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Determination of Star Formation Timescale and Pattern Speed of Spiral Galaxies

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Abstract. We propose a method to determine the star formation timescale and pattern speed simultaneously in spiral galaxies. Though they are important and fundamental parameters in galactic dynamics and star formation scenarios, it has hitherto been difficult to derive their values directly from observations. Our method utilizes azimuthal offsets between arms of H II regions and molecular clouds, and has been successfully applied to three nearby galaxies so far through the use of CO and Hα images. As derived star formation timescales fall into the narrow range of 4–13 Myr, which is consistent with typical timescales for molecular clouds to collapse gravitationally, a dominant mechanism of global star formation in spiral arms might be the gravitational collapse of molecular clouds.

1. Method

We define a star formation timescale ($t_{\rm SF}$) to be the average time needed for molecular clouds to form massive stars. In spite of its importance in any star formation scenario, its value has not been determined theoretically or observationally. An easy way to estimate its value is to calculate the Jeans timescale ($\propto [G\rho]^{-1/2}$) for molecular clouds, and its typical value is about 6 Myr for $\rho = 100\,{\rm cm}^{-3}$. Meanwhile, a pattern speed ($\Omega_{\rm P}$) is defined as an angular rotational velocity of a spiral pattern, and is especially important for spiral density wave theory (Lin & Shu 1964). As it cannot be derived from observations, several indirect methods, such as the Tremaine–Weinberg method (Tremaine & Weinberg 1984), have been proposed.

An advantage of our method is that we can derive $t_{\rm SF}$ and $\Omega_{\rm P}$ simultaneously. Assuming circular rotation, the angular offset (θ) and the angular rotational velocity (Ω) should have a linear correlation as $\theta = (\Omega - \Omega_{\rm P}) \cdot t_{\rm SF}$. As these two values can be derived directly from observations, it is easy to make a 2D plot of them and fit it with a line using the least χ^2 method. The $t_{\rm SF}$ and $\Omega_{\rm P}$ are determined by the gradient and abscissa intercept of the fitted line, respectively (see Egusa, Sofue, & Nakanishi 2004 for details).

2. Application and Results

We applied our method to four nearby spiral galaxies (NGC 4254, NGC 4303, NGC 4321, and NGC 5194). All these galaxies are classified as “grand-design”;

that is, their arm classes are 9 or 12 according to Elmegreen & Elmegreen (1987). CO data are from our mosaic observation with the Nobeyama Millimeter Array (NMA) for NGC 4254 and from BIMA SONG (Helfer et al. 2003) for the rest. Hα images are from Koopmann, Kenney, & Young (2001) for NGC 4254, Knapen et al. (2004) for NGC 4303, and Martin & Kennicutt (2001) for the other two. Rotational velocities are derived from a CO velocity field for NGC 4254, and from Sofue et al. (1999) for the BIMA SONG galaxies.

Three of the four galaxies have a clear offset between the CO and Hα, so that we can fit each θ–Ω plot (Fig. 1) to derive $t_{\rm SF}$ and $\Omega_{\rm P}$. The corotation radius ($R_{\rm CR}$) occurs where the disk matter and spiral pattern rotate at the same speed, and can be calculated from the derived $\Omega_{\rm P}$ and rotation curves. The results listed in Table 1 indicate that CO lines are detected only within the corotation radii, and that the star formation process in spiral arms might be dominated by the gravitational collapse of molecular clouds.

The remaining galaxy (NGC 4321) has no offset between the CO and Hα, which might be due to large non-circular motions from the bar potential or material (not density) spiral arms being dragged by the bar.

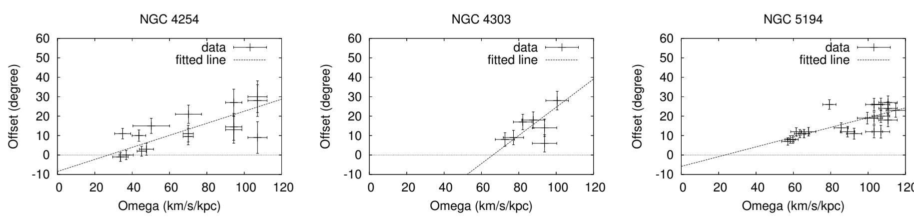

Figure 1. The θ–Ω plots and fitted lines.

Table 1. Results from the fitting

	NGC 4254	NGC 4303	NGC 5194
$t_{\rm SF}$ (Myr)	5.3 ± 0.9	12.5 ± 5.5	4.3 ± 0.5
$\Omega_{\rm P}$ (km/s/kpc)	27 ± 10	66 ± 50	23 ± 10
$R_{\rm CR}$ (kpc)	~ 5	–	~ 9

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