TIGHTLY CORRELATED H I AND FUV EMISSION IN THE OUTSKIRTS OF M83

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Received 2010 June 17; accepted 2010 July 5; published 2010 August 10

ABSTRACT

We compare sensitive H i data from The H i Nearby Galaxy Survey and deep far-ultraviolet (FUV) data from the Galaxy Evolution Explorer in the outer disk of M83. The FUV and H i maps show a stunning spatial correlation out to almost 4 optical radii ($r_{25}$), roughly the extent of our maps. This underscores that H i traces the gas reservoir for outer-disk star formation (SF), and it implies that massive (at least low level) SF proceeds almost everywhere that H i is observed. Whereas the average FUV intensity steadily decreases with increasing radius before leveling off at $\sim 1.7 \ r_{25}$, the decline in H i surface density is more subtle. Low H i columns ($\lesssim 2 \ M_{\odot} \ pc^{-2}$) contribute most of the mass in the outer disk, which is not the case within $r_{25}$. The time for SF to consume the available H i, inferred from the ratio of H i to FUV intensity, rises with increasing radius before leveling off at $\sim 100 \ Gyr$, i.e., many Hubble times, near $\sim 1.7 \ r_{25}$. Assuming that the relatively short H2 depletion times observed in the inner parts of galaxies hold in outer disks, the conversion of H i into bound, molecular clouds seems to limit SF in outer galaxy disks. The long consumption times suggest that most of the extended H i observed in M83 will not be consumed by in situ SF. However, even these low SF rates are enough for moderate chemical enrichment in a closed outer disk to be expected.

Key words: galaxies: evolution – galaxies: individual (M83) – galaxies: ISM – radio lines: galaxies – stars: formation

1. INTRODUCTION

In this Letter, we compare wide-field images of atomic hydrogen (H i) and far-ultraviolet (FUV) emission, a tracer of recent star formation (SF), in the far outer disk of the nearby spiral galaxy M83. SF in the outer disks of galaxies has been the subject of numerous studies, including direct optical observations of massive SF (e.g., Ferguson et al. 1998; Lelièvre & Roy 2000; Cuillandre et al. 2001; de Blok & Walter 2003) and studies of the star-forming interstellar medium (ISM) using CO emission (Braine et al. 2007; Gardan et al. 2007) or dust (Zaritsky 1994; Popescu & Tuffs 2003). With its large field of view and excellent sensitivity, the Galaxy Evolution Explorer (GALEX) revolutionized this field, revealing widespread, extended SF in the far outer reaches (i.e., far beyond the optical disks) of many galaxies (Thilker et al. 2005, 2007; Gil de Paz et al. 2005, 2007a; Boissier et al. 2007). At the same time, it has long been known that many galaxies host extended H i distributions (e.g., Bosma 1981; Kamphuis & Briggs 1992; Bajaja et al. 1994; Boomsma et al. 2008; Walter et al. 2008), including M83 (e.g., Huchtmeier & Bohnenstengel 1981).

Mainly due to the lack of matched wide-field and sensitive UV and 21 cm observations, it is still largely unclear how these two extended components—SF traced by FUV emission and atomic hydrogen—relate to one another. Although the integrated star formation rates (SFRs) in extended UV (XUV) disks represent only a small fraction of the total SFR, the H i–SFR connection at large radii bears on a number of aspects of galaxy structure and evolution, such as the shapes and edges of stellar disks (Pohlen & Trujillo 2006) or chemical enrichment gradients across galaxies (Gil de Paz et al. 2007b). The consumption of outer-disk H i by SF affects the availability of this gas for fueling SF in inner galaxy disks, a necessary process for galaxies to sustain SF over cosmological times (e.g., Shlosman et al. 1989; Blitz 1997; Bauermeister et al. 2010). Finally, comparing UV and H i in the extreme (low-density, often low-metallicity) environment of outer galaxy disks can illuminate the limiting conditions for cloud and SF ("SF threshold").

In this Letter, we combine sensitive, large field-of-view H i data from The H i Nearby Galaxy Survey (THINGS; Walter et al. 2008) with extremely deep FUV data from GALEX to study the relationship between H i (the dominant component of the ISM at large radii) and FUV emission in the nearby spiral galaxy M83. Previous, shallower GALEX observations showed that M83 hosts one of the most prominent examples of an XUV disk (Thilker et al. 2005, 2007). This unique data set allows us to trace the distribution of H i and FUV emission across a $\sim 50'$ field of view, corresponding to almost four optical radii $r_{25}$ (defined as the 25th B-band mag arcsec$^{-2}$ isophote). We use these data to measure the location (Section 3) and amount (Section 4) of FUV emission relative to the H i. In Section 5, we investigate the distribution of H i surface densities in different radial regimes across M83.

2. DATA AND METHODOLOGY

We use H i data from the NRAO7 Very Large Array (VLA) obtained as part of THINGS to construct a map of H i 21 cm emission across a $\sim 50'$ field of view (Figure 1, lower left panel). This map has been corrected for primary beam attenuation (the VLA primary beam FWHM is $\sim 30'$). To maximize sensitivity for extended emission, we apply the “natural” weighting

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7 The National Radio Astronomy Observatory is a facility of the National Science Foundation operated under cooperative agreement by Associated Universities, Inc.
scheme, which yields a sensitivity (1σ rms) of ~0.8 mJy beam$^{-1}$ (or ~0.2 $M_\odot$ pc$^{-2}$) and a resolution of ~13′. M83 is known to contain a significant amount of its total H$\text{I}$ content in the form of diffuse, low column density H$\text{I}$ in its outer disk (e.g., Huchtmeier & Bohnenstengel 1981), which our interferometric observations will not pick up by design. Because we are focusing on H$\text{I}$ emission associated with (localized) SF, the potentially missing flux on very large ($\gtrsim 15'$) scales is not a concern in the current study. When quoting H$\text{I}$ surface densities we include a factor of 1.36 to account for helium and heavier elements.

The GALEX FUV data are part of our GI program GI3-050. Due to two bright stars near M83, the GALEX observations were carried out in petal pattern mode allowing for the field of view to be centered on the galaxy. The GALEX field of view is slightly larger than the area covered by the H$\text{I}$ map. We thus restrict our analysis to the ~50' field covered by both maps. M83 was observed for nine orbits (~13.5 ks) yielding a FUV map about $13h37m1s$ and decl. $= -29^\circ 52' 16''$. The exposure time for the UV data is 13.5 ks, which makes it one of the deepest UV integrations on a nearby galaxy to date. The UV maps reveal a rich spiral structure within the star-forming disk, a diffuse extended envelope of UV emission and multiple arms, arcs, and filaments that reach out to almost four optical radii (i.e., roughly the edge of the map). All these structures show a stunning degree of correlation with the H$\text{I}$ map, indicating (qualitatively) a tight spatial correlation of atomic hydrogen and UV emission far into the outer disk of M83.

Figure 1 shows that H$\text{I}$ (lower left panel) and UV emission (top panels) are detected far into the outer disk of M83 (the edge of the maps corresponds to ~3.5 $r_{25}$). It also shows a remarkable spatial coincidence of major features found in the maps. Figure 2 shows this even more clearly: plotted are (smoothed) H$\text{I}$ contours of 0.2 $M_\odot$ pc$^{-2}$ ($\sim 2.5 \times 10^{19}$ atoms cm$^{-2}$) on top of the GALEX FUV map. Almost every H$\text{I}$ feature has a corresponding feature in the FUV map. Even very remote structures, such as the tip of the extended, western H$\text{I}$ arm show FUV emission and thus signs of recent SF activity. This close correspondence implies that the extended H$\text{I}$ disk represents the reservoir from which the young stars emitting the FUV emission are forming (presumably with an intermediate stage of bound molecular gas). It also implies, quite surprisingly, that massive SF proceeds—if at a low level—almost everywhere H$\text{I}$ is observed.

