We present deep R and narrowband Hα images of Arp 78 obtained with the WIYN 3.5 m telescope on Kitt Peak. GALEX observations had shown a very extended UV structure for this system, reaching beyond the optical radius of Arp 78 and also beyond its previously known Hα radius. Our new Hα data now show agreement not only with the spatial extent of the near- and far-UV maps, but also in terms of structural details. Star formation rates derived from L(Hα) and L(FUV) are in reasonable agreement, indicating that in this case the upper stellar IMF in the UV-bright outer arm is relatively normal. The star-forming sites in the outer arms are younger than ~15 Myr and massive enough to properly sample the IMF up to high masses; their low optical visibility evidently is a property of their youth.

Subject headings: galaxies: individual (Arp 78) — galaxies: interactions — galaxies: stellar content — ultraviolet: galaxies

Online material: color figures

1. INTRODUCTION

A major surprise from early data taken with the GALEX ultraviolet explorer satellite was the detection of extended near- and far-UV (NUV, FUV) emission in the extreme outer environment of star-forming galaxies like M83 and NGC 4625 (Thilker et al. 2005; Gil de Paz et al. 2005). Other examples include both apparently undisturbed spirals where the UV emission reveals the inside-out growth of the stellar disk and galaxies that are surrounded by filaments and substructure indicative of tidal encounters with active star formation (SF) going on within these filaments.

An analysis 189 disk galaxies (types S0–Sm) within 40 Mpc from the GALEX Atlas of Nearby Galaxies (Gil de Paz et al. 2007; Thilker et al. 2007) establishes that extended UV (XUV) galaxies are surprisingly common, showing up in >30% of this sample. Two classes of XUV galaxies are defined from this sample. Arp 78 (NGC 772), which we study here, belongs to this class of objects, which make up >20% of the 40 Mpc sample and of which over 75% show optical or Hα morphological evidence for recent interactions or external perturbations. A prototype of this class is M83.

These galaxies have structured, UV-bright, optically faint emission features beyond their normal optical radii and in regions beyond the traditional SF threshold. The latter is defined as the surface brightness contour corresponding to \( \Sigma_{\text{SFR}} = 3 \times 10^{-3} M_\odot \text{yr}^{-1} \text{kpc}^{-2} \), evaluated at 1 kpc resolution. With Kennicutt (1998)'s star formation rate (SFR) calibration, this threshold corresponds to \( \mu_{\text{FUV}} = 27.25 \text{ AB mag arcsec}^{-2} \) or \( \mu_{\text{NUV}} = 27.35 \text{ AB mag arcsec}^{-2} \). These UV surface brightness thresholds correspond to an Hα column density threshold for actively star-forming zones, as predicted by Schaye (2004; see also Thilker et al. 2007), as well as to the Hα "edge" in galaxies from Martin & Kennicutt (2001)'s sample, as demonstrated by Boissier et al. (2007).

A great deal of discussion has focused on objects where UV emission was detected at larger radii than Hα emission from Hα regions, as was the case for Arp 78. A variety of possible explanations for this discrepancy have been put forward, e.g., a top-light IMF as a consequence of a low level of SF with the resulting low star cluster masses precluding the formation of ionizing stars while still forming enough stars below the ionization limit to account for the FUV flux (Weidner & Kroupa 2006; Boissier et al. 2007). Wholesale truncations of the IMF at the upper end also have been suggested to simply cut off sources of photoionization. This situation could be attributed to the low gas column densities in the outskirts of galaxies. Under these conditions fragmentation of a molecular cloud happens too quickly for it to grow to a point where it can readily produce stars massive enough to ionize the surrounding gas (Krumholz & McKee 2008).

Alternatively, age effects have been discussed, in the sense that presumably episodic SF events ceased in the outskirts of some galaxies long enough in the past for Hα regions to have faded below detection, but recently enough for the stellar UV flux to still be measurable (Zaritsky & Christlein 2007). Leakage of ionizing photons in the very low density environment of these outer regions provides yet another possible explanation, as this would act to decrease the observability of photoionized regions (Oey & Kennicutt 1997).

In some undisturbed face-on spirals, Ferguson et al. (1998) were the first to show that very deep Hα exposures revealed small and low-luminosity Hα regions beyond—and sometimes far beyond—the optical radius, giving evidence for low-level SF activity going on beyond the optical radius and interpreted as a signature of the inside-out growth of stellar disks. Another factor then is the question of detectability of Hα regions versus the UV light of stars.

