Pathways through an Eclectic Universe
ASP Conference Series, Vol. 390, © 2008
J. H. Knapen, T. J. Mahoney, and A. Vazdekis, eds.

The Star Formation Law as a Function of Galactic Properties

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Abstract. The relation between molecular gas quantity and star formation rate, known as the Schmidt law, is tested for its dependency on galactic morphology, with an emphasis on the presence of bars. The galaxy sample is based on a survey of the ^{12}CO($J = 1 \rightarrow 0$) emission in nearby galaxies completed at the Nobeyama Radio Observatory 45 m telescope, combined with previous surveys with similar resolution. These data were compared to star formation rates derived using internal extinction corrected Hα. The slope of the Schmidt law is found to vary considerably with sample distance, from 0.7 to 1.4. The Schmidt law is categorized according to the presence of bars. Consequently, we find that barred galaxies occupy the denser regime of the Schmidt law, but with no apparent difference in the star formation efficiency, indicating that bars stimulate central inflow of gas, but that star formation still occurs according to a common star formation law as with non-barred galaxies.

1. Introduction

Past studies have shown that the Schmidt law, or the power law relation between gas surface density Σ and star formation rate (SFR), is to some extent a universal characteristic of spiral galaxies in general (e.g., Kennicutt 1998; Wong & Blitz 2002; Komugi et al. 2005, 2006, 2007). Dynamical properties of galaxies, however, are also known to have effects on the nature of star formation. It is therefore natural to expect that these dynamical characteristics (such as Hubble type and the presence of bars) also affect the transition law from gas to stars. This preliminary study aims to address this issue by categorizing the Schmidt law according to the presence of galactic scale bars.

2. Data

We observed a total of 69 galaxies in the ^{12}CO($J = 1 \rightarrow 0$) line with the Nobeyama Radio Observatory (NRO) 45 m telescope (beamsize 16″) during three observing runs from May 2005 to January 2006. The galaxies were observed with a single pointing at the center.

Combined with previous measurements at the NRO 45 m (Nishiyama & Nakai 2001) and similar angular resolution (22″) single dish data from the IRAM 30 m telescope (Combes et al. 1988; Planesas, Gómez-González, & Martín-Pintado 1989; Braine et al. 1993; Böker, Lisenfeld, & Schinnerer 2003), our data set comprises 189 nearby (mainly spiral) galaxies, of which 162 are detected at better than 5σ level. The morphology of the samples spans a wide range, from early to late types. Most of the galaxies lie within 30 Mpc, clustered around 20 Mpc representing the Virgo cluster (see S. Komugi et al., in preparation, for details). The SFR in units of $M_\odot\,\mathrm{pc}^{-2}\,\mathrm{yr}^{-1}$, was derived from narrow-band Hα imaging by Young et al. (1996) and the calibration by Kennicutt (1998). Internal extinction was corrected using the Hα/Hβ ratio from spectroscopic data from Ho, Filippenko, & Sargent (1997). SFRs for 66 galaxies were corrected for extinction using this method, and the present paper focuses on this subsample.

3. The Schmidt Law and the Effect of Distance

Figure 1 is the relation between SFR and surface gas density Σ ($M_\odot\,\mathrm{pc}^{-2}$) assuming a uniform CO–$H_2$ conversion factor of $X_{\mathrm{CO}} = 2.8 \times 10^{20}\,(\mathrm{cm}^{-2})$ for samples with non-irregular morphology. A linear fit is given for subsamples with distances larger or smaller than 15 Mpc.

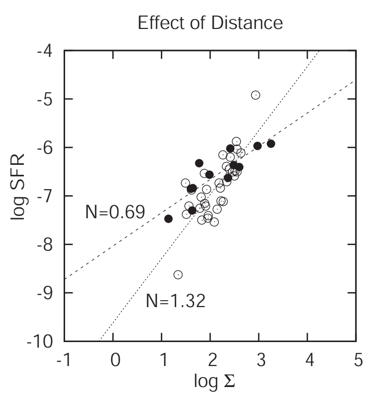

Figure 1. The obtained Schmidt law. Galaxies with a distance of 15 Mpc or less are filled circles, and with distances greater than 15 Mpc open circles. The dashed and the straight lines are the best fits for the closer and farther galaxies, respectively.

The observing beams of both the NRO 45 m and the IRAM 30 m telescopes subtend different scales depending on the distance to the galaxy. It is important to know what effect this can have on the Σ–SFR relation. The Schmidt law index, N, is defined by $\mathrm{SFR} \propto \Sigma^N$. A best fit to the closer galaxies gives a slope of $N = 0.69 \pm 0.13$, and $N = 1.32 \pm 0.19$ for the farther galaxies. The two are significantly different.

