Discovery of an extended UV disk in the nearby galaxy NGC 4625

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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 four 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 HI distribution. The masses of these complexes are in the range $10^{3-4} M_\odot$ with their Hα emission (when present) being dominated by ionization from single stars.

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

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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 four times its optical radius at $\mu_B=25$ mag arcsec$^{-2}$ (D25 radius hereafter). Although Swaters & Balcells (2002) already showed the presence of an extended low-surface-brightness component in their optical surface-brightness profiles of this galaxy, the 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. 2005a, 2005b, in prep.).

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$^1$. In spite of the interaction with NGC 4618, NGC 4625 shows a remarkably regular HI velocity field and a well-defined rotation curve (Bush & Wilcots 2004). To the South-East we report the discovery of a low-surface brightness galaxy only $\sim4$ arcmin 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 FUV and NUV bands by GALEX on April 5th 2004 for 3268 seconds 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 arcsec in the FUV and NUV channels respectively.

$^1$Note that Odewahn (1991) estimated a rather closer distance for this system of 6.0 Mpc
Deep ground-based optical imaging data in $B$ and $R$ bands were obtained previously with the prime-focus camera of the 2.5-m Isaac Newton Telescope (La Palma, Spain) on May 28th 1995 (see Swaters & Balcells 2002 for details). On August 20th 2004, we obtained an $H\alpha$ image at the Palomar Observatory 5-m telescope using COSMIC and a 6563/20 narrow-band filter. The total exposure time was 800 seconds. The seeing on all three optical images is in the range 1.2-1.4 arcsec. Neutral hydrogen observations in the line of 21 cm of the NGC 4618/4625 system were obtained with the Westerbork Synthesis Radio Telescope (WSRT) as part of the WHISP survey (Kamphuis, Sijbring, & van Albada 1996; Swaters et al. 2002).

We have derived surface photometry for NGC 4625 in the FUV, NUV, $B$, and $R$ bands, $H\alpha$, and $H_\text{I}$ using circular annuli centered on RA(J2000)=12$^h$41$^m$52.6$^s$ and DEC(J2000)=+41$^\circ$16'21.5". 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 distribution 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 (Figure 2a). 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 [to be called hereafter NGC 4625A, RA(J2000)=12$^h$42$^m$11.1$^s$; DEC(J2000)=+41$^\circ$15’10"] seen ~4 arcmin to the south-east of NGC 4625 (see Figure 2b). Deep optical spectroscopy would be required to establish if 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 (Figure 3) shows very blue UV colors for the innermost regions of the galaxy [(FUV–NUV)\textless 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 arcsec 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 \[E(B - V) = 0.1 \text{mag}\]\(^2\), and (2) the radial profiles of reddening-free color indices, like the \((\text{FUV} - \text{NUV})\) 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 it is not associated with any \(\text{H} \alpha\) region or bright UV cluster we then identify this transition region with an underlying, evolved (intrinsically red) Population II component\(^3\). The sharply declining surface brightness profile of NGC 4625 in this region (between 25-50 arcsec) suggests that the (extrapolated) contribution of this population to the even more distant, extended UV emission is negligible. Finally, we note that the XUV disk shows very blue colors, especially in \((\text{NUV} - B)\) with a rather flat profile in \((\text{FUV} - \text{NUV})\) and \((B - R)\), but a clear bluing in the \((\text{NUV} - B)\) 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 \textit{Hubble Space Telescope} should provide fundamental clues for answering this question.

Compared with the distribution of the UV emission, the azimuthally-averaged \(\text{H} \alpha\) emission in the XUV disk is much fainter than that of the innermost regions of the galaxy (see Figures 2b & 3). On the other hand, the \(\text{H} \text{i}\) 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 \(\text{H} \text{i}\) map (FWHM ≃ 15 arcsec).

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 (Gil de Paz et al. 2005, in prep.).

\(^2\)Derived from the global infrared-to-UV ratio \[\log(\text{TIR}/\text{FUV}) = 0.23\] assuming the relationship between \((\text{TIR}/\text{FUV})\) and \(A_{\text{FUV}}\) given by Buat et al. (2005) and an 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).

