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Comparing Gaseous and Stellar Orbits in a Spiral Potential

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Abstract. It is generally assumed that gas in a galactic disk follows closely non self-intersecting periodic stellar orbits. In order to test this common assumption, we have performed MHD simulations of a galactic-like disk under the influence of a spiral galactic potential. We also have calculated the actual orbit of a gas parcel and compared it to stable periodic stellar orbits in the same galactic potential and position. We found that the gaseous orbits approach periodic stellar orbits far from the major orbital resonances only. Gas orbits initialized at a given galactocentric distance but at different azimuths can be different, and scattering is conspicuous at certain galactocentric radii. Also, in contrast to the stellar behavior, near the 4:1 (or higher order) resonance the gas follows nearly circular orbits, with much shorter radial excursions than the stars. Also, since the gas does not settle into a steady state, the gaseous orbits do not necessarily close on themselves.

1. Introduction

Differences between stellar orbital dynamics and gas dynamics in disk galaxies play a fundamental role in the interpretation (or misinterpretation) of kinematics observations in order to deduce general physical properties of galaxies (see Gómez 2006, for example). It is frequently assumed that gas follows a path similar to non self-intersecting periodic stable stellar orbits. But, large scale gaseous and stellar flows should show distinct behaviors, since the gas suffers violent shocks and is sensitive to physical processes, like pressure gradients and magnetic fields, that do not affect the stars.

In this work, we show a direct comparison of stellar and gaseous orbits subjected to the same spiral potential. We calculated a set of MHD and particle simulations in the same axisymmetric + spiral arm potential. The MHD setup consists of a gaseous disk with an exponential density profile, initially in rotational equilibrium between the axisymmetric potential, the thermal and magnetic pressure gradients, and magnetic tension. The equilibrium is perturbed by the spiral potential described in Pichardo et al. (2003). The calculation is performed in the arm reference frame, which rotates with a pattern speed of $20\,\mathrm{km\,s^{-1}\,kpc^{-1}}$. After the simulation is started, the gas rapidly settles into a spiral pattern, with two arms with a pitch angle of $\sim 9^{\mathrm{o}}$ up to the inner Lindblad

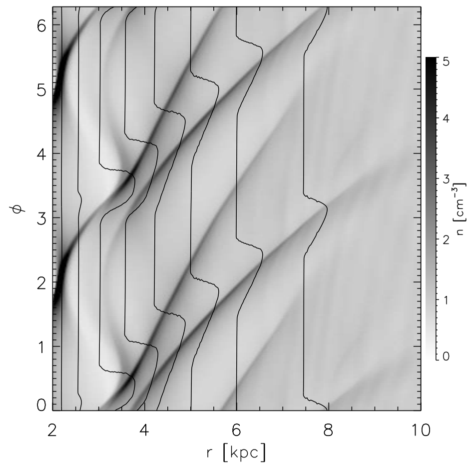

Figure 1. Comparison of stellar (*contours*) and gas density (*grayscale*) 1 Gyr into the simulation. The stellar density is that corresponding to the background + spiral arms potential. The gas in the simulation forms 4 arms, as opposed to the two arms in the perturbation. Also, the gaseous arms have a smaller pitch angle.

resonance (ILR), and two pairs of spiral arms with $\sim 9^{o}$ and $\sim 13^{o}$ between the ILR and the 4:1 resonance, even though the spiral perturbation has a pitch of 15.5^{o}

It is noticeable an instability in corotation which develops 2.8 Gyr into the simulation. It is present in a variety of MHD simulations performed, but absent in the purely hydrodynamical ones.

2. Stellar and gas orbits

Figure 2 shows some of the orbits obtained, both for the stars and gas, in between the resonant radii. Although the gaseous orbits are complex and sensitive to the position chosen to start the integration, in the regions away from the major resonances they all show a similar evolution. In the region where only two gaseous arms are present, the gaseous and stellar orbits are similar in shape and radial range spanned. But, as the second pair of gaseous arms appear, the orbit shapes start to differ. As opposed to stars, gas may change direction rapidly by developing shocks, which generate pressure gradients that distort the path the gas may follow if subjected to gravitational forces only.

