that superwinds also enrich the IGM with dust, which could affect observations of high-redshift objects (Aguirre 1999; Alton et al. 1999; Aguirre et al. 2001; Heckman et al. 2000). This question is even more crucial, since similar outflows are now known to be common in high-redshift starbursts (Pettini et al. 2001; Shapley et al. 2003).

Several lines of evidence suggest that superwinds contain dust (Shopbell & Bland-Hawthorn 1998; Heckman et al. 2000). Optical imaging polarimetry shows light scattered by dust in the halos of starburst galaxies, including M82 (e.g., Scarrott et al. 1991; Alton et al. 1994). Far-IR and submillimeter imaging reveal thermal emission from extraplanar dust in several edge-on starburst galaxies (Alton et al. 1999). Finally, the strong correlation between the strength of the blueshifted interstellar Na D line and the line-of-sight reddening in superwinds (Heckman et al. 2000) strongly suggests the dust is actually outflowing. What remains unclear is the physical relationship between the cool, dust-bearing gas and the warm and hot gas probed by optical lines and X-rays, respectively. Comparison of sensitive, high-resolution images of the dusty material with Hα and X-ray emission images would shed light on this relationship. Dust is highly reflective in the ultraviolet (UV; Draine 2003), so imaging of starburst superwinds in the UV can trace the location of dust, if one can account for UV emission by photoionized or shock-heated gas. Indeed, Ultraviolet Imaging Telescope (UIT) near-UV data for M82 show evidence of UV light in the halo corresponding to known Hα features (Marcum et al. 2001). Here we present *Galaxy Evolution Explorer* (*GALEX*) ultraviolet images of two prototypical starburst superwind galaxies: NGC 253 and M82. The images reveal prominent UV light in the superwind region. Our goal is to understand the origin of this light.

2. OBSERVATIONS

NGC 253 was observed by *GALEX* on 2003 October 13 for 3289 s. M82 was observed by *GALEX* on 2003 December 8 for 3083 s. The *GALEX* data include far-ultraviolet (FUV;

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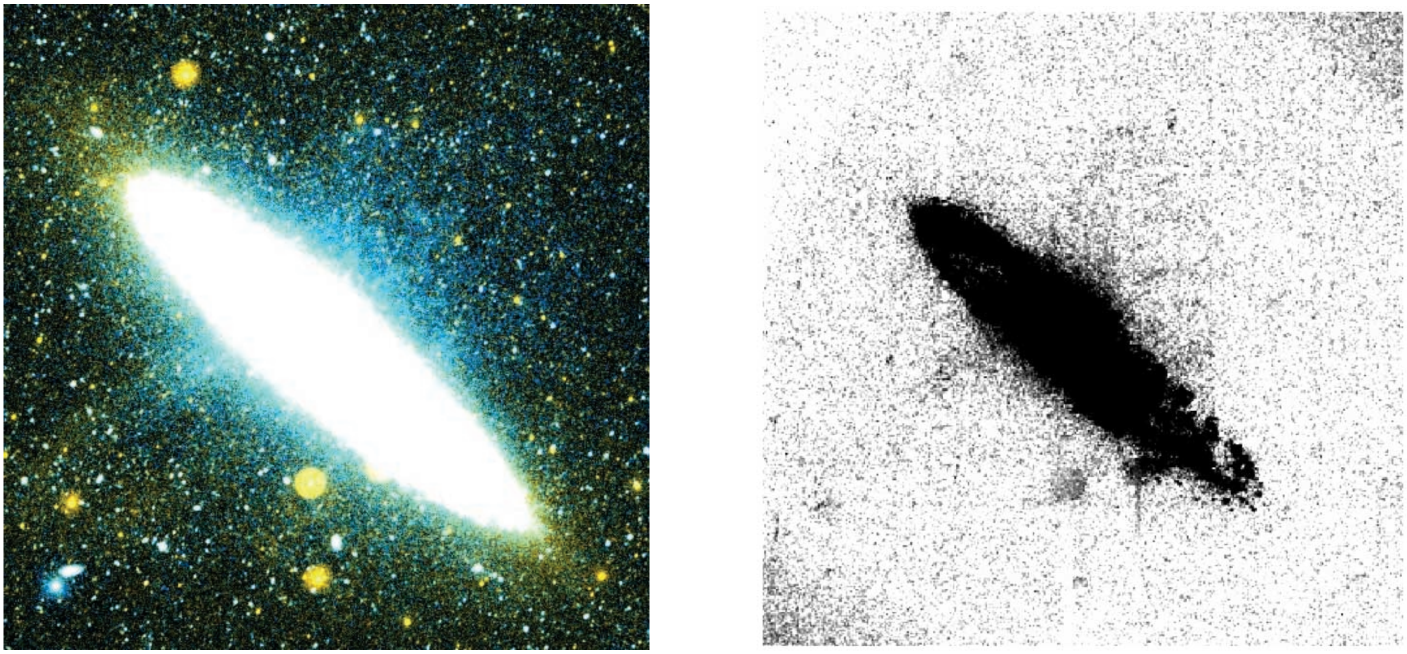

