

3D Barred Model of the Milky Way Including Gas

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Abstract. We present a 3D N-body simulation of the Milky Way including 4×10^5 star- and dark-like particles and 2×10^4 gas particles, initially distributed according to an axisymmetric, observationally constrained, mass model. The whole system is self-gravitating and the gas hydrodynamics is solved using the SPH method. The simulation leads to the spontaneous formation of a central bar that strongly affects the gas dynamics. We compute $(l - V)$ diagrams for both the gaseous and the stellar particles as a function of the angle of the bar with respect to the observer and compare the results for the gas with HI and CO observations.

1. Introduction

Since the first direct evidences for the Galactic bar (Blitz & Spergel 1991; Weinberg 1992), gas and stellar dynamics in the Milky Way have experienced a clear renewal of interest. Several new photometric and kinematic data have already been or are on the way to be used to constrain analytical triaxial bulge models (e.g. Stanek, these proceedings). By performing numerical simulations, the problem can be tackled differently: time sampled snapshots of the numerical galaxy can be compared to the observations varying various model parameters (see e.g. Wada et al. 1994). Invaluable information can then be inferred concerning quantities hard to observe, like the bar pattern speed. Nevertheless, so far none of the dynamical models have included in a completely self-consistent way three dimensional gaseous, stellar, and dark components. This is however a prerequisite to highlight various global asymmetries or instabilities, or if the evolution of the model needs to be followed for Gyrs since secular evolution processes are especially active in barred galaxies (see e.g. Martinet 1995).

2. Initial Conditions

Our initial axisymmetric 3D mass distribution includes four components (see Table 1): an exponential stellar disk of constant thickness, a composite power-law stellar nucleus-spheroid (NS), a dark halo (DH) to ensure an almost flat rotation curve out to about 30 kpc, and a dissipative gas component consisting of a kind of smoothly truncated Mestel disk with a central core and an outward linearly increasing scale height. The gas mass inside the solar circle is $4.1 \cdot 10^9 M_{\odot}$. The parameters of this mass model have been adjusted to several observational constraints, like the rotation curve and local mass densities, assuming $R_0 = 8$ kpc.

Table 1. Initial mass model of the simulation. The oblate NS and DH have a common axis ratio $e = 0.5$.

Components	# particles	Space density	Parameters
Disk	150,000	$\propto \exp(-R/h_R) \cdot \text{sech}(z/h_z)$	$h_R = 2.5$ kpc $h_z = 250$ pc $M = 4.4 \cdot 10^{10} M_\odot$
NS	50,000	$\propto \frac{m^p}{1 + m^{p-q}},$ $m^2 = (R^2 + z^2/e^2)/a^2$	$p = -1.8, q = -3.3$ $a = 1$ kpc $M = 3.0 \cdot 10^{10} M_\odot$
DH	200,000	$\propto \exp(-\mu),$ $\mu^2 = (R^2 + z^2/e^2)/b^2$	$b = 9.4$ kpc $M = 3.1 \cdot 10^{11} M_\odot$
Gas	20,000	$\propto \frac{1}{R\sqrt{R^2+h_g^2}} \exp(-\frac{3}{2}\frac{R^2}{R_g^2} - \frac{1}{2}\frac{z^2}{s^2R^2})$	$s = 0.017$ $h_g = \frac{1}{2}(h_R + b)$ $R_g = 20$ kpc $M = 1.13 \cdot 10^{10} M_\odot$

To each of the stellar and dark components is assigned an individual isotropic Maxwellian velocity distribution such that the velocity dispersion and the mean azimuthal velocity (no streaming motion in other directions) satisfy the Jeans equations. Initially, the gas particles have circular velocities and a uniform sound speed of 10 km s^{-1} , providing only a rough hydrostatic equilibrium. The non-inclusion of star formation presently is the strongest limitation of the model.

3. Time Evolution

The system has been integrated for 2.6 Gyr using the PM method on a polar-cylindrical grid to compute the gravitational forces (Pfenniger & Friedli 1993) and the Lagrangian SPH technique (see e.g. Benz 1990) with isothermal internal energy to compute the pressure and viscous forces acting on the gas. The central radial resolution of the grid is 38 pc and the gas smoothing length near the center is of the same order. The time integrator is a synchronized leap-frog with an adaptive time-step $\Delta t \leq 0.1$ Myr able to fully resolve shocks (variable Δt in time but constant for all particles). *The evolution is completely self-consistent and free from any imposed symmetry.*

