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The Connection between Molecular Gas and Star Formation in XUV Disks

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Abstract. We found that star-forming regions in extended ultraviolet (XUV) disks are generally consistent with the molecular-hydrogen Kennicutt-Schmidt law that applies within the inner, optical disk. This is true for star formation rates based on Hα + 24 μm data or FUV + 24 μm data. We estimated that the star-forming regions have ages of $1 - 7$ Myr and propose that the presence or absence of molecular gas provides an additional "clock" that may help distinguish between aging and stochasticity as the explanation for the low Hα-to-FUV flux ratios in XUV disks. This contribution is a summary of the work originally presented in Watson et al. (2016).

Keywords. HII regions, ISM: molecules

1. Introduction

XUV disks are generally characterized by far-ultraviolet (FUV) emission that extends out to at least twice the optical radius (Gil de Paz *et al.* 2005; Thilker *et al.* 2005). This is interesting from a star formation perspective because it tells us that stars formed at these extreme radii within the last 100 Myr. What may be even more interesting is that, in about half of XUV disks, the Hα emission decreases sharply at about the optical radius (Goddard *et al.* 2010). Hα and FUV emission do trace different populations; Hα traces $M > 17\,M_\odot$ stars that live for < 10 Myr and FUV traces $M > 3\,M_\odot$ stars that live for < 100 Myr. But they agree as star formation tracers within the optical disk. Therefore, a number of authors have investigated why there is a discrepancy in XUV disks.

Arguably, there are two leading explanations for the low Hα-to-FUV flux ratios in XUV disks. The first leading explanation is aging of stellar populations (e.g., Gogarten *et al.* 2009; Alberts *et al.* 2011). Imagine a burst of star formation that occurred more than 10 Myr in the past, but less than 100 Myr. The most massive stars would have died off, leaving the $\sim 3\,M_\odot$ stars to emit at FUV. A second leading explanation is stochasticity (e.g., Goddard *et al.* 2010; Koda *et al.* 2012). The star-forming regions in XUV disks may in general have low mass, such that they can only rarely populate the initial mass function with the most massive stars that are responsible for Hα emission.

2. Results

The main motivation for our work is to help understand star formation in the extreme conditions of XUV disks. To that end, we asked three main questions: Where do the star-forming regions in XUV disks lie relative to the Kennicutt-Schmidt law? Which star formation rate tracer correlates best with the molecular gas density? What is the evolutionary state of XUV disk star-forming regions?

First, we placed the XUV disk star-forming regions on the molecular-hydrogen Kennicutt-Schmidt law (Figure 1; Watson *et al.* 2016). Considering all the points in Figure 1, the