Here we present deep narrowband Hα imaging of Arp 78, including its outer regions, to check whether we can find Hα flux from Hα counterparts to the XUV flux detected by GALEX. Our approach involves comparing SFRs derived from \( L(\text{Hα}) \) with those based on \( L(\text{FUV}) \) assuming a normal relationship between these two measures of massive stellar populations. In this way we can check whether or not the outer regions of Arp 78 have normal young stellar populations.

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2. ARP 78–NGC 772

Arp 78 is a luminous (\( M_B = -21.6 \)) galaxy with pronounced spiral structure at an adopted distance of 34 Mpc (\( v_r = 2472 \) km/s).
It is experiencing multiple interactions involving its spectroscopically confirmed low-luminosity ($M_B = -18.2$) elliptical satellite, NGC 770, at a projected distance of $\sim 30$ kpc, plus two more companions ($M_B = -15.5$ and $-16.2$, respectively) within projected distances $\sim 400$ kpc (Zaritsky et al. 1997).

The outer regions of Arp 78 feature an obviously disturbed, one-sided spiral arm–like morphology that appears to be a tidally driven structure. The XUV emission in Arp 78 is clearly associated with this region, as seen in Figure 1. Whether or not the stellar population age in the filaments agrees with the nuclear starburst age of $\sim 2$ Gyr as determined by Ganda et al. (2007) and possibly even with the stellar population age of 3 Gyr given by Geha et al. (2005) for the counterrotating disk in the companion NGC 770, are subjects of our ongoing more extensive multiband analysis.

### 3. OBSERVATIONS AND DATA REDUCTION

Our optical observations were obtained using the WIYN$^3$ 3.5 m telescope at Kitt Peak equipped with the MiniMosaic camera. MiniMo consists of two $2K \times 4K$ CCD chips with a spatial sampling of 0.14" pixel$^{-1}$ resulting in a field of view of $9.5' \times 9.5'$. The seeing in the $R$ band was $\approx 1.0'$ and $\approx 1.2''$ in $H\alpha$.

Data reduction consisted of overscan- and bias-subtraction, flat-fielding, and cosmic-ray removal. We took special care to correct for slight gain variations between the two CCDs to yield a flat background across the full FoV by multiplying them individually with correction factors $\approx 1$ until sky-noise and background level were identical in all readout zones. The resulting frames were then aligned by matching the positions of several stars in each frame and stacked; bad-pixel masks were used to remove bad pixels and the small gap between the detectors.

Obtaining a proper continuum subtraction requires that we match the point-spread function (PSF) in the $R$ and $H\alpha$ filters. We accomplished this by iteratively smoothing the $R$-band image with a Gaussian of varying widths in the $x$- and $y$-directions until the PSFs in both filters matched and residuals were acceptable. To remove the continuum contribution from the $H\alpha$ image, we measured the intensity of several stars in both the $R$ band and $H\alpha$ frame, scaled the $R$ band so that the stars have on average the same count rates in both $R$ and $H\alpha$ and subtracted this frame from the $H\alpha$ narrowband exposure. The resulting scaling factor is in good agreement with that derived from the widths of the filter transmission curves, but allows for a more accurate continuum subtraction. Although the WIYN W16 narrowband filter also includes the [N II] emission lines, we refer to the continuum subtracted data as $H\alpha$ images since this is the dominant source of emission line flux.

The GALEX images have been obtained from the GALEX science archive at the Space Telescope Science Institute. To minimize offsets introduced by slightly differing coordinate systems we aligned the FUV and NUV frames relative to the optical data by matching the positions of several stars. The full width at half-maximum of the FUV PSF is 4.2" sampled with 1.5" pixels (Morrissey et al. 2007).

### 4. RESULTS AND IMPLICATIONS FOR IMF

Figure 1 shows the FUV image of Arp 78 as gray scale with WIYN narrowband $H\alpha$-brightness contours overplotted. To suppress noise from the image we used adaptive and median-
filtering of the FUV image. The Hα contours, however, have been constructed from the original continuum-subtracted Hα frame to make sure this filtering does not induce artifacts into our results.

This figure clearly shows a nearly perfect match between the FUV and H α regions, as is expected if both the UV flux and Hα flux are emitted by the young stars in the same regions where the IMF extends up to high stellar masses. The close coincidence between FUV- and Hα-emitting regions both in the inner disk and in the outer tidal features is inconsistent with a scenario where a low level of star formation in the XUV disk leads to a low upper stellar mass cutoff of the IMF. It also excludes timing models where the FUV-emitting star clusters are systematically too old to produce significant Hα emission through photoionization, i.e., older than ≈7 Myr.