The arbitrary value of 15 Mpc is chosen so that the 16″ beam corresponds to a scale of 1.2 kpc, or 600 pc from the nucleus. Sakamoto et al. (1999), Regan et al. (2001), Sofue et al. (2003) and others have shown that many spirals have a central exponential molecular disk, with a characteristic radius of roughly this size. If this is a universal characteristic, observing galaxies closer than 15 Mpc will truncate this exponential structure. Assuming that the star-forming nuclear disk is also exponential (as is often observed), the Schmidt law index of $N = 0.69$ can be explained by this effect of observationally truncating an exponential structure with an original Schmidt law index of $N = 1.32$ (S. Komugi et al., in preparation). The categorization of the Schmidt law for the presence of bars must therefore be done separately for these sample distances.

4. The Effect of Bars

The primary goal of this study is to see the effect of bars on the Schmidt law sequence. Bars are understood in general to feed gas into the central kpc of galaxies (e.g., Kuno et al. 2007). Under this assumption, one of two cases may be observed: 1) bars concentrate gas into the central kpc, but a common Schmidt law explains the SFR in the same way as non-barred galaxies, or 2) due to the central condensation of gas, bars induce additional star formation to that which can be predicted by the Schmidt law, in which case the star formation efficiency (SFE) will rise and a different sequence in the Schmidt law can be seen. The Schmidt law categorized by the existence of bars can be seen in Figure 2.

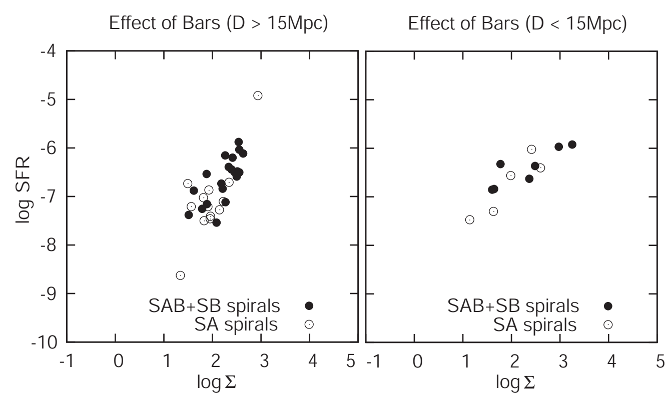

Figure 2. The Schmidt law categorized by barred/non-barred galaxies. *Left:* Galaxies with distance of more than 15 Mpc. *Right:* Galaxies with distance of less than 15 Mpc.

Apparently, barred galaxies occupy the denser regime, confirming that bars condense gas into the central region. A sequential offset between barred and non-barred galaxies is not seen, however, and the two morphological types seem to follow a common Schmidt law. Case 1 is supported, therefore. This can be further visualized in terms of the SFE, in Figure 3. The SFE as a function of Σ seems to be independent of the existence of bars, although with considerable dispersion.

These observations imply that in a statistical sense, bars do concentrate gas into the central kpc but do not raise the SFE, and that star formation occurs according to a common Schmidt law as in non-barred galaxies.

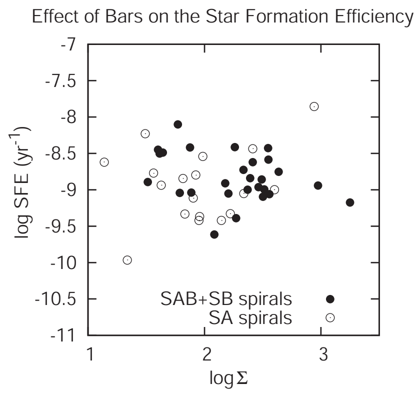

Figure 3. The SFE for all the galaxies in Figure 1. The SFE is derived as SFR/Σ.

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Discussion

Shlosman: Wouldn't it be natural to look for star formation along the bars and not in the central regions, if you want to find how the bars affect the efficiency of SF? Inside the bar the nature of the gas flow changes and the shear is known to affect the star formation. For example, in strong bars the star formation is heavily damped because of a strong shear.

Komugi: Of course. A reliable estimate of extinction is difficult, however (see Lundgrens talk on M83), altering the Schmidt law. Considering that my study is sensitive to SFR calibrators we believe that extinction corrected (via Hα/Hβ) Hα should be used. Once we have narrow-band Hβ images, a point-to-point Schmidt law in bars would absolutely be the thing to do. We only infer the central region in this case because the spectroscopic slits on the centers were only $2'' \times 4''$ in size and therefore not applicable to the bars.

Kennicutt: How were the SFRs in your study measured, and how did you correct for extinction?

Komugi: 1) SFRs for normal galaxies in Komugi's (2005) central kpc: Hα/Hβ from Ho et al. (1997). Disks: assume $A_V \propto N(\mathrm{H}_2)$ (see Lundgren's talk). 2) SFRs for the CO survey: Hα/Hβ leading to $E(B-V)$ from Ho et al. (1997) with $2'' \times 4''$ aperture spectrometry.

Erwin: In dividing your sample into barred and non-barred galaxies, how did you treat the RC3 "S" classification, which is distinct from the SA (unbarred), SAB (weakly barred) and SB (strongly barred) classifications?

Komugi: I re-checked the samples, and found only 3 S's, for one of which Hβ was available, so they are not plotted on the Schmidt law.

From left to right: Shinya Komugi, Fumi Egusa and Yoshihiko Yamada. Claire Dobbs is in the background to the right.