FIG. 1.—NGC 253 in UV and Hα. *Left*: Two-color image, with *GALEX* NUV in red and FUV in blue. *Right*: Continuum-subtracted Hα image. The images are 30′ (22.7 kpc) on each side, with north up and east on the left, and are aligned with each other. The intensity scales in both panels are logarithmically scaled and stretched to emphasize the faint, diffuse emission, so the bright disk of the galaxy is saturated.

$\lambda_{\rm eff} = 1528$ Å, $\Delta\lambda = 268$ Å) and near-ultraviolet (NUV; $\lambda_{\rm eff} = 2271$ Å, $\Delta\lambda = 732$ Å) images with a circular field of view with radius of ∼38′. The spatial resolution is ∼5″. Details of the *GALEX* instrument and data characteristics can be found in Martin et al. (2005) and Morrissey et al. (2005).

We also use previously obtained Hα data. The Hα image of NGC 253 is described in detail in Hoopes et al. (1996). The Hα image of M82 is part of a mosaic of the M81-M82 system taken with the Burrell-Schmidt Telescope at KPNO, and is described in Greenawalt et al. (1998).

3. ANALYSIS

3.1. *Ultraviolet Morphology*

Figure 1 compares the two-color *GALEX* image of NGC 253 with the Hα image. Extended Hα emission was noted by Strickland et al. (2002). Diffuse emission extends several kpc into the halo on both sides of the disk northeast of the galaxy center, with the brightest and more extended emission toward the east end of the disk. Strickland et al. (2002) found that the X-ray emission matched the Hα emission in morphology. These features are also visible in the *GALEX* images.

Figure 2 shows the UV and Hα images of M82 (in the same manner as Fig. 1). The M82 images show a bright, complex network of filaments, very different in appearance from NGC 253. The morphology in the UV and Hα images is strikingly similar. Prominent Hα filaments are seen perpendicular to the disk on both sides, surrounded by a lower surface brightness component of diffuse light (see also Ohyama et al. 2002). The filaments are also visible in the UV, but there is less contrast between the filaments and the diffuse UV light. The *GALEX* images are much more sensitive than the earlier UIT NUV image (Marcum et al. 2001) and show that the UV-Hα correlation in morphology extends to very faint Hα filaments, and also exists in the FUV (which was not detected by UIT). Strickland et al. (2004) noted that the X-ray and Hα morphology are similar on all scales, and this is also true for the UV light. The Hα and X-ray "cap" (Devine & Bally 1999; Lehnert et al. 1999) 11 kpc above the north side of the disk is visible in both *GALEX* bands. We will address the UV properties of these and other nearby starbursts, including possible reasons for the striking differences between M82 and NGC 253, in a forthcoming paper (Hoopes et al. 2005, in preparation).

3.2. *Luminosities and Flux Ratios*

Table 1 compares the UV and Hα luminosities of the halo with the total and bolometric luminosities. The measurements have been corrected for Galactic foreground extinction using $E(B-V) = 0.019$ for NGC 253 and $E(B-V) = 0.159$ for M82 (Schlegel et al. 1998). A correction factor of 0.59 has been applied to remove [N II] from the Hα flux. The extraplanar UV light in both cases is less than 0.1% of the bolometric luminosity of the starburst. The observed halo luminosity is 7% (10%) of the total *observed* NUV (FUV) luminosity of NGC 253, and for M82 it is 43% (65%). The Hα luminosity of the halo is 4% of the total Hα luminosity for NGC 253 and 21% for M82.

Figure 3 shows flux ratios measured in square regions 30″ on each side. The *GALEX* monochromatic fluxes were multiplied by the effective filter bandpass to give units of ergs cm^{-2} s^{-1}. Figure 3 also shows model predictions for the continuum (Balmer, bremsstrahlung, and two-photon) and line emission of shock-heated and photoionized gas (Dopita & Sutherland 1996; Ferland 1996). The shock models span shock velocities from 100 to 900 km s^{-1} and include both shock and precursor emission. The photoionization models are of spherically symmetric clouds ionized by a central source (the UV continuum of the ionizing source is not included in the model predictions) and that span stellar temperatures ranging from 30,000 to 50,000 K and electron densities from 0.1 to 10 cm^{-3}. Solar abundances were assumed in both cases.

Most of the regions have too much UV light (relative to Hα) to be explained by nebular emission alone. The observed FUV/Hα ratios in some of the brighter regions in the M82 halo

