Resolving the Rise and Fall of Star Formation in Galaxies
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Is star formation in gas-rich bars suppressed?

Fumiya Maeda

Institute of Astronomy, Graduate School of Science, The University of Tokyo, 2-21-1 Osawa, Mitaka, Tokyo 181-0015, Japan

Abstract. Whether the star formation efficiency (SFE) in the bar region is lower than those in the other regions in a barred galaxy has recently been debated. We statistically investigate the SFEs along the bars in nearby gas-rich massive star-forming barred galaxies by distinguishing the center, bar-end, and bar regions for the first time. The molecular gas surface density is derived from archival CO(1–0) and/or CO(2–1) data and the star formation rate surface density is derived from a linear combination of far-ultraviolet and mid-infrared intensities. To distinguish the three regions, we targeted 18 galaxies with a large apparent bar length ($\geq 75''$). The resulting SFE in the bars is about $0.6 - 0.8$ times lower than that in the disks, which suggests the star formation in the bars tends to be systematically suppressed.

Keywords. galaxies: ISM – galaxies: structure

1. Introduction

It has been commonly known that massive star formation in bars of barred galaxies is suppressed. A low star formation efficiency (SFE $= \Sigma_{\rm SFR}/\Sigma_{\rm mol}$) in the bar region has been reported for many barred galaxies such as NGC 1300 (Maeda et al. 2020), NGC 4303 (Yajima et al. 2019), and NGC 5236 (Hirota et al. 2014). However, in contrast to the studies that observed the individual barred galaxies, recent statistical studies have suggested that the SFE in the bars is not systematically lower than those in other regions and is, in fact, environmentally independent (Muraoka et al. 2019; Díaz-García et al. 2021; Querejeta et al. 2021).

What makes this inconsistency? Two methodological differences exist. First difference is the definition of the bar. While the galactic center and bar-end are distinguished as other environments from the bar in most of the previous studies focused on individual galaxies, the definition of the bar in recent statistical studies includes (part of) center and bar-end, which may make the difference of SFEs between bars and disks small because of the high SFE in the center and bar-end. Second difference is the spatial resolution. The recent statistical studies included galaxies in the sample whose apparent bar major axis is as small as several times the angular resolution of the images they used. In this case, the center, bar, and bar-end cannot be distinguished, which may also smooth the differences in the SFE between the environments.

We aim to statistically determine whether the SFE in the bar region is lower than those in other regions by distinguishing the galactic center, bar-end, and bar, similar to previous studies that focused on individual barred galaxies. To distinguish between these environments and avoid the smoothing the differences in the SFE, we focus on 18 gas-rich galaxies whose bar major axis is at least five times larger than the angular resolution of the images we used ($15''$).

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2. Sample Selection and Data Analysis

We first select 35 nearby barred galaxies with a large apparent bar major axis from the HyperLeda database according to the following criteria: (1) The morphological type is SAB or SB and the Hubble T stage is in $T = 0 - 7$. (2) The recessional velocity is < 2000 km s^{-1} ($\sim$ 27 Mpc). (3) The inclination is $< 70°$. (4) The Galactic latitude (b) is $|b| > 10°$. (5) GALEX FUV and WISE 22 μm data available. The $\Sigma_{\rm SFR}$ is derived from a linear combination of them. (6) CO(1–0) or/and CO(2–1) data cubes available. Here, we refer to the catalogs of previous CO survey projects (NRO CO atlas, COMING, HERACLES, and PHANGS-ALMA) and search the ALMA archival data sets. (7) Bar semi-major axis ($R_{\rm bar}$) is $\geq 37.''5$. This selection is based on the requirement that the major axis of the bar ($2R_{\rm bar}$) must be at least five times larger than the angular resolution of the WISE 22 μm ($15''$) to distinguish between the center, bar, and bar-end.

Then, we select 18 galaxies with gas-rich bar from the 35 galaxies. We define a gas-rich bar as a bar region where more than 40% area is $\Sigma_{\rm mol} \geqq 5$ $M_\odot$ pc^{-2}. Here, we calculate the $\Sigma_{\rm mol}$ by assuming the Galactic CO-to-H_2 conversion factor and a CO(2–1)/CO(1–0) ratio of 0.65. All CO data cubes are used after convolving them to a beam size of $15''$. We define the center, bar, and bar-end regions of the galaxy based on the stellar bar structure defined by the cataloged ellipse. We define a rectangle with a width of $2 \times 1.25 \times R_{\rm bar}$, height of $2R_{\rm bar}(1 - \epsilon_{\rm bar})$, and position angle of the bar (Figure 1(a)). Here, the $\epsilon_{\rm bar}$ is ellipticity. In this rectangle, we define the center, bar, and bar-end as the regions where the distance to the minor axis of the ellipse (R) is $0.0 - 0.25R_{\rm bar}$, $0.25R_{\rm bar} - 0.75R_{\rm bar}$, and $0.75R_{\rm bar} - 1.25R_{\rm bar}$, respectively. The region outside of this rectangle and inside the FoV of the CO data cube is defined as a disk. Most of the 18 galaxies are massive ($M_{\rm star} \geqq 10^{10}$ $M_\odot$) and located in the upper side of the main sequence. The angular resolution is $15''$, which corresponds to $0.3 - 1.8$ kpc.