Several small isolated regions seen in the UV GALEX images but lacking Hα emission can be identified as background galaxies in our WIYN optical images; they are marked by encircled crosses in Figure 1. There are also a few horizontal structures visible in the Hα contour map: these originate in chip defects or saturated stars that could not perfectly be corrected for in the data reduction process.

4.1. Comparing SFRs from FUV/NUV and Hα

The existence of H II regions could be consistent with models where the upper IMF is biased in outer regions of galaxies, e.g., the Weidner & Kroupa (2006) models. To test for this possibility we compare the SFRs obtained from the FUV and Hα luminosities using Kennicutt (1998)'s calibrations. Although those were obtained—and hence are strictly accurate only—for close-to-solar metallicity, they provide a reasonable first estimate for the outer regions of Arp 78. While central spectroscopy has revealed solar to slightly supersolar abundances (Ganda et al. 2007), we expect the outer regions to have subsolar—albeit probably not dramatically subsolar—abundances. If IMF biasing exists in the XUV regions, then we expect the SFR derived from the Hα luminosity to be significantly lower than that based on FUV data.

To obtain the fluxes in the outer tidal filaments, we masked the outer ring-like structure (cf. Fig. 2) and obtained integrated count rates for this region from which we derive fluxes. Using the Galactic extinction law from Valencic et al. (2004) we derive a value of $A_{\text{FUV}} = 0.63$ mag at 1540 Å from the Galactic extinction $E(B-V) = 0.073$ mag toward Arp 78 (Schlegel et al. 1998). At the distance of 34 Mpc toward Arp 78, this yields a FUV luminosity of $2.5 \times 10^{39}$ erg cm$^{-2}$ Å$^{-1}$. Based on uncertainties in the background determination and sky- and readout noise we estimate that this luminosity is accurate to $\pm \pm 15\%$. From this FUV luminosity we estimate a SFR of $\text{SFR}_{\text{FUV}} = (0.3 \pm 0.05) M_\odot$ yr$^{-1}$ using the calibration from Kennicutt (1998).

To derive an Hα flux we use the calibration data from the R band to convert the count rates we measure into physical units. For the photometry in the region identical with the one used to derive the FUV flux we considered two extreme cases: To derive an upper limit to the SFR we only count pixels with counts $>1 \sigma$ above the background level as determined from the nearby sky. Using an effective filter width of 62 Å for the WIYN-W16 filter yields $L(\text{Hα}) = 3.2 \times 10^{38}$ erg s$^{-1}$ for the regions marked in Figure 2, corresponding to a SFR in the tidal debris region of $\text{SFR}_{\text{Hα}} = 0.24 M_\odot$ yr$^{-1}$, also based on the Kennicutt (1998) calibration. A 3 $\sigma$ threshold, taken to be a lower limit to the true SFR, reduced the $\text{SFR}_{\text{Hα}}$ to 0.15 $M_\odot$ yr$^{-1}$. The uncertainty is dominated by potential systematic errors, such as imperfect registration of the FUV and Hα frames, variations of the continuum scaling factor (on the order of 10% or 0.02 $M_\odot$ yr$^{-1}$) and large-scale fluctuations in the background subtraction due to remaining flat-field errors ($=0.05 M_\odot$ yr$^{-1}$ if integrated over the masked area). We therefore adopt a $\text{SFR}_{\text{Hα}} = 0.2 \pm 0.05$ (random) $\pm 0.1$ (systematic) $M_\odot$ yr$^{-1}$. Thus the ratio of FUV-to-Hα SFRs lies in the range of 0.5–1.2, close to expectations for a normal upper stellar mass function.

The observed ratio of SFRs depends on a variety of factors other than the present-day average upper stellar mass distribution. FUV luminosities can be reduced by dust absorption internal to Arp 78. The $L(\text{Hα})$ is very dependent on detecting faint emission against a comparatively bright optical sky background. This problem can be especially serious in low surface brightness regions where 30%–50% of the Hα flux may be in the form of diffuse emission (e.g., Ferguson et al. 1996). In addition, the calibration for the SFR derived from Hα is only valid for solar metallicity galaxies, while the outskirts of Arp 78 are likely to have somewhat subsolar metallicities. Investigating the metallicity dependence of SFR indicators with our GALEV models (cf. Bicker & Fritzé 2005), we found that SFRs in low-metallicity regions are overestimated by factors up to 2 if derived from $L(\text{Hα})$ and by up to 50% if calculated from $L(\text{FUV})$ using calibrations obtained for close-to-solar metallicity environments.

