Pattern speeds in interacting galaxies

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Abstract. We investigate pattern speeds in spiral galaxies where the structure is induced by an interaction with a companion galaxy. We perform calculations modeling the response of the stellar and/or gaseous components of a disc. Generally we do not find a unique pattern speed in these simulations, rather the pattern speed decreases with radius, and the pattern speed for individual spiral arms differ. The maximum pattern speed is \( \sim 20 \text{ km s}^{-1} \text{ kpc}^{-1} \) for the discs with a live stellar component, decreasing to \( 5 \text{ km s}^{-1} \text{ kpc}^{-1} \) at the edge of the spiral perturbation. When only the gas is modeled, \( \Omega_p \) is typically very low (5 km s\(^{-1}\) kpc\(^{-1}\)) at all radii.

Key words. galaxies: kinematics and dynamics – galaxies: interactions – galaxies: spiral – galaxies: structure – hydrodynamics – stellar dynamics

1. Introduction

Most grand design spiral patterns are believed to be due to interactions with other galaxies (Toomre & Toomre 1972), or are driven by bars (Kormendy & Norman 1979; Bottema 2003, Athanassoula et al., this volume). Here we investigate the first of these scenarios, by performing numerical simulations of interacting galaxies. In this instance, there is not necessarily a singular pattern speed for the spiral arms, as indicated by recent observations of M51 (Meidt et al. 2008a).

2. Method

We use the Smoothed Particle Hydrodynamics Code (SPH) to model a galaxy subject to an interaction. The first galaxy is modeled by assuming a spherical potential for the halo, with 3 different scenarios for the galactic disc: a) a live stellar disc, no gas; b) a logarithmic stellar potential and a live gaseous disc and c) a disc containing live gaseous and stellar components. The stars and/or gas are allocated velocities such that the Toomre instability parameter, \( Q \), is globally 2, but in addition, the galaxy was allowed to evolve in isolation until any flocculent structure disappears. In all simulations 1 million particles are used. For the case of stars and gas there are 500,000 gas particles and 500,000 stellar particles, and in all cases the total mass of the disc is \( 5 \times 10^9 \text{ M}_\odot \).

We adopt a similar approach to Oh et al. (2008) to model the interaction. The interacting galaxy is represented by a sink particle (Bate et al. 1995) and is of relatively low mass, equal to the mass of the disc or 2.5% of the total mass of the first galaxy. The interacting galaxy takes a parabolic orbit, reaching a closest approach of 25 kpc after a time of 370 Myr. Initially this galaxy is at a distance of 50 kpc.
3. Results

3.1. Stellar disc

Fig. 1 shows the column density of a stellar disc, at a time of 820 Myr. The interacting galaxy is 70 kpc from the centre of the plot. The spiral arms are relatively weak and broad.

We calculate the pattern speed of the spiral arms according to

$$\Omega_p = \frac{\phi(\rho_{\text{max}})_2 - \phi(\rho_{\text{max}})_1}{t_2 - t_1}$$

(1)

where $\rho_{\text{max}}$ is the peak density of a particular spiral arm at a given radius, and $t_1$ and $t_2$ are times during the simulation. First we select points covering a particular spiral arm at time $t_1 = 800$ Myr, when a strong spiral pattern has emerged. Then the azimuthal angle of the spiral arm is located for different radii. This process is repeated at time $t_2 = 925$ Myr, to obtain the change in azimuthal angle of the spiral arm at each radius, and thus $\Omega_p$. Given there are 2 spiral arms, this method leads to a pattern speed for each spiral arm. These pattern speeds are shown versus radius in Fig. 2, the
errors reflecting the uncertainty in locating the peak density of the spiral arm.

The magnitude of the pattern speeds are not dissimilar from some of those measured for spirals (e.g., Clemens & Alexander 2001; Grosbøl et al. 2006), although the spiral arms clearly exhibit different pattern speeds. This difference is a consequence of the asymmetry of the system, i.e. that the interaction induces one arm on one side of the disc first. The pattern speeds for each arm also decrease with radius, roughly as expected for spiral patterns induced by interactions.

3.2. Gaseous disc

We also performed calculations with just gas. The gas constitutes 1% of the mass of the galactic disc. This value is unrealistically small, but the low gas mass is chosen to avoid gravitational instabilities, which would halt the calculation. Essentially, we are only investigating the reaction of the gas to the interaction, not the self gravity of the gas. These calculations are also not a particularly realistic case as they ignore the perturbation experienced by the stellar disc from the interaction (instead the stellar disc is represented by a symmetric potential). However the case with just gas is explored for completeness.

In Fig. 3, we show the disc when only the gas is included, at the same time (800 Myr) as Fig. 1. The spiral arms are clearly much narrower, more prominent, and more dense than for the stellar disc. The evolution of the gas and stellar discs is also different. The gaseous spiral arms rotate much slower than the stellar arms. Consequently the pattern speed is very low, \( \sim 4 \text{ km s}^{-1} \text{ kpc}^{-1} \) and does not show much variation with radius (Fig. 4). The difference compared to the stellar disc is that one spiral arm is still linked to, and rotates at the same angular velocity as, the orbiting galaxy.

3.3. Evolving both the stars and gas

Finally we show calculations with gas and stars, again where the gas represents 1% of the mass of the stellar disc. Thus the mass of the stellar disc is \( 5 \times 10^9 \text{ M}_\odot \) and the gaseous disc \( 5 \times 10^8 \text{ M}_\odot \), although the actual number of gas and stellar particles in the calculation are equal. Fig. 5 shows the column den-
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Fig. 6. The pattern speed is shown for the gaseous arms, from the simulation with stars and gas. The gas is largely coupled to the stars, hence \( \Omega_p \) is higher than when only gas particles are present. Again there is a clear difference in the pattern speeds of each spiral arm.

Fig. 6. The pattern speed is shown for the gaseous arms, from the simulation with stars and gas. The gas is largely coupled to the stars, hence \( \Omega_p \) is higher than when only gas particles are present. Again there is a clear difference in the pattern speeds of each spiral arm.

The pattern speed across the disc is generally not constant, and pattern speeds in each arm differ. For a stellar disc, \( \Omega_p = 5 - 20 \) km s\(^{-1}\) kpc\(^{-1}\), decreasing with radius approximately as \( 1/r \). With only gas, the pattern speeds are much lower (3 – 6 km s\(^{-1}\) kpc\(^{-1}\)). When stars and gas are included, the gas tends to follow the stellar distribution, thus the pattern speeds of the gaseous spiral arms are higher (5 – 17 km s\(^{-1}\) kpc\(^{-1}\)).

These calculations may be improved by using a more consistent initial galaxy set up (e.g., Kuijken & Dubinski [1995]). A natural extension of this work would also be to compare with observations by applying the Tremaine-Weinberg (Tremaine & Weinberg [1984]) method to these calculations (see also Meidt et al., 2008).

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