Simulations of Gas Flow from a Galactic Disk to the BH-dominated Central Disk

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Abstract. With a help of hydrodynamical models, we explore fundamental modes of gas flow in central parts of a galaxy potential with non-axisymmetric perturbations of various strengths. Our grid-based algorithm allows us to get a detailed picture of gas dynamics down to about 10 pc from the galaxy center, where the central black hole becomes dominant. Gas inflow in a bar with an Inner Lindblad Resonance often stops at the nuclear ring. We find that embedded bars in resonant coupling are unlikely to increase the inflow, but for certain gas parameters in a single bar, inflow to the center develops in a spiral shock, similar to the patterns observed in nuclear discs of real galaxies. The spiral pattern persists for very weak non-axisymmetries of the potential.

1. Introduction

Interstellar gas falls towards the center of a galaxy if torques act on it and remove its angular momentum. On scales larger than several parsecs, gravitational torques from non-axisymmetric mass distribution in stars dominate. They can be caused by external factors (interactions and mergers) or internal ones (bars and other results of disk instabilities). Here, we focus on gas flow in barred galactic potentials: if the bar is strong enough, the $x_1$ orbits aligned with it develop cusps at their apocenters, and gas clouds there run onto each other, causing shocks. The shocked gas loses angular momentum to the bar, and a considerable inflow occurs at radii where shocks are present. In a bar with an Inner Lindblad Resonance (ILR), orbiting gas shifts gradually from $x_1$ to $x_2$ orbits, and eventually settles in a nuclear ring, located approximately at the bar’s ILR, at a radius of order 1 kpc.

Accumulation of gas in the nuclear ring may trigger a nuclear starburst, but Active Galactic Nuclei (AGN) require mass accretion to within a few parsecs of the galaxy center. A mechanism of bars within bars has been proposed to drive further inflow, and thus feed the AGN in a manner similar to the inflow on large scales (Shlosman, Frank & Begelman 1989). In its original form, it involved a cascade of nested, independently rotating gaseous bars, with the inner bar forming as a result of dynamical instability in the gaseous nuclear disk. Such instability develops rapidly, and may cause a significant inflow, but one should not expect well-ordered flow morphology there. On the other hand, bars within bars observed in the stellar component of galaxies are likely to be of different
nature: even if they form as an effect of gravitational instability, their motion is well-ordered, and their lifetime longer.

Here we present some preliminary results on fundamental modes of gas flow in strong single and double bars, and in weak oval distortions, and we examine how efficient they can be in feeding the nucleus. We give a comprehensive account of this work elsewhere (Maciejewski et al. 2001).

2. Numerical code, potential and initial conditions

We used the grid-based Eulerian hydrodynamical code CMHOG, written by James M. Stone at the University of Maryland and adopted to the polar grid in two dimensions, with isothermal equation of state, by Piner et al. (1995). The code implements the piecewise parabolic method (PPM), and the use of square cells gives high resolution at the center: up to 0.4 pc at the radius of 20 pc. Self-gravity of gas is neglected, and the numerical viscosity is very low — the infall to the center is negligible in an axisymmetric potential for timescales considered here.

The grid extends from 20 or 100 pc to 16 kpc in radius, and the gas flow is followed in a potential of Model 2 of a doubly barred galaxy constructed by Maciejewski & Sparke (2000). Azimuthal averaging of the secondary bar gives our potential of a singly-barred galaxy. The semi-major axis of the main bar is 6 kpc with a rotation period of 0.171 Gyr; the corresponding values for the secondary bar are 1.2 kpc and 0.056 Gyr. Gas is initially distributed uniformly over the grid, and forced to rotate around the center with the circular velocity in the azimuthally averaged potential. Then the outer bar of Model 2 is introduced by gradual transfer of mass from the bulge. In runs with double bars, the secondary bar is introduced in the same way, after the flow in the primary bar has stabilized.

3. Gas inflow in single and double bar compared

General features of gas flow in a single strong, fast-rotating bar with two ILRs can be seen in Fig.1, with shocks showing up best in the square of velocity divergence in the gas (div$^2$ v, div v < 0). Gas loses angular momentum in the principal shocks (PS) along the leading sides of the bar and falls towards the center. Inside the ILR (i.e. between the inner and outer ILR) a gaseous nuclear ring (NR) forms, and the inflow stagnates there, with star formation likely. A weak spiral density wave propagates inwards from the nuclear ring, but the rate of gas inflow to the center is very small: less than $10^{-4}$ $M_\odot$/yr.

By extending the concept of multiple gaseous bars proposed by Shlosman et al. (1989) to the stellar bars, it is thought that the secondary bar may force gas deeper into the potential well, if gas flow in the secondary bar is analogous to the one above. To verify this view, Maciejewski & Sparke (2000) constructed a model of a dynamically possible doubly barred galaxy. They started with the potentials of two rigid, independently rotating bars embedded in a disk and halo, and searched for particle distributions that could support the assumed potential. Despite the absence of a conserved Jacobi integral in this system, the orbits are not mostly chaotic. Particle motions appear well-ordered, if one
looks not at orbits, but at sets of particles forming closed curves which return to their original position after two bars realign. These sets (called here loops) are equivalent to orbits in a time-independent potential.