3. Results

Figure 1(b) and (c) display the SFE profiles from $R/R_{\rm bar} = 0.0$ to 1.25 that are normalized by the SFE in the disk of the sample galaxies. We find the SFE in the bar to be systematically lower than that in the disk regardless of whether $\Sigma_{\rm mol}$ is measured using CO(1–0) or CO(2–1). The median normalized SFE (SFE/SFE$_{\rm disk}$) is $0.6 - 0.8$ in $R/R_{\rm bar} = 0.25 - 0.75$. The SFE/SFE$_{\rm disk}$ is at a minimum at around $R/R_{\rm bar} = 0.5$. These results suggest that massive star formation in the bar region is systematically suppressed in comparison with the disk region in massive ($M_{\rm star} \geqq 10^{10}$ $M_\odot$) high sSFR (i.e., upper side of the main sequence) galaxies with gas-rich bar and disk. Although the SFE in the bar region is systematically suppressed, its scatter is approximately 0.5 dex; some areas possess SFEs comparable to those in the disk, whereas others possess significantly lower SFEs than those in the disk. Additionally, the degree of suppression of star formation appears to vary among galaxies and within a galaxy.

Our results are inconsistent with the results of nonenvironmental dependence on the SFE by similar recent statistical studies (Muraoka et al. 2019; Díaz-García et al. 2021; Querejeta et al. 2021). The possible causes of this inconsistency are the differences in the definition of the bar region, spatial resolution, the CO-to-H_2 conversion factor, and sample galaxies.

4. Discussion: Relationship between the velocity width and SFE

The degree of the star formation suppression seems to vary among galaxies and within a galaxy. What determines the degree of the suppression? One promising parameter is the strength of noncircular motion in the bar region. Star formation has been arguably suppressed by some dynamical effects, such as strong shock, large shear, and fast cloud-cloud collisions, which are caused by the noncircular motion. Here, we investigate the

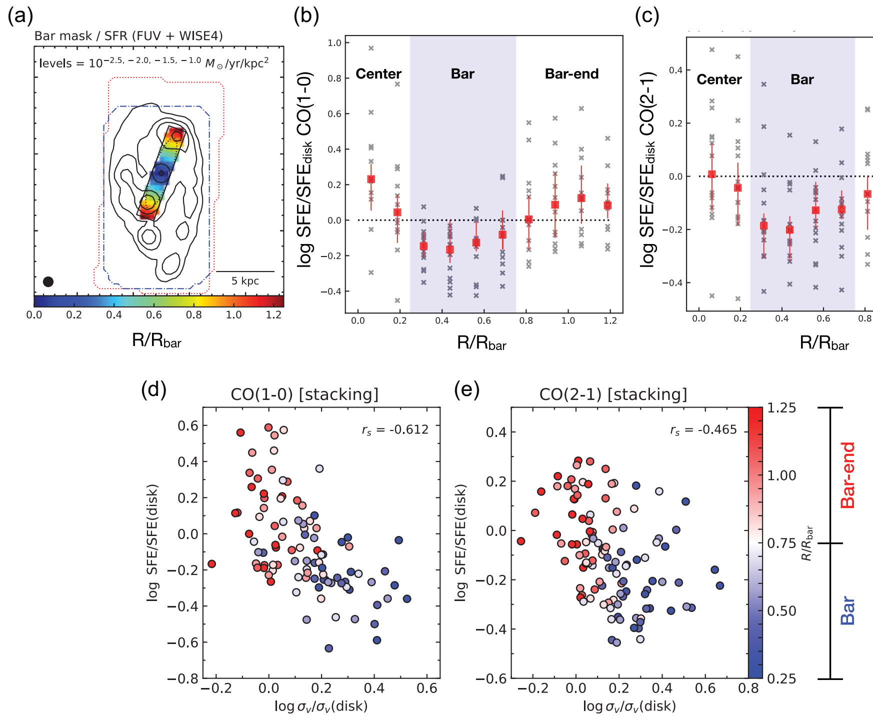

Figure 1. (a) Environmental mask (NGC 3627). The contours show the $\Sigma_{\rm SFR}$. The FoVs of the CO(1–0) and CO(2–1) observations are represented as a red dotted and blue dash-dotted lines, respectively. The black ellipse is the cataloged bar structure. Color map shows the normalized distance to the minor axis of the ellipse. (b-c) SFE profiles as a function of the $R/R_{\rm bar}$ derived from CO(1–0) and CO(2–1). The data points of each galaxy is shown by gray crosses and the median value and IQR of all sample galaxies in each bin are shown as a red square and bar, respectively. For each galaxy, we show the median SFE in each bin normalized by the median SFE in the disk. (e-f) Relationship between normalized velocity width of the CO spectrum and normalized SFE in the bar and bar-end regions. The velocity width, which is derived from the stacking profile, is normalized by that in the disk region. The Spearman's correlation rank (r_s) is given in the top right corner.

relationship between the velocity width of the CO spectrum and SFE in the bar, bar-end, and disk regions. Figure 1(d-e) show the relationship between the normalized velocity width of the CO spectrum and normalized SFE in the bar and bar-end regions. The velocity width is normalized by that in the disk region of the galaxy. We find negative correlations between the normalized velocity width and SFE. The σ_v in the bar-end is $\sim 0.8 - 1.2$ times larger than that in the disk, whereas that in the bar is is $\sim 1.2 - 4.0$ times larger than that in the disk. This negative correlation would support the idea that the larger the noncircular motion, the lower the SFE.

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