Figure 3 shows some of the orbits calculated near the major resonances. The gas is unable to follow the large departures from circularity present in the stellar orbits. For example, near the 4:1 resonance, the stellar orbit might span more than a kpc in radial excursions, while the gas remains close to the circular orbit, with a radial deviation of the order of 200 pc, although the deviations are such that allow for the gaseous arms to extend beyond this resonance, as opposed to the stellar arms.

It is also noticeable that the gaseous orbits show some dispersion. This is so because the numerical simulation does not really reach a steady state. The gaseous arms

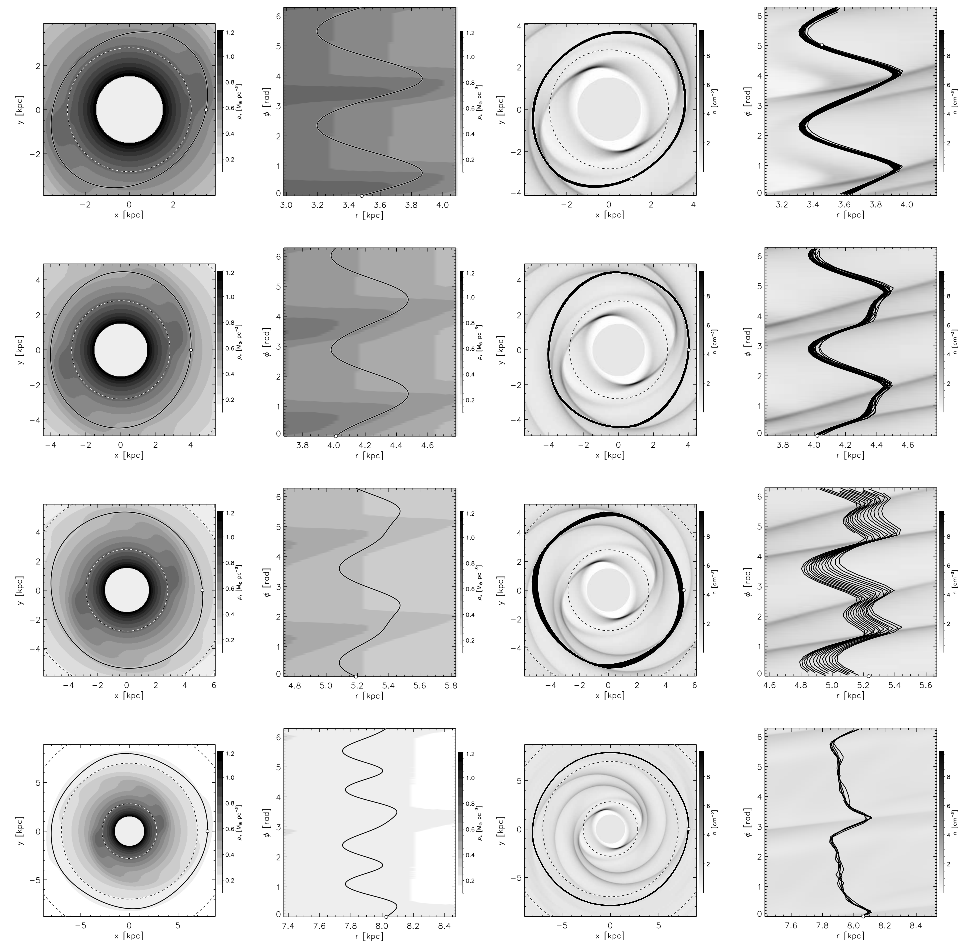

Figure 2. Comparison of stellar and gaseous orbits between resonances. The first two columns show the stellar orbits in $x-y$ (*first column*) and $r-\phi$ (*second column*) space. The grayscale shows the stellar mass density corresponding to the background plus the spiral arm potentials. The last two columns show the gaseous orbits, again in $x-y$ (*third column*) and $r-\phi$ (*fourth column*) space, plotted over the gas density from the simulation. The initial position for the integration of the orbits is marked by the small open circle. Since the model corresponds to a trailing spiral, the gas rotates clockwise in the cartesian plots, and down from the top in the polar ones. The inner Lindblad, 4:1 and corotation resonances are also shown (*dashed circles*).