Even after allowing for these effects, the SFRs derived from the Hα and FUV luminosities are in acceptable concordance. The estimated SFR across the outer tidal arm structure in Arp 78 as defined in Figure 2 is $\text{SFR}\text{(outer)} = 0.2 \pm 0.1 M_\odot$ yr$^{-1}$. This result indicates that the upper mass stellar IMF is normal in the sense that the satisfactory agreement within reasonable observational uncertainties between SFRs derived from FUV and Hα luminosities does not require significantly abnormal IMF slope or a peculiarly low upper stellar mass cutoff.

4.2. Extended UV Emission and the IMF in Arp 78

The UV-bright outer arm of Arp 78 contains several H II regions with $L(\text{Hα}) \geq 10^{39}$ erg s$^{-1}$. Photoionization requires some component of the region to have an age of $\leq 7–9$ Myr and for a normal mass function the inferred young stellar
masses in these regions are \(10^4 M_\odot\). Hence, these young clusters are sufficiently massive to properly sample the IMF up to high masses (Weidner & Kroupa 2006; Boissier et al. 2007).

Why then is the XUV outer arm structure so obvious in Arp 78 while the optical counterpart is faint? This appears to be an effect similar to what is observed in the context of tidal dwarf galaxies, where the mass and the NIR light can be dominated by stars inherited from the spiral disk while the short-wavelength light is due to stars formed in a major outer SF event triggered by the ongoing interactions in this system. Evidently this tidal arm feature has not persisted for sufficient time to build up an optically luminous stellar population. For example, Neff et al. (2005) show that FUV - \(R\) can readily exceed 4 mag in transitory features with ages of <500 Myr.

### 5. SUMMARY

Deep narrowband H\(\alpha\) imaging from the WIYN 3.5 m telescope on Kitt Peak allowed us to detect H\(\alpha\) emission in spatial coincidence with the extended GALEX FUV structure across the inner part and, in particular, across the XUV extended outer structures of Arp 78, which very probably are of tidal origin. We calculated the SFR across these outer structures and found a value of \(0.2 \pm 0.1 M_\odot\) yr\(^{-1}\) from both the FUV and H\(\alpha\) luminosities. The agreement between these two measures points to a relatively normal upper stellar IMF in this system. We also find the individual star-forming regions in this system to be younger than 15 Myr and sufficiently massive to properly sample the IMF up to high masses.

The XUV-strong and optically faint outer structures of Arp 78 are consistent with ongoing SF superimposed on an older stellar population torn out from the spiral disk by tidal forces. A detailed investigation of stellar population ages and metallicities across Arp 78 will be the subject of a forthcoming paper.

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**Facilities:** WIYN(MiniMo), GALEX

**REFERENCES**

Bicker, J., & Fritze, U. 2005, A&A, 443, L19
Boissier, S., et al. 2007, ApJS, 173, 524
Ferguson, A. M. N., Wyse, R. F. G., Gallagher, J. S., III, & Hunter, D. A. 1996, AJ, 111, 2265
———, 1998, ApJ, 506, L19
Ganda, K., et al. 2007, MNRAS, 380, 506
Geha, M., Guhathakurta, P., & van der Marel, R. P. 2005, AJ, 129, 2617
Gil de Paz, A., et al. 2005, ApJ, 627, L29
———, 2007, ApJS, 173, 185
Kennicutt, R. C., Jr. 1998, ARA&A, 36, 189
Krumholz, M. R., & McKee, C. F. 2008, Nature, 451, 1082
Martín, C. L., & Kennicutt, R. C., Jr. 2001, ApJ, 555, 301
Morrissey, P., et al. 2007, ApJS, 173, 682
Neff, S. G., et al. 2005, ApJ, 619, L91
Oey, M. S., & Kennicutt, R. C., Jr. 1997, MNRAS, 291, 827
Schaye, J. 2004, ApJ, 609, 667
Schlegel, D. J., Finkbeiner, D. P., & Davis, M. 1998, ApJ, 500, 525
Thilker, D. A., et al. 2005, ApJ, 619, L79
———, 2007, ApJS, 173, 538
Valencic, L. A., Clayton, G. C., & Gordon, K. D. 2004, ApJ, 616, 912
Weidner, C., & Kroupa, P. 2006, MNRAS, 365, 1333
Zaritsky, D., & Christlein, D. 2007, AJ, 134, 135
Zaritsky, D., Smith, R., Frenk, C., & White, S. D. M. 1997, ApJ, 478, 39