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The Wavy-Pattern of Stellar Rotation Curves in SB0 Galaxies

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Abstract. We discuss the "rotation" curves of SB0 galaxies with self-consistent models constructed with Schwarzschild's method. Their distribution functions are compared with that of N-body simulations.

1. Introduction

The observed stellar rotation curves of early-type barred galaxies generally display similar "wavy-patterns" with a line-of-sight velocity (LOSV) minimum well inside the bar (Bettoni 1989). A few galaxies show counterrotation in the region of this minimum (cf. Galletta, these proceedings). It is unclear whether such counterrotation could be due to the projection of the velocity field of elliptical streamlines, or to actual retrograde orbits. Bettoni reported the attempt to project the N-body model of Sparke & Sellwood (1987) so as to fit observed rotation curves with the theoretical one. Although the solution is not unique, projection effects seem to dominate. