Radial distributions of arm–gas offsets as an observational test of spiral theories

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Abstract

Theories of stellar spiral arms in disk galaxies can be grouped into two classes based on the longevity of a spiral arm. Although the quasi-stationary density wave theory supposes that spirals are rigidly rotating, long-lived patterns, the dynamic spiral theory predicts that spirals are differentially rotating, transient, recurrent patterns. In order to distinguish between the two spiral models from observations, we performed hydrodynamic simulations with steady and dynamic spiral models. Hydrodynamic simulations in steady spiral models demonstrated that the dust lane locations relative to the stellar spiral arms (hereafter, arm–gas offsets) depend on radius, regardless of the strength and pitch angle of the spiral and the model of the interstellar medium. In contrast, we found that the dynamic spiral models show no systematic radial dependence of the arm–gas offsets. The arm–gas offset radial profile method, together with the other test methods, will help us to distinguish between the two spiral models in observed spiral galaxies.

Key words: galaxies: kinematics and dynamics — galaxies: spiral — ISM: kinematics and dynamics — methods: numerical

1 Introduction

Spiral structures in galaxies have been interpreted as “standing waves” in a stellar disk (the quasi-stationary density wave hypothesis; Lin & Shu 1964; Bertin & Lin 1996). The density waves generate spiral perturbations and affect the gas flows. When the gas inside a corotation radius overtakes a spiral arm as it moves around a galactic disk, the gas is expected to form a standing shock, called a “galactic shock,” at the upstream side of the spiral arm (e.g., Fujimoto 1968; Roberts 1969; Shu et al. 1973). Since such a galactic shock strongly compresses the gas, the galactic spiral dust-lanes and the associated star formation around spiral arms have since been regarded as consequences of the galactic shocks. The galactic shock hypothesis qualitatively explains the CO–Hα offset distributions observed in some spiral galaxies such as M51 (e.g., Egusa et al. 2009; Louie et al. 2013). However, it is still unclear whether a spiral arm rotates with a single pattern speed for several rotational periods (i.e., ~1 Gyr), as predicted by the quasi-stationary density wave hypothesis.

In contrast, a transient spiral hypothesis was proposed in the 1960s (Goldreich & Lynden-Bell 1965; Julian &
This hypothesis has been extended to a transient recurrent spiral, “dynamic spiral”, hypothesis by N-body simulations of stellar disks (Dobbs & Baba 2014); the amplitudes of stellar spiral arms change on the time scale of galactic rotation or even less (i.e., a few hundreds of Myr; Sellwood & Carlberg 1984; Baba et al. 2009, 2013; Fuji et al. 2011; Sellwood 2011; Grand et al. 2012; D’Onghia et al. 2013; Pettitt et al. 2015), and the spiral at any given radius co-rotates with materials (Wada et al. 2011; Grand et al. 2012; Kawata et al. 2014). Fuji et al. (2011) revealed a self-regulating mechanism that maintains multi-arm spiral features for at least 10 Gyr. The “dynamic equilibrium” nature of stellar spiral arms can be attributed to their co-rotational nature (Baba et al. 2013). Furthermore, Dobbs and Bonnell (2008) and Wada, Baba, and Saitoh (2011) performed hydrodynamic simulations of the gas flows in dynamic spirals, and showed that gas does not flow through a spiral arm, but rather effectively falls into the spiral potential minimum from both sides of the arm, “large-scale colliding flows.” The dynamic spiral hypothesis is also supported by observations (e.g., Foyle et al. 2011; Ferreras et al. 2012).

Some observational tests for discriminating between quasi-stationary density waves (i.e., steady spirals) and dynamic spirals have been proposed (Dobbs & Baba 2014). In this paper, we propose a new indicator to discriminate between the two spiral models based on the radial distributions of arm–gas offset angles. The dust lane locations relative to a stellar spiral arm depend on the gas flow in the spiral galaxy. In the following sections, we demonstrate that the arm–gas offset distributions show different radial dependences between hydrodynamic simulations of steady spiral and dynamic spiral models. This difference suggests that measuring the radial distribution of the arm–gas offset angles can be a new observational means of distinguishing between the two spiral models.