Figure 3 quantifies the coincidence of H$\text{I}$ and FUV.$^8$ The y-axis gives the fraction of the total FUV (gray) or H$\text{I}$ (black) flux found in regions (i.e., along lines of sight) with H$\text{I}$ surface densities lower than the value on the x-axis. For example, for an x-axis H$\text{I}$ surface density of 2 $M_\odot$ pc$^{-2}$, we identify all area (i.e., lines of sight) in the maps with $\Sigma_{\text{HI}} < 2 M_\odot$ pc$^{-2}$. We then add up the H$\text{I}$ (FUV) emission from this area and divide this H$\text{I}$ (FUV) flux by the H$\text{I}$ (FUV) flux of the entire map to get the fraction of flux found below the H$\text{I}$ surface density of 2 $M_\odot$ pc$^{-2}$. For comparison, we also plot (dotted line) the

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$^8$ For this plot (and the following), we exclude regions near foreground stars and background galaxies identified from the GALEX pipeline source catalogs and from comparing UV and optical imaging.
fraction of area as a function of H\textsubscript{i} surface density (e.g., in the above example, the fraction of the entire M83 H\textsubscript{i} map with \(\Sigma_{\text{H}\textsubscript{i}} < 2 \ M_\odot \text{pc}^{-2}\)).

The key point in Figure 3 is that the FUV curve (gray) tracks the H\textsubscript{i} curve (black) much more closely than it follows the area curve (dotted). The area curve is the expected distribution for FUV emission, if it were randomly distributed across the map. The fact that the H\textsubscript{i} and FUV curves are quite similar thus shows that rather than being randomly distributed, the distribution of FUV flux seems to follow that of the H\textsubscript{i}. Also, while most of the area in our map is covered by low column (or no) H\textsubscript{i}, the FUV comes mostly from lines of sight with relatively high \(\Sigma_{\text{H}\textsubscript{i}}\). For example, 90% of the area has H\textsubscript{i} surface densities \(<2 M_\odot \text{pc}^{-2}\), while only \(\sim 25\%\) of the FUV flux comes from this area. This behavior is expected if FUV is spatially correlated with H\textsubscript{i} emission and implies that a substantial amount of H\textsubscript{i} (high surface densities) seems to be a necessary prerequisite to SF.

### 4. RADIAL TRENDS

Having seen that FUV and H\textsubscript{i} emission are remarkably coincident, we now ask how the amount of FUV emission compares to the mass of H\textsubscript{i} along a line of sight. The H\textsubscript{i} is concentrated into features (the arms and filaments in Figures 1 and 2) with a relatively low filling fraction, and we have just seen that FUV emission is largely coincident with these features. Our approach here is to look at the mean ratio of H\textsubscript{i}-to-FUV along these features as a function of radius, asking “where there is H\textsubscript{i}, what is its average surface density and what is the associated average FUV intensity?” For this, we consider only emission from areas that have H\textsubscript{i} surface densities (in a smoothed 30\arcmin resolution version of the H\textsubscript{i} map) \(\gtrsim 0.5 M_\odot \text{pc}^{-2}\).

Figure 4 shows the average H\textsubscript{i} and FUV intensities along these features. Differences are immediately apparent: the FUV profile (gray) decreases over many orders of magnitude from the inner parts into the outer disk before it levels off at about 1.7 \(r_{25}\) (note that the FUV emission is not corrected for internal extinction, which is significant at small radii). The FUV emission at large radii is still detected with good sensitivity; the profile is always well above the gray dotted line, which shows the typical 5\sigma sensitivity. This supports the qualitative conclusion from Figure 2 that the extended H\textsubscript{i} structures in M83 seem to coincide with FUV emission, indicating recent SF activity out to largest radii. In contrast to the FUV profile, the H\textsubscript{i} surface density (black) shows only a moderate change with radius. The typical (azimuthally averaged) H\textsubscript{i} surface density is \(\sim 2-4 M_\odot \text{pc}^{-2}\).

Assuming FUV emission to arise mostly from young massive stars forming at a steady rate, we can convert the measured FUV intensities into SFR surface densities, \(\Sigma_{\text{SFR}}\) (using the same procedure as Bigiel et al. 2010). Then the ratio of the two profiles \(\Sigma_{\text{H}\textsubscript{i}}/\Sigma_{\text{SFR}}\) (which is proportional to \(\Sigma_{\text{H}\textsubscript{i}}/I_{\text{FUV}}\)) is the H\textsubscript{i} depletion time, the time it takes (present day) SF to deplete the current supply of H\textsubscript{i}. This quantity is shown as a function of radius in the right panel of Figure 4 (note that inside \(\sim 0.5 r_{25}\) we do not expect \(\Sigma_{\text{H}\textsubscript{i}}/I_{\text{FUV}}\) to trace the gas depletion time, as both \(H_2\) and extinction become important).