The simulation, illustrated in Figure 1, leads to a growing central bar after about 1 Gyr, while $m = 1$ modes appear in the stellar disk. The bar itself never really behaves like a bi-symmetric solid rotating body, but instead undergoes many asymmetrical distortions, particularly strong during its first rotations. Such perturbations also induce irregular gas flows (like the one-side void inside 3 kpc occurring at $t = 1.5$ Gyr) capable of producing peculiar signatures in the gaseous ($l - V$) diagrams. The gas particles near the center condense into a nuclear ring which progressively shrinks and finally forms a small disk of about 300 pc radius. In this process, the ring suffers several instabilities, like tilting, warping and off-centering. There is also an increasing central gas core accreting

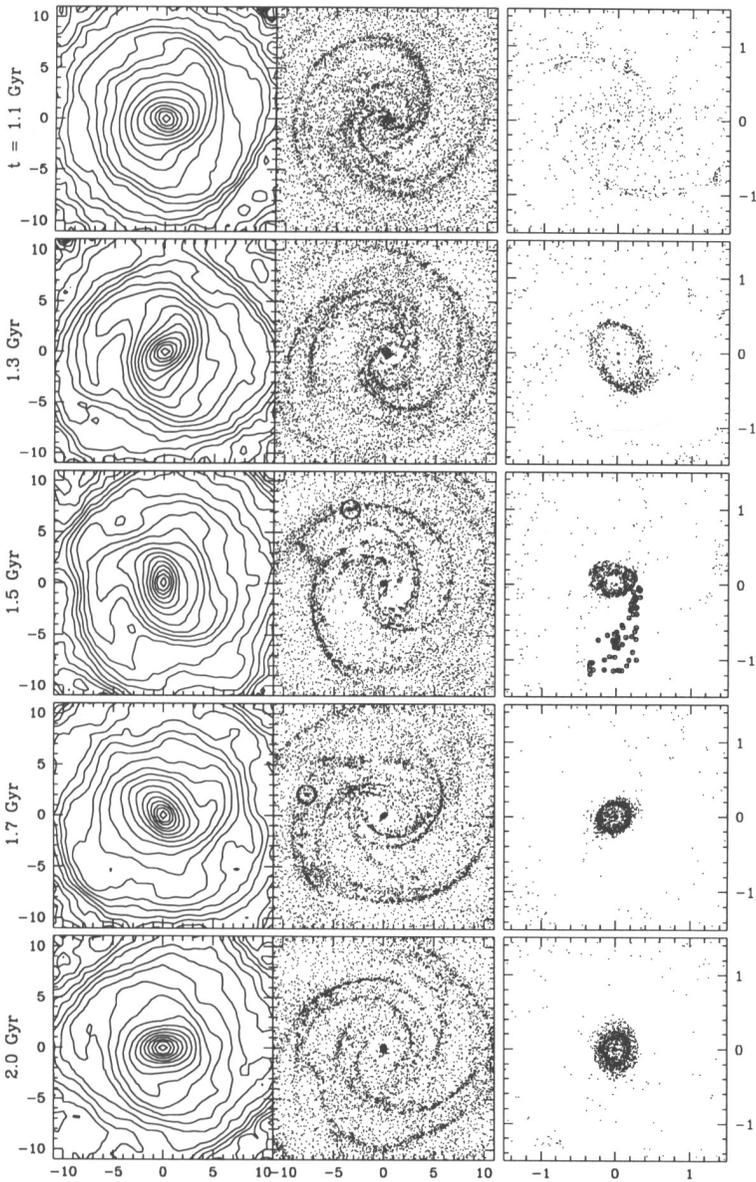


Figure 1. Face-on configuration of the visible components at various times. Left: stellar (disk+NS) isodensity curves. Middle: gas particles, same scale. The position of the observer in Figures 2d and 3b is indicated by a solid circle. Right: zoom on the central gas. The encircled dots at 1.5 Gyr show the particles responsible for the elongated strip in Figure 3b. The length unit is 1 kpc.