2 Models and methods

We performed hydrodynamic simulations in rigidly rotating spiral potentials and N-body/hydrodynamic simulations of stellar and gas disks with the N-body/smoothed particle hydrodynamics (SPH) simulation code ASURA-2 (Saitoh & Makino 2009, 2010).

2.1 Steady spiral models

To simulate the gas flows in spiral galaxies with stationary density waves, we impose the rigidly rotating spiral potentials into the axisymmetric potential. The gravitational potential of the model galaxy consists of an axisymmetric and a non-axisymmetric (i.e., spiral) parts. The static axisymmetric part of the gravitational potential comprises a stellar disk, a spherical bulge and a halo. The initial radial distribution of the gas follows an exponential profile with a scale-length of ∼ 11 kpc, which is motivated by the observations of the Milky Way galaxy (e.g., Bigiel & Blitz 2012). Figure 1 shows the circular velocity curves of each component.

The gravitational potential of the spiral arm is given by

\[
\Phi_{\text{sp}}(R, \phi, z; t) = \frac{A(R, z)z_0}{\sqrt{z^2 + z_0^2}} \cos\left[m(\phi - \Omega_p t + \cot i_p \ln \frac{R}{R_0})\right],
\]

where \(A, m, i_p, \Omega_p,\) and \(z_0\) are the amplitude of the spiral potential, the number of stellar spiral arms, the pitch angle, the pattern speed, and the scale-height, respectively.

Fig. 1. Circular velocity curves of each component. In the cases of the rigidly rotating spiral arms, all components are assumed to be external potentials (section 3.1). For the case of the dynamically evolving barred-spiral, only the dark matter halo is treated as an external potential, but other components are solved by the N-body/SPH methods (section 3.2).
considered. The temperature of the gas is assumed to be $10^4$ K to effectively include a contribution of turbulent motions. This ISM model corresponds to that assumed in the classical galactic shock theory (e.g., Roberts 1969). The second series is hydrodynamic simulations with a more realistic ISM model, which includes the self-gravity, radiative cooling for a wide temperature range of $20 < T < 10^8$ K (Wada et al. 2009), heating due to far-ultraviolet radiation (Gerritsen & Icke 1997), star formation, and supernova feedback (Saio et al. 2008). The self-gravity is calculated by the Tree with GRAPE method with a software emulator of GRAPE, Phantom-GRAPE (Tanikawa et al. 2013). Model parameters are summarized in Table 1. The simulations are performed in a frame co-rotating with the spiral arms until $t = 350$ Myr. To avoid strong transients in the gas flows caused by a sudden introduction of the spiral potential, we increase its amplitude linearly from $t = 100$ to 200 Myr.

### 2.2 Dynamic spiral models

We performed 3D, high-resolution N-body/SPH simulations of a Milky Way-like galaxy model. An initial axisymmetric model of stellar and gaseous disks, a classical bulge embedded in a dark matter halo has the circular velocity curves of each component shown in figure 1. We take into account the self-gravity of the gas, cooling, heating, star formation, and supernova feedback (section 2.1). In this model, the stellar bar is developed by a bar instability (Ostriker & Peebles 1973; Efstathiou et al. 1982) at $t \approx 1.5$ Gyr. In this paper, we focus on the gas flows and spatial distributions in simulated unbarred ($t \approx 1$ Gyr) and barred ($t \approx 2.5$ Gyr) spiral galaxies.