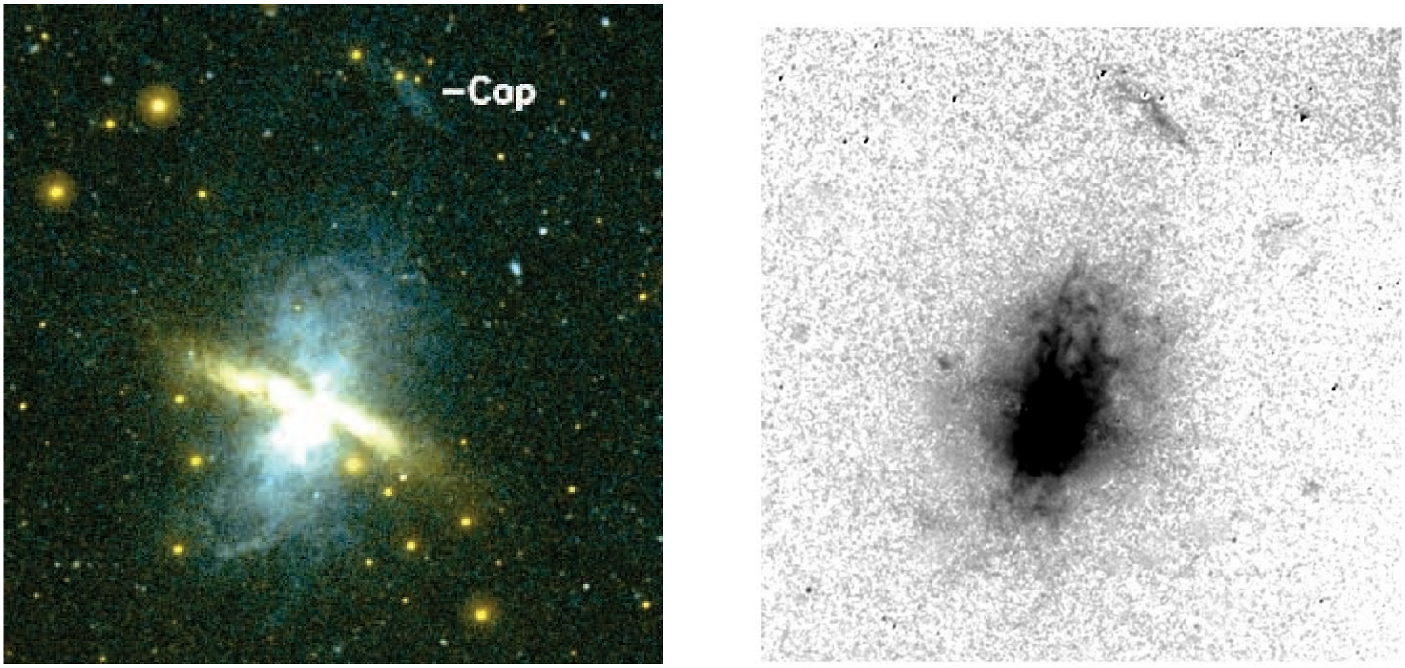

FIG. 2.—M82 in UV and Hα. *Left*: Two-color image, with *GALEX* NUV in red and FUV in blue. *Right*: Continuum-subtracted Hα image. The images are 21′ (22.0 kpc) on each side, with north up and east on the left, and are aligned with each other. The intensity scales in both panels are logarithmically scaled and stretched to emphasize the faint, diffuse emission, so the bright disk of the galaxy is saturated.

are consistent with a significant contribution from shock ionization, but these values have *not* been corrected for extinction intrinsic to the wind. The optical spectrum of the M82 wind indicates a reddening of $E(B-V) \gtrsim 0.21$ mag (Heckman et al. 1990), which would increase the observed FUV/ Hα ratios by a factor of $\gtrsim$3.9 ($\gtrsim$2.6 for NUV/ Hα). This implies that the wind is substantially brighter in FUV and NUV than would be possible for photoionized or shock-heated gas. The absence of O VI emission seen in *Far Ultraviolet Spectroscopic Explorer* data limits shock speeds in the bright M82 filaments to $v_s \leq 160$ km s^{-1} (Hoopes et al. 2003), much slower than the wind velocity ($v \geq 10^3$ km s^{-1}; Strickland & Stevens 2000). Taken together, these facts imply that another source is required to explain the excess extraplanar UV light. The diffuse morphology argues against star formation in the wind as the source. The most likely remaining mechanism is scattering of stellar continuum from the starburst by dust in the halo.

4. DISCUSSION

The spectral slopes β in the halo implied by the observed FUV/NUV ratio are listed in Table 1. The values are redder than an unreddened starburst ($-2.5 \leq \beta \leq -2.0$) and in fact agree well with observed (i.e., reddened) values of local starbursts ($-2.0 \leq \beta \leq -0.6$; Meurer et al. 1999). While it is clear that dust in a starburst environment may have properties that differ from the standard Galactic dust models (Gordon et al. 1997; Popescu et al. 2000), the FUV/NUV ratio is in general agreement with the dust-scattering models of Draine (2003), in which the dust albedo is greater in the NUV than in the FUV.

In a sample of local star-forming galaxies, Buat et al. (2002) found that the observed Hα flux was on average 2.5%–5.0% of the observed UV flux near 2000 Å (similar to the *GALEX* NUV band). The observed Hα flux of the NGC 253 halo is 5% of the NUV flux, and for M82 the corresponding value is 12%. This may indicate that not all of the Hα emission in the M82 halo is scattered light, although polarization measurements indicate the presence of some scattered light in the Hα filaments and the more extended diffuse Hα component of M82 (e.g., Scarrott et al. 1991). Scattered light could be a substantial component of the fainter NGC 253 halo.

Lehnert et al. (1999) suggested that the Hα cap near M82 is the result of a collision between the hot wind fluid and a preexisting neutral cloud. If this scenario is correct, our results imply that the cloud is not primordial, since it contains dust. The cloud may have been pushed out of M82 by the starburst wind, or stripped from either M82 or M81 by the tidal interaction between the two galaxies.

Our results establish for the first time a close morphological correspondence between the dust and the hotter phases of the winds probed in Hα and X-ray emission. We have direct evidence that the hotter gas is outflowing (e.g., Strickland & Stevens 2000), so the new UV images provide further evidence for out-

TABLE 1
MEASURED PROPERTIES

Galaxy	Distance (Mpc)	$L_{H\alpha}$ Halo (ergs s^{-1})	$L_{H\alpha}$ Total (ergs s^{-1})	L_{NUV} Halo (ergs s^{-1})	L_{NUV} Total (ergs s^{-1})	L_{FUV} Halo (ergs s^{-1})	L_{FUV} Total (ergs s^{-1})	L_{bol}[a] (ergs s^{-1})	β[b]
NGC 253	2.6	1.5×10^{39}	3.8×10^{40}	3.1×10^{40}	4.5×10^{41}	2.1×10^{40}	2.2×10^{41}	7.8×10^{43}	-1.5
M82	3.6	1.3×10^{40}	6.1×10^{40}	1.5×10^{41}	3.5×10^{41}	7.1×10^{40}	1.1×10^{41}	2.0×10^{44}	-0.6

NOTE.—The measured luminosities were corrected for foreground Galactic extinction. Calibration uncertainties are ∼10 % in the UV bands (Morrissey et al. 2005) and are of similar magnitude in Hα.

[a] The bolometric luminosities were taken from Strickland et al. (2000; NGC 253) and McLeod et al. (1993; M82).

[b] The spectral slope, defined via $F_\lambda \propto \lambda^\beta$, was estimated from the FUV/NUV flux ratio, following Kong et al. (2004).

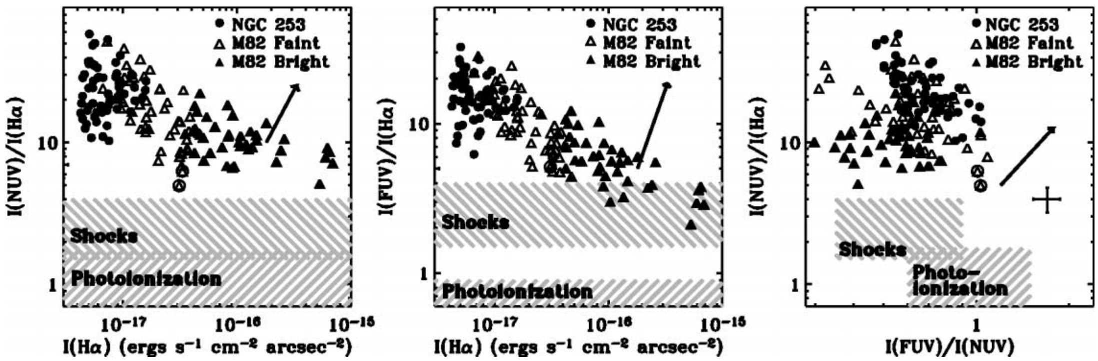

FIG. 3.—Comparison of measured ratios with model predictions. The points are the measured values and have been corrected for Galactic foreground extinction using the extinction law of Cardelli et al. (1989). The hatched regions indicate the range of model predictions. The models are described in the text. We have not attempted to correct for internal extinction. Reddening vectors for $E(B-V) = 0.21$ (measured in the M82 wind by Heckman et al. 1990) are shown in each panel, assuming the Calzetti (2001) starburst extinction law. The M82 points are separated into bright and faint, based on their Hα surface brightness, with the division occurring at $I(\mathrm{H}\alpha) = 4 \times 10^{-17}$ ergs s^{-1} cm^{-2} arcsec^{-2}. The two circled triangles are in the M82 Hα cap. Representative error bars are shown in each panel.

flowing dust (Heckman et al. 2000). This is consistent with the idea that the cool, dusty material is ambient interstellar gas in the disk or inner halo that has been has been entrained and accelerated by the hot outflowing gas generated in the starburst.

If this dust is ejected into the intergalactic medium, there could be important implications for cosmological observations. While the dust density is small, over cosmological distances the resulting extinction could be significant (Aguirre 1999; Heckman et al. 2000). Alton et al. (2001) point out that intergalactic dust may affect the determination of the evolution of the cosmic star formation rate, for example. More work is needed to understand the effects of intergalactic dust.