The H\textsubscript{i} depletion time rises from the optical disk \(r_{25}\) out to \(\sim 1.7 r_{25}\) and then remains relatively constant across the far outer disk of M83 at about 100 Gyr, i.e., many Hubble times. This very long timescale has several implications. First, it is much longer than the \(\sim 2\) Gyr depletion time of the molecular gas observed in the inner disks of galaxies (Bigiel et al. 2008; Leroy et al. 2008). Assuming bound, molecular clouds form stars with roughly the same efficiency in the inner and outer disks, this extremely long H\textsubscript{i} depletion time suggests that the process of building these molecular clouds is the bottleneck for forming stars at large radii. Combined with the rather low H\textsubscript{i} columns that dominate at large radii, the regulating and/or limiting factor for SF in these environments may well be that of driving the H\textsubscript{i} to high enough densities to trigger the atomic-to-molecular phase transition and subsequent SF.
Figure 4. Left: H\textsc{i} (black) and FUV (gray) emission averaged in 6.5′′ wide azimuthal rings (deprojected radial profiles) in regions of significant H\textsc{i} emission, i.e., along the arms in the extended disk of M83 (see the text). The error bars show the (1σ) uncertainty in the mean in each annulus. The left axis provides the mass surface density scale for the H\textsc{i} profile, and the right axis the intensity scale for the FUV profile (we note that in order to convert the FUV intensity scale—in units of mJy arcsec\(^{-2}\)—into SFR surface densities \(\Sigma_{\text{SFR}}\)—in units of \(M_{\odot}\) yr\(^{-1}\) kpc\(^{-2}\)—one needs to multiply \(I_{\text{FUV}}\) by \(\sim 3.46\); compare to Bigiel et al. 2010). The gray dotted line indicates the typical 5σ sensitivity for the (averaged) FUV emission in an (outer disk) annulus. The respective H\textsc{i} sensitivity is below the lower plot limit. H\textsc{i} and FUV emission show quite distinct radial trends: whereas average H\textsc{i} surface densities remain relatively constant along the filaments in the outer disk, the mean FUV intensity continues to drop before leveling off at 1.7\(r_{25}\). Right: intensity ratio of H\textsc{i} and FUV radial profiles. Converting FUV intensity into \(\Sigma_{\text{SFR}}\), this ratio yields the H\textsc{i} depletion time (right axis). At large radii, this depletion time remains relatively constant at about 100 Gyr, i.e., many Hubble times.

Figure 5. Normalized histograms of H\textsc{i} surface density (left panel)—the right panel shows the same distribution but mass-weighted—for each line of sight in three radial regimes—0–1\(r_{25}\) (gray), 1–2\(r_{25}\) (black hashed), and 2–3\(r_{25}\) (black dotted)—and for the entire H\textsc{i} disk of M83 (thick black line). We bin emission between 0.2 (the sensitivity of the H\textsc{i} map) and 15 \(M_{\odot}\) pc\(^{-2}\) in equally sized bins. The plots show that low H\textsc{i} columns dominate most of the area at all radii in M83 and that while higher columns contribute most to the mass within the optical disk, low column H\textsc{i} dominates the mass budget in the outer disk.

The long H\textsc{i} depletion time also implies that the extended H\textsc{i} reservoir in the outer disk is long-lived, or at least that \textit{in situ} SF is unlikely to consume the gas. This means that this gas is, in principle, available as fuel for SF in the inner disk, if it can be efficiently transported into the inner part of the galaxy (e.g., Wong et al. 2004; Vollmer & Leroy 2010). Single-dish observations sensitive to the entire H\textsc{i} distribution (compare Section 2) suggest that M83 hosts a very large reservoir of H\textsc{i} beyond the optical disk—as much as 80% of the total H\textsc{i} mass (Huchtmeier & Bohnenstengel 1981, and references therein). The total mass of this H\textsc{i} reservoir may well exceed \(\sim 10^{10}\) \(M_{\odot}\), which would, in principle, be enough to sustain present-day SF in the inner disk of M83 for 2–3 times longer than is possible from the H\textsc{\textit{2}} alone (Lundgren et al. 2004).