\(^3\)A similar smooth red envelope is also seen in the outer parts of NGC 4618 (see Figure 1a)
3.2. Stellar complexes

Inspection of our deep, arcsec-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-selected complexes in the XUV disk yields UV luminosities in the range $10^{23.0−24.5}$ erg s$^{-1}$ Hz$^{-1}$ (dots and diamonds in Figure 4). If we assume that their stars formed instantaneously, the corresponding stellar masses would be in the range $10^{3−4}$ M$_\odot$. Figures 2b & 4 also show that most of the H$\alpha$ emission in the XUV disk comes from very compact sources with $L_{\text{H}\alpha} < 10^{37.6}$ erg s$^{-1}$. These H$\alpha$ luminosities are compatible with being produced by single stars having masses less than 60 M$_\odot$, or 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 H$\alpha$ emission (e.g. Thilker et al. 2005a). 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 H$\alpha$ emission is detected very far out in the disk), the H$\alpha$ emission does decline with radius much faster than the UV light (Figure 3). In Figure 4 we compare the H$\alpha$ and FUV luminosities of individual complexes in the optically-bright disk of NGC 4625 (inside D25; triangles), in the inner regions of the XUV disk (between D25 and 130 arcsec in radius; dots), and in the outer XUV disk (beyond 130 arcsec; diamonds). This figure shows that while regions inside D25 have H$\alpha$ to UV ratios similar to those expected for continuous star formation models, those in the XUV disk have somewhat lower H$\alpha$ 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 (dots).

We note that the H$\alpha$ to UV ratios derived for individual complexes in the XUV disk are systematically higher than those found for the azimuthally-average surface brightness profiles (adopting an average 7 arcsec-radius aperture; thick solid magenta line). This can be explained by the presence of diffuse UV emission from stars of intermediate age (a few $10^8$ yr) in the inter-arm region or from scattering by 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 time-scales of the order of the UV emission (and also comparable to the galaxy dynamical time-scale) but much longer than that of H$\alpha$. 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 ISM to the ionizing photons (Meurer et al. 2004), especially in its outermost regions, the use of azimuthal averages computed over spatial scales with dynamical time-scales that are much longer than the evolutionary time-scale of the emission under study (like 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 M 83, NGC 5055 and NGC 2841. Early results indicate that the presence of a large HI disk is a necessary but not sufficient condition for the XUV emission to be present (Thilker et al. 2005b, in prep.). Objects with characteristics similar to those of NGC 4625, i.e., galaxies in interacting and/or paired SBm systems showing extended neutral-gas disks (like NGC 3664 or NGC 4027) might be also good candidates to show XUV emission.

In the case of NGC 4625 the star formation in the outer HI 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 \( \sim 0.5 \) Gyr. This, we note, is of the same order as the time-scale of the UV emission. Since NGC 4618 does not show XUV emission despite having a relatively extended HI 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 are 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 HI disk is thought to be a consequence of its small \( M_{\text{disk}}/M_{\text{halo}} \) mass ratio (Dubinski, Mihos, & Hernquist 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 thought to be also a fundamental ingredient in the initial growth of disks of spiral galaxies at high redshift.

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Fig. 1.— a) GALEX false-color RGB composite image (R=NUV; G=0.2×FUV+0.8×NUV; B=FUV) of the NGC 4618/NGC 4625 system with an arcsinh stretch (Lupton et al. 2004). b) POSS2 blue-plate DSS image of the same region with the 21 cm H\textsubscript{i} contours overimposed (1 2 4 6 8 11 15 20 ×10\textsuperscript{20} cm\textsuperscript{−2}). The H\textsubscript{i} contours were obtained from our 30 arcsec-resolution convolved map. The 3\(\sigma\) level of this H\textsubscript{i} map is at 1.5×10\textsuperscript{20} cm\textsuperscript{−2}. The morphology of the XUV disk is remarkably similar to that of the H\textsubscript{i} disk.
Fig. 2.— a) GALEX false-color image of NGC 4625 (color scheme as in Figure 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 labelled the newly discovered companion of NGC 4625 as NGC 4625A. Contours of the continuum-subtracted H$\alpha$ 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 four times the D25 radius (47 arcsec). 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 towards 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.
Fig. 4.— Hα vs. FUV luminosity of FUV-selected complexes inside D25 (triangles), in the inner XUV disk (dots) and the outer XUV disk (diamonds). We also show the model predictions for the luminosities of single massive stars (Vacca, Garmany, & Shull 1996; Sternberg, Hoffmann, & Pauldrach 2003) and instantaneous bursts with different ages and masses for a Salpeter IMF with mass range 0.1-100 M⊙ (Bruzual & Charlot 2003). Model curves are plotted without any reddening. The thick solid magenta line represents the expected luminosity inside an average aperture of 7 arcsec in radius and a surface-brightness given by the azimuthally-averaged profiles shown in Figure 3. A reddening vector of E(B − V)=0.1 mag is also shown in the lower right corner.