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REFERENCES

Aguirre, A. 1999, ApJ, 525, 583
Aguirre, A., Hernquist, L., Katz, N., Gardner, J., & Weinberg, D. 2001, ApJ, 556, L11
Alton, P. B., Bianchi, S., & Davies, J. 2001, Ap&SS, 276, 949
Alton, P. B., Davies, J. I., & Bianchi, S. 1999, A&A, 343, 51
Alton, P. B., Draper, P. W., Gledhill, T. M., Stockdale, D. P., Scarrott, S. M., & Wolstencroft, R. D. 1994, MNRAS, 270, 238
Buat, V., Boselli, A., Gavazzi, G., & Bonfanti, C. 2002, A&A, 383, 801
Calzetti, D. 2001, PASP, 113, 1449
Cardelli, J. A., Clayton, G. C., & Mathis, J. S. 1989, ApJ, 345, 245
Devine, D., & Bally, J. 1999, ApJ, 510, 197
Dopita, M. A., & Sutherland, R. S. 1996, ApJS, 102, 161
Draine, B. T. 2003, ApJ, 598, 1017
Ferland, G. J. 1996, in Hazy, A Brief Introduction to Cloudy, Univ. Kentucky Dept. Phys. Astron. Internal Rep.
Gordon, K. D., Calzetti, D., & Witt, A. N. 1997, ApJ, 487, 625
Greenawalt, B., Walterbos, R. A. M., Thilker, D., & Hoopes, C. G. 1998, ApJ, 506, 135
Heckman, T. M., Armus, L., & Miley, G. K. 1990, ApJS, 74, 833
Heckman, T. M., Lehnert, M. D., Strickland, D. K., & Armus, L. 2000, ApJS, 129, 493
Hoopes, C. G., Heckman, T. M., Strickland, D. K., & Howk, J. C. 2003, ApJ, 569, L175
Hoopes, C. G., Walterbos, R. A. M., & Greenawalt, B. E. 1996, AJ, 112, 1429
Kong, X., Charlot, S., Brinchmann, J., & Fall, S. M. 2004, MNRAS, 349, 769
Lehnert, M. D., Heckman, T. M., & Weaver, K. A. 1999, ApJ, 523, 575
Marcum, P. M., et al. 2001, ApJS, 132, 129
Martin, D. C., et al., 2005, ApJ, 619, L1
McLeod, K. K., Rieke, G. H., Rieke, M. J., & Kelly, D. M. 1993, ApJ, 412, 111
Meurer, G. R., Heckman, T. M., & Calzetti, D. 1999, ApJ, 521, 64
Morrissey, P., et al., 2005, ApJ, 619, L7
Ohyama, Y., et al. 2002, PASJ, 54, 891
Pettini, M., Shapley, A. E., Steidel, C. C., Cuby, J., Dickinson, M., Moorwood, A. F. M., Adelberger, K. L., & Giavalisco, M. 2001, ApJ, 554, 981
Popescu, C. C., Tuffs, R. J., Fischera, J., & Völk, H. 2000, A&A, 354, 480
Scarrott, S. M., Eaton, N., & Axon, D. J. 1991, MNRAS, 252, 12P
Schlegel, D. J., Finkbeiner, D. P., & Davis, M. 1998, ApJ, 500, 525
Shapley, A. E., Steidel, C. C., Pettini, M., & Adelberger, K. L. 2003, ApJ, 588, 65
Shopbell, P. L., & Bland-Hawthorn, J. 1998, ApJ, 493, 129
Strickland, D. K., Heckman, T. M., Colbert, E. J. M., Hoopes, C. G., & Weaver, K. A. 2004, ApJS, 151, 193
Strickland, D. K., Heckman, T. M., Weaver, K. A., & Dahlem, M. 2000, AJ, 120, 2965
Strickland, D. K., Heckman, T. M., Weaver, K. A., Hoopes, C. G., & Dahlem, M. 2002, ApJ, 568, 689
Strickland, D. K., & Stevens, I. R. 2000, MNRAS, 314, 511