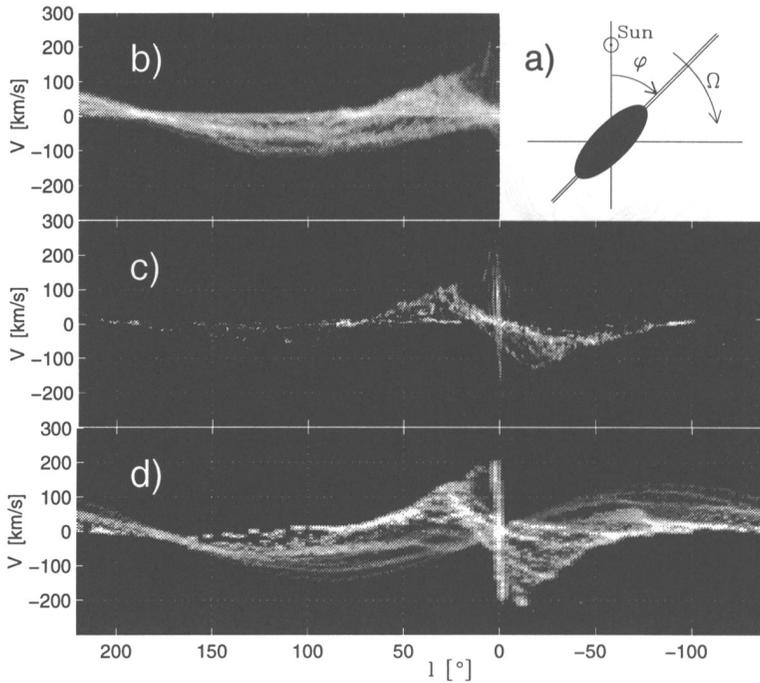


Figure 2. a) Definition of the angle φ of the bar relative to the observer. φ is positive in the direction of rotation. b) HI $(l-V)$ map for $0 \leq l \leq 220^\circ$ (Hartman & Burton 1995). c) CO $(l-V)$ map (Dame et al. 1987). d) Distance weighted $(l-V)$ diagram from the simulation at $t = 1.7$ Gyr and for $\varphi \approx 30^\circ$. All $(l-V)$ plots are averaged over $|b| < 2.25^\circ$. Higher density regions are whiter.

gas from the nuclear ring/disk. The final properties of the bar are a semi-major axis $a \approx 3.5$ kpc, an axis ratio $b/a \approx 0.6 - 0.7$ and a pattern speed $\Omega_p \approx 50$ km s⁻¹ kpc⁻¹, locating the CR around 4 kpc, the ILR slightly outside 1 kpc and the OLR close to 7 kpc. A comparison with symmetrized simulations (i.e. imposed reflection symmetries about the z -axis and the $z = 0$ plane) without gas (Fux et al. 1995) and with gas indicates that the imposed symmetries generate more extended bars, whereas the presence of gas makes them slightly rounder.

4. Gaseous $(l-V)$ Diagrams

For the moment, the longitude-velocity diagrams of the gas particles have only been explored every 100 Myr, as a function of the relative angle φ of the bar with respect to the observer located at $R = R_o$ (see Figure 2a). It comes out that for a given angle φ , these diagrams are time-dependent. Moreover, for each value of φ there is a modulo π choice in orienting the bar, allowing for two possible $(l-V)$ diagrams. These would look identical under reflexion symmetry about the z -axis, but can appear very different in our symmetry-free case.

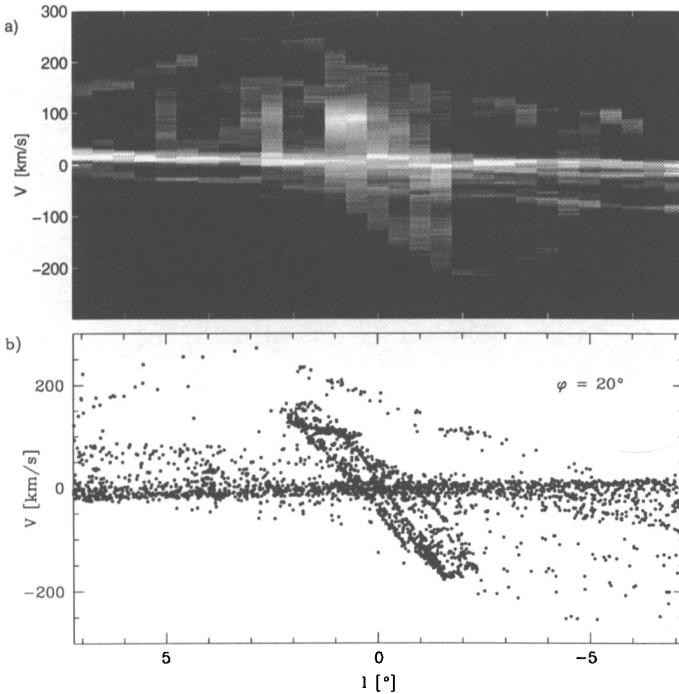


Figure 3. a) Details of the CO ($l - V$) map in the Galactic central region. Note the positive high velocity emission strip reaching very negative longitudes. b) Gaseous ($l - V$) plot available from the simulation at $t = 1.5$ Gyr and with $\varphi \approx 20^\circ$, restricted to the gas particles inside $|b| < 2.25^\circ$; this most resembles the CO ($l - V$) map.

When computing ($l - V$) diagrams over a large longitude range in order to confront them with observations, one should weight the contribution of each particle by its inverse squared distance relative to the observer. Figure 2 shows such a diagram for a realistic position angle of the bar at a time where similarities with the observed HI and CO maps clearly emerge. The gas in our simulation can be considered as a mixture of atomic and molecular gas.