### 3 Results

#### 3.1 Arm-gas offset angles in steady spirals

Our results show that the locations of galactic shocks strongly depend on radius. Figure 2 shows the radial distributions of the offset angle of the dense gas relative to the spiral potential, “the arm–gas offsets.” In the tightly winding, weak spiral case (Si10F02iso model; figure 2A), the galactic shock is located on the upstream side except for $R < 2$ kpc. This is consistent with the predictions made by the classical galactic shock theory (Roberts 1969). However, the galactic shock is away from the potential minimum and moves upstream if it is near the co-rotation radius ($R_{cr} = 10$ kpc). This is because the Mach number is a function of radius (e.g., Shu et al. 1973). Such radial dependence is consistent with Gittins and Clarke (2004), who found that the pitch angle of gaseous arms is smaller than that of stellar arms (see also Kim & Kim 2014).

### Table 1. Model parameters for the steady spiral models and properties of spiral arms in dynamic spiral models.

| Models      | $i_{sp}$ | $F$ | Gas self-gravity | ISM model   |
|-------------|----------|-----|------------------|-------------|
| Steady spirals |          |     |                  |             |
| Si10F02iso  | 10       | 2   | No               | Isothermal  |
| Si10F05iso  | 10       | 5   | No               | Isothermal  |
| Si20F05iso  | 20       | 5   | No               | Isothermal  |
| Si20F05msg  | 20       | 5   | Yes              | Multiphase  |
| Dynamic spirals |         |     |                  |             |
| DynUnBar    | $\sim 25$ | $\lesssim 5$ | Yes               | Multiphase  |
| DynBar      | $\sim 30$ | $\lesssim 8$ | Yes              | Multiphase  |

*Note that the “multiphase” ISM model includes cooling, heating, star formation and supernova feedback (see section 2 for details). For comparison, typical values of $i_{sp}$ and $F$ for dynamic spiral models are presented.

Fig. 2. Panels (A)–(D): the azimuth angle of the gas relative to the potential minimum ($\Delta \phi_{sp}$) as functions of radius for models with steady spirals at $t = 350$ Myr. The potential minimum of each radius is located at $\Delta \phi_{sp} = 0$. The negative value of an offset angle ($\Delta \phi_{sp} < 0$) corresponds to a leading side (i.e., downstream inside the co-rotating radius). The dotted (black) lines indicate the locations of shocks in the Si10F02iso model (panel A). The solid (green) lines indicate the locations of shocks in the Si10F05iso model (panel B). Panels (E) and (F): same as panels (A)–(D), but for dynamic spiral models at $t = 1.12$ Gyr (panel E) and 2.55 Gyr (panel F). The model galaxy is an “unbarred” grand-design spiral at $t < 1.5$ Gyr, but is a “barred” grand-design spiral after then (J. Baba et al. in preparation). The locations of the grand-design spirals are defined by the phases of the dominant Fourier modes (i.e., $m = 2$ or 3). The background gray-scale map presents a stellar density. The grand-design spiral is located at $\Delta \phi_{sp} = 0$. At $t = 2.55$ Gyr (panel F), a stellar bar is seen at $R < 3$ kpc. (Color online)
The radial trend of arm–gas offset angles in steady spirals depends qualitatively on neither the strength nor the pitch angle of the spiral. If we compare results with the different $\mathcal{F}$ models (figures 2A and 2B), the galactic shock locations in the Si10F05iso model are shifted farther downstream (see also Woodward 1975). Solid green lines in figures 2B and 2C indicate the locations of galactic shocks in the Si10F05iso model. The locations of galactic shocks in both models are almost the same. This is a natural consequence of the definition of $\mathcal{F}$. Note that the shocked layers in spiral potentials are not always dynamically stable, “wiggle instability.” This is consistent with the previous time-dependent, multi-dimensional hydrodynamic simulations (e.g., Wada & Koda 2004; Shetty & Ostriker 2006; Dobbs & Bonnell 2006; Kim et al. 2014). The physical origin of wiggle instabilities is a standing problem, although the wiggle instabilities result in the formation of substructures such as spurs in the inter-arm regions.