In a doubly barred system there are loops that follow the outer bar in its motion, and other ones that follow the inner bar. In the model with resonant coupling (corotation of the small bar matches the outer ILR of the main one) that we consider here, loops supporting the secondary bar in its motion do not extend out to the outer ILR of the main bar, forcing the secondary bar to end well inside its corotation. The requirement of self-consistency puts strict limits on parameters of acceptable double bars, and rules out many hypothetical doubly-barred systems as being far from self-consistent. It is essential to examine gas flows in a dynamically possible model: modeling gas flows in arbitrary potentials of double bars may be misleading, as we do not know if such double bars can exist.

Fig. 2 shows that outer regions of gas flow remain unaffected by the introduction of the secondary bar: the principal shock retains its shape and position. The secondary bar affects the central regions most strongly, but no stationary straight dust lanes form there. Rather, the flow organizes into various elliptical and circular rings, with mass accumulating first at the twin peaks at the ends of the secondary bar, and then settling in an inner elliptical ring. Gas inflow to the center remains very small: it averages about $3 \times 10^{-5} \, M_\odot / \text{yr}$.

It is easy to understand this modeled flow in terms of the underlying orbital structure. In a double bar gas stays around stable loops, and loops supporting the secondary bar end well inside its corotation. However, straight shocks form only in a bar extending almost to its corotation (i.e. fast bar, Athanassoula
Figure 2. Three snapshots of gas flow in the model of a doubly barred galaxy, with density on the top and $div^2\mathbf{v}$ on the bottom. The times are 0.695 Gyr (left), 0.780 Gyr (middle), and 2 Gyr (right). The primary bar is always vertical, and the secondary bar is outlined by the solid line. Dotted lines indicate (innermost out) positions of the inner ILR of the main bar, the maximum of the $\Omega - \kappa/2$ curve at 0.55 kpc (where the secondary bar is close to having an ILR), the outer ILR of the main bar, and corotation of the secondary bar at 2.19 kpc.

Therefore, what would be a straight shock in a fast bar, here curls and forms a ring instead. Also, no loops corresponding to $x_2$ orbits in the secondary bar have been found, thus one should not expect offset shocks. Finally, loops supporting the secondary bar originate from the $x_2$ orbits in the main bar — they are rather round, with no cusps, so there is no reason for shocks in the gas flow to develop. Thus, some self-consistent doubly barred galaxies may lack principal shocks and dust lanes, and double bars may not provide an efficient mechanism for fueling gas into the galactic center. Observations support this finding: infrared color maps of Seyfert galaxy centers (Regan & Mulchaey 1999) show no symmetric straight dust lanes unrelated to the main bar, and the only doubly barred galaxy in the sample (NGC 3081) differs from the rest by having a central ring flattened along the secondary bar.

4. Feeding the nucleus with a dynamically warm dissipative medium

Regan & Mulchaey (1999) and Martini & Pogge (1999) report an unexpectedly high frequency of nuclear spiral patterns in their samples of Seyfert 2 galaxies.
Englmaier & Shlosman (2000) found nuclear spirals in their models for some combinations of the potential and gas sound speed. Their spirals are weak and can be described by a linear wave theory.

We modeled gas flow in the same singly-barred potential as in Fig.1, with the sound speed in gas increased from 5 to 20 km s\(^{-1}\). Although the principal shock persists, the nuclear ring is replaced by a nuclear spiral (Fig.3), with \(\text{div}^2\mathbf{v}\) half that of the principal shock: in this model, gas falls towards the center in a spiral shock. Our potential has an inner ILR, but the shock extends further inwards, reaching the inner grid boundary at the 20 pc radius. The inflow to the center is very large, up to 0.15 \(M_\odot\)/yr, which is enough to power a weak AGN, although the evolution after the shock crosses the grid boundary should be interpreted with caution.

5. Gas inflow in a weak bar

We investigated how much the strong inflow for high sound speed decreases if we weaken the bar. A new potential was set up, differing from the one above by the quadrupole moment of the bar being 10 times smaller, and the bar’s axial ratio lowered from 2.5 to 1.5. Although no feature similar to the straight principal shocks in a strong bar is present in the flow, a nuclear spiral still forms inside the ILR (Fig.4, left). One should expect a flow like this, since the \(x_1\) orbits supporting the weak bar in this model are round, with no cusps, and thus do not induce shocks in gas. Inside the ILR, as in the strong bar, gas on \(x_1\) and \(x_2\) orbits interacts, giving rise to the spiral structure. The arm-interarm density contrast of the spiral is much lower than in the case of a strong bar, and linear theory is sufficient to describe the gas flow: the spiral pattern does not extend to the galaxy center (Fig.4, center). Adding a central black hole (or mass concentration) removes the inner ILR, and allows the spiral pattern extend to the center (Fig.4, right). Surprisingly, this does not increase the inflow, which is small in both cases — below 0.005 \(M_\odot\)/yr.
6. Conclusions

We have investigated basic modes of gas flow in the central parts of galaxies by focusing on isothermal, non-selfgravitating fluid in an external potential. Later on, one can add other physical mechanisms (self-gravity, star formation, magnetic fields) which will build on this picture, and avoid confusion often caused by heuristic explanations that include many physical mechanisms in a simplified way.

In the fixed potential of a single bar, various modes of gas flow can develop, some of which are able to sustain the fueling of an AGN. In a mode with low sound speed, a single strong bar with an ILR can be very inefficient in feeding the nucleus. Adding an embedded secondary bar may not increase the inflow, but if the sound speed in the nuclear gas is high, a spiral shock develops in a single strong bar, resulting in an inflow large enough to feed an AGN. The shock in a strong bar corresponds to a nuclear spiral in a weak bar, but gas inflow there is too small to feed an AGN.

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