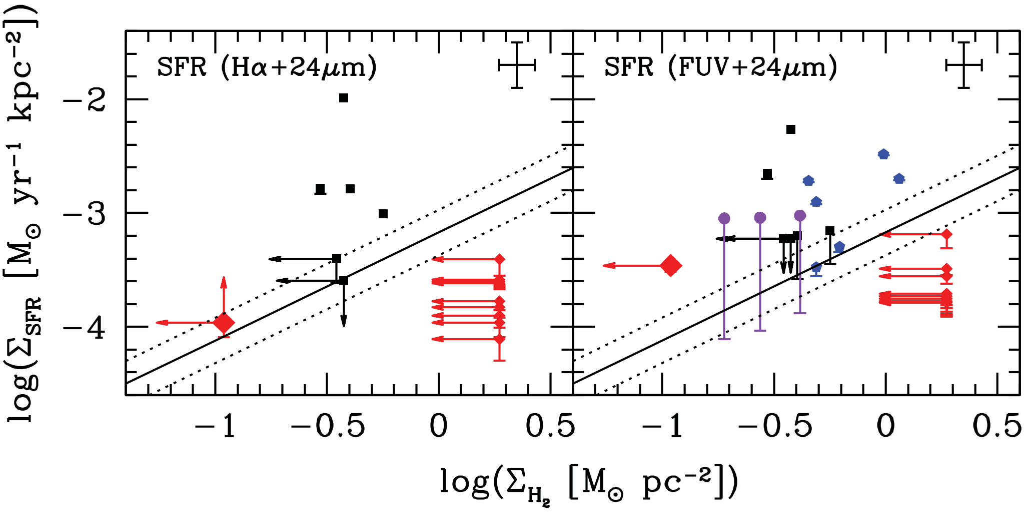

Figure 1. We used the IRAM 30 m telescope to obtain a deep upper limit on the CO(1-0) intensity in one star-forming region at $r = 3.4\,r_{25}$ in the XUV disk of NGC 4625 (large diamond). We also used published CO data for star-forming regions in the outer disks of NGC 6946, M33, and NGC 4414 (small squares, pentagons, and circles; Braine & Herpin 2004; Braine *et al.* 2007, 2010). We measured the SFRs for each of the regions using Hα, FUV, and 24 μm data (Ferguson *et al.* 1998; Kennicutt *et al.* 2003; Gil de Paz *et al.* 2007; Kennicutt *et al.* 2008; Dale *et al.* 2009). The solid line shows the fit for the optical disk of normal spiral galaxies with 1σ scatter shown as dotted lines (Leroy *et al.* 2013). This figure is a reproduction of Figure 4 from Watson *et al.* (2016).

star-forming regions in XUV disks are in general consistent with the same molecular-hydrogen Kennicutt-Schmidt law that applies within the optical disk (solid line).

The star-forming regions with CO detections tend to lie above the relation for the optical disk. This is consistent with the evolutionary effects seen by Schruba *et al.* (2010) when the measurement aperture contains few star-forming regions. If you place your aperture on a single molecular cloud that has not yet started forming stars, it will have high molecular hydrogen surface density and low star formation rate (SFR) surface density. If instead you place your aperture on a young cluster that has used up or expelled the molecular gas, it will have low molecular hydrogen surface density and high SFR surface density. Since we selected Hα- or FUV-bright star-forming regions, it follows that the regions are in the latter category.

Our conclusions are the same for SFRs based on Hα+24 μm data (left panel of Figure 1) or FUV + 24 μm data (right panel).

We also studied whether the ages of the star-forming regions in XUV disks are consistent with the presence or absence of molecular gas (Figure 2). We estimated that the ages of the star-forming regions are between $1 - 7$ Myr and those ages are not correlated with the CO detection rate. We would have expected all the regions in Figure 2 to have molecular gas because molecular clouds live for a few ×10 Myr and all the regions are younger than this. We can test this hypothesis with deeper CO data. The additional "clock" provided by the presence or absence of molecular gas may also help us break the degeneracy between stochasticity and aging as the explanation for the low Hα-to-FUV flux ratios in XUV disks.

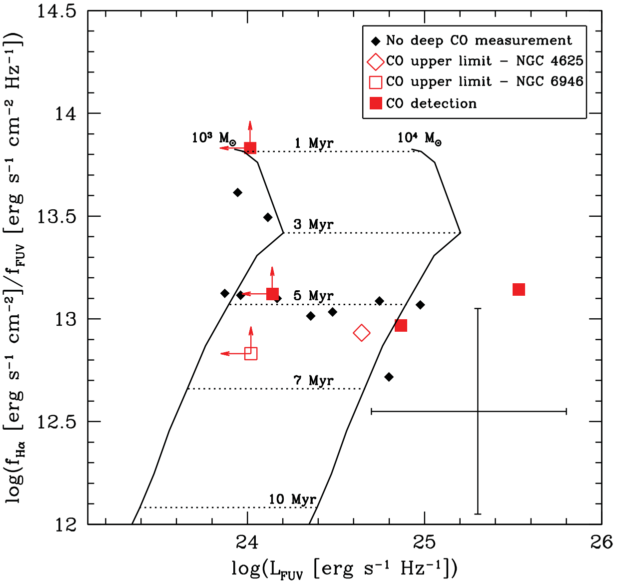

Figure 2. We estimated that the ages of the star-forming regions (points with CO status shown in the legend) are between 1 – 7 Myr by comparing the Hα-to-FUV flux ratios to STARBURST99 models of cluster evolution (solid lines; Leitherer *et al.* 1999). This figure is a reproduction of Figure 5 from Watson *et al.* (2016).

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