The moderate SF activity at large radii should also chemically enrich the H\textsc{i} envelope. If the disk remained in its present configuration for \(\sim 5\) Gyr, then the integrated outer-disk SFR (\(\sim 0.05\) \(M_{\odot}\) yr\(^{-1}\) beyond \(r_{25}\)) and a stellar yield of \(\sim 0.06\) (M. Krumholz & A. Dekel 2010, in preparation) imply a mass of heavy elements equal to about 1% of the total outer-disk H\textsc{i} mass (as determined from our map). This is only a coarse estimate, but it shows that even the low observed outer-disk SFR may enrich the outer-disk gas to a moderate metallicity. This fits to observations of emission from hot dust (Dong et al. 2008) and fairly decent metallicities (Gil de Paz et al. 2007b; Bresolin et al. 2009) in the XUV disk of M83.

5. DISTRIBUTION OF H\textsc{i} SURFACE DENSITIES

We have seen that low-level SF is pervasive in the H\textsc{i} arms and filaments in the outer disk of M83. We have also seen that the absolute level of this SF is very low compared to that found in galaxy disks. What drives this drop in the fraction of H\textsc{i} that eventually ends up in stars? A number of authors have suggested
that a drop in H\textsc{i} column or volume density leads to some critical prerequisite for cloud formation not being met (e.g., Elmegreen & Parravano 1994; Schaye 2004; Bush et al. 2010). We conclude by briefly examining how H\textsc{i} surface densities actually change between inner and outer disks.

The left panel in Figure 5 shows the (normalized) distribution of $\Sigma_{\text{HI}}$ for lines of sight in different radial regimes (see caption for details). The right panel shows the same data, but now each line of sight is weighted by mass, so that the left panel gives the distribution of surface densities and the right panel shows at what column most of the mass is found.

In the left panel, the histograms from different regimes are not particularly distinct though one can see some enhancement in the H\textsc{i} columns found inside $r_{25}$ (visible also as the “bump” in the radial profile in the left panel of Figure 4 between $\sim 0.2$ and $\sim 0.7 r_{25}$). These differences are much easier to see in the mass-weighted histograms on the right. While in the optical disk H\textsc{i} surface densities between $\sim 2$ and $8 M_{\odot}$ pc$^{-2}$ contribute roughly equally to the integrated H\textsc{i} mass in this regime, it is clearly the lowest H\textsc{i} columns that contribute most to the mass in the outer disk (i.e., beyond $r_{25}$). In fact, there appears to be a radial trend in the sense that as one moves inward from the far outer disk, an increasing fraction of the H\textsc{i} mass comes from lines of sight with relatively high H\textsc{i} surface density.

We saw that in the outer disk of M83, high H\textsc{i} surface densities, likely a prerequisite for molecular gas and subsequent SF, contribute a decreasing fraction to the overall H\textsc{i} mass as one moves to large radii. The extended arms seen in Figure 1 thus seem to represent merely the “tip of the iceberg” of the extended H\textsc{i} distribution in M83. These arms, however, appear to be the regions where pervasive SF can proceed even at extreme galactocentric radii.

F.B. acknowledges support from NSF grant AST-0838258 and earlier support from the Deutsche Forschungsgemeinschaft (DFG) Priority Program 1177. Support for A.L. was provided by NASA through Hubble Fellowship grant HST-HF-51258.01-A awarded by the Space Telescope Science Institute, which is operated by the Association of Universities for Research in Astronomy, Inc., for NASA, under contract NAS 5-26555. We have made use of the NASA/IPAC Extragalactic Database (NED), which is operated by the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration. This research has made use of NASA’s Astrophysics Data System (ADS). We acknowledge the use of the HyperLeda database (http://leda.univ-lyon1.fr).

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