The steady spiral models with more realistic ISM models also show the similar radially dependent arm–gas offset angles. In figure 2D, we show the radial distribution of the arm–gas offsets for the Si20F05msg model, which include self-gravity of the gas, radiative cooling, heating, and stellar feedback. As suggested by Lee (2014), the self-gravity of the gas may shift the shock location downstream (Sawa 1977; Wada 2008), but a clear radial dependence of the arm–gas offset is still seen in the Si20F05msg model. This suggests that an arm–gas offset distribution does not depend on ISM modeling, but is essentially determined by the dynamical properties of the spiral arm.

### 3.2 Arm–gas offset angles in dynamic spirals

We investigate the dust-lane locations in dynamically evolving spiral arms. Figure 3 shows the $B$-band brightness distributions of stars with dust extinction at $t = 1.12$ and $t = 2.55$ Gyr. The model galaxy is an “unbarred” grand-design spiral at $t < 1.5$ Gyr, and then becomes a “barred” grand-design spiral. At $t = 2.55$ Gyr, a stellar bar is seen at $R < 3$ kpc. Properties of spirals are analyzed by using the 1D Fourier decomposition method as follows:

$$A_m(R) = \int_0^{\pi} \frac{\mu(R, \phi)}{\bar{\mu}(R)} e^{-im\phi} d\phi,$$

where $\mu(R, \phi)$ is the stellar mass distribution and $\bar{\mu}(R)$ is the azimuthally averaged surface stellar density at radius $R$, and $A_m(R)$ denotes a complex amplitude of the $m$th mode, respectively. We analyze angular positions and angular phase speeds of spiral arms with the Fourier density peak method (Wada et al. 2011; Roca-Fabrega et al. 2013).

The angular phase speeds of spiral arms in dynamic spiral models follow the galactic rotation at almost all radii or radially decrease (figure 3, bottom). This is similar to the simulated multi-armed spirals (e.g., Baba et al. 2013), as well as the simulated barred spirals (e.g., Grand et al. 2012), which have the radially dependent rotation of spiral arms, but slightly faster than the galactic rotation. This suggests that spiral arms even in barred galaxies could not be rigid-body rotating patterns predicted by the quasi-stationary density wave theory.

In contrast to the steady spiral models, we can clearly see that the dust lanes are along with stellar spiral arms in the dynamic spiral model (figure 3, top). As shown in figures 2E and 2F, the radial distributions of the arm–gas offset angle show no clear radial dependence in dynamic spiral models. This is because the gas does not flow through the spiral arm, and the gaseous arm remains until the stellar arm disperses (see also Dobbs & Bonnell 2008; Wada et al. 2011).
4 Discussion and summary

In this study, we performed numerical simulations with steady and dynamic spiral models and compared the locations of dense gas around spiral arms. The steady spiral models predict that the dust lanes are located downstream of the spiral arm in the inner regions and shift upstream of the spiral in the outer regions. In contrast, the dynamic spiral models show no systematic radial dependence of the arm–gas offsets, since the gas motions follow large-scale colliding flows to form spiral arms. Thus, our results suggest that a radial profile of arm–gas offset angle can be used to distinguish between the two spiral models.

To measure the radial distributions of arm–gas offsets, spatially-resolved wide-field maps of old stars and cold gas are required. Kendall, Kennicutt, and Clarke (2011) used stellar mass density maps and gas shocks traced by the Spitzer/IRAC 8-μm data, and investigated arm–gas offset profiles of nearby spiral galaxies. Forthcoming integral field spectroscopic surveys such as the MaNGA Survey (Bundy et al. 2015) and wide-field mapping by ALMA will provide us accurate, spatially resolved stellar and gas maps of nearby galaxies, and will facilitate discrimination between the two spiral theories.

However, we should note that the steady and dynamic models are not the only options. For example, Dobbs et al. (2010) presented a tidally induced spiral model in which the pattern speed is slower than the galactic rotation everywhere but decreases as a function of radius. In order to determine the nature of spiral structures in a spiral galaxy, a single test is not enough. Other methods, such as CO–Hα offset measurement (Egusa et al. 2009) and velocity-field modeling (Kuno & Nakai 1997; Miyamoto et al. 2014), are complementary to the test proposed in this paper.

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