in the simulation oscillate slightly around the positions quoted above. This means that the gaseous orbits does not necessarily close on themselves, i.e., the gaseous orbits are not periodic. This should not be surprising, since periodic orbits should be expected in steady state only.

Excluding the cusps due to large scale shocks (not present in stellar orbits), the gaseous and stellar orbits are more similar in the regions in between resonances, when the stars follow rounder paths, with smaller radial excursions. Near the resonances, the stars follow orbits with regions of small curvature radius, that a gas parcel cannot follow. The gas, therefore, either looses angular momentum and migrates away from

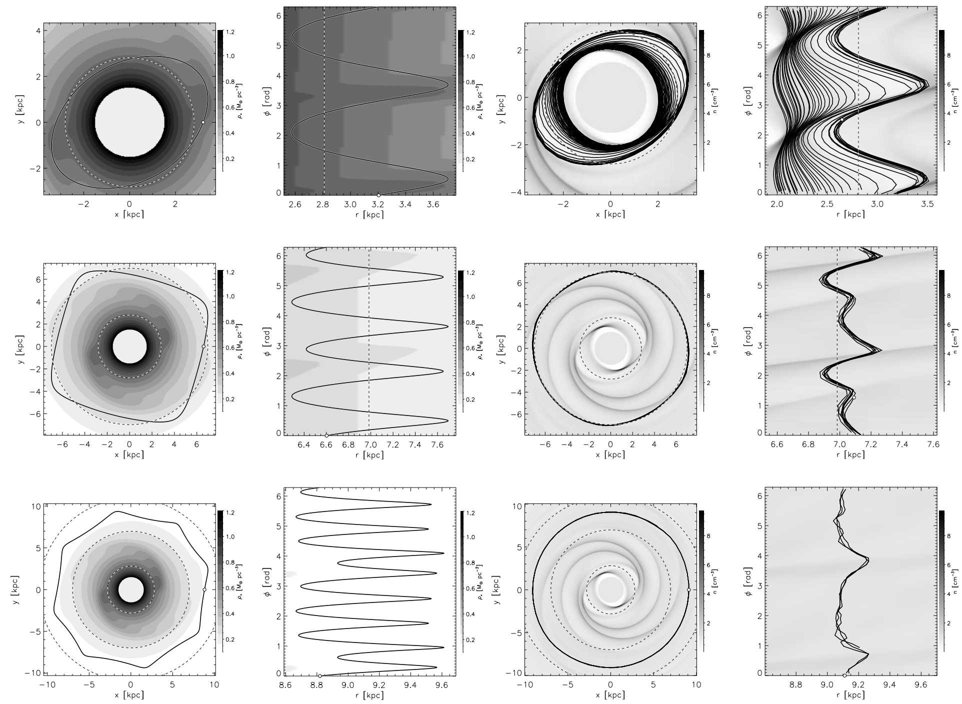

Figure 3. Similar to fig. 2, for orbits near resonances.

the resonance (top row in fig. 3) or settles into a rounder orbit (middle and bottom rows in the same figure). The gravitational resonances are still present, so the velocity along the orbit is not uniform and pressure waves are formed, which allow the spiral arm to extend beyond the resonant radius.

Since the spiral structure of the Milky Way is well fitted by four arms in the gas and two in stars, the paths that these components follow cannot be the same. Even if gravity is the dominant force in galactic dynamics, other physical processes may have an important impact on the formation of structure.

Further details may be found in Gómez, Pichardo, & Martos (2013).

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