A well-known puzzling feature in the observed ($l - V$) data around the Galactic center is the presence of gas in regions forbidden to pure circular motion. Part of it can be explained by the signature of bar-elongated x_1 or anti-bar x_2 periodic orbits (Binney et al. 1991) or by more sophisticated gas flow modeling (Mulder & Liem 1986; Jenkins & Binney 1994) in a fixed bar potential. However, these approaches do not account for the intriguing gas strip at $V \leq 100 \text{ km s}^{-1}$ extending in the negative longitude region down to about $l = -5^\circ$ (see Figure 3a). Our simulation displays at least once such a peculiarity, as shown in Figure 3b. The spatial positions of the gas particles populating the “forbidden” strip in this figure are highlighted in Figure 1. A closer look to the simulation reveals that these particles were previously strongly shocked near the bar end, then

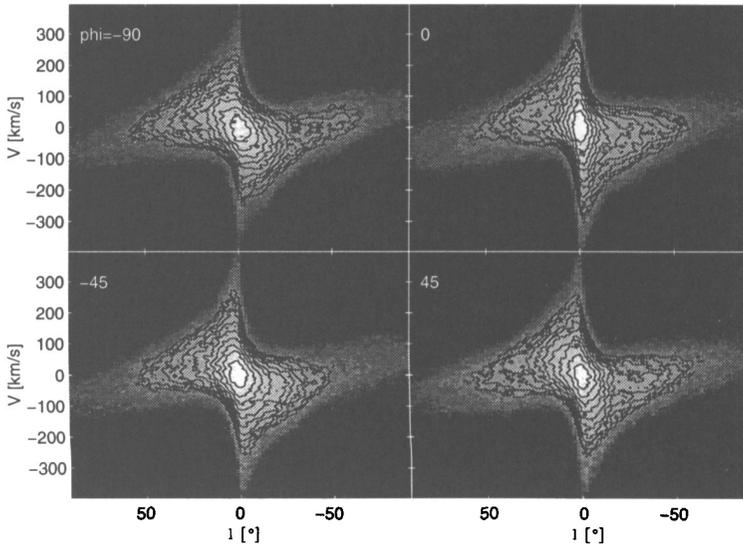


Figure 4. Distance unweighted ($l - V$) diagram of the stellar disk as a function of φ at $t = 2.5$ Gyr, averaged over all b . Diagrams for φ and $\varphi + \pi$ have been added together to reduce noise.

quickly fell toward the center to finally overtake it with high positive radial velocities. Clearly, the high degree of asymmetry displayed by the observations and achieved here, for instance at $t = 1.5$ Gyr, cannot occur in standard bi-symmetric bar models.

5. Stellar ($l - V$) Diagrams

Constraining the bar properties using stellar ($l - V$) diagrams will probably prove to be at least as powerful as the methods based on gas dynamics. Since observations in this field mainly rely on star counts, corresponding model diagrams do not have to take into account a distance weighting factor as for the gas. Figure 4 gives a first example of what can be expected from such diagrams. The signatures obviously depend on the bar orientation. A detailed confrontation with observations will be published elsewhere.

6. Conclusion

A fully consistent numerical 3D barred model of the Milky Way in good qualitative agreement with HI and CO kinematic observations at both small and large longitudes has been presented. In particular, morphological and kinematical asymmetries naturally occur during the simulation which are able to reproduce the high velocity CO feature at negative longitudes in the ($l - V$) diagram.

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Discussion

D. Christodoulou: Your simulations run for just a few Gyrs. If you managed to take it to 15 Gyr, which of the features would you expect to survive (bar, spirals, nuclear ring)? How much mass is accumulated in the nuclear ring?

R. Fux: Integration over a Hubble time would be unrealistic because the initial conditions mimic the *present* state of the Milky Way and the absence of star formation favor the growing of the central gas concentration, thus shortening the life-time of the bar. At 1.5 Gyr, the ring mass is about $6 \times 10^8 M_{\odot}$.

K. Stanek: Is your evolved disk similar to the real disk of the Galaxy (i.e. scale height, velocity ellipsoid, etc.)?

R. Fux: At $t = 1.5$ Gyr, the scale height of the stellar disk is about 350 pc outside corotation and its maximum l.o.s. velocity dispersion towards Baade's Window about 130 km s^{-1} . Its velocity ellipsoid has become spontaneously anisotropic with local velocity dispersions close to the observed ones for the Galactic old disk.

P. Teuben: To what extent are the features like a tilted or offset nuclear disk due to \sqrt{N} -noise, or robust. Is the tilt related to vertical instability strip?

R. Fux: They are robust with a density contrast far above the one resulting from noise fluctuations. A vertical instability strip does exist, but we haven't yet checked that the associated orbit families are consistent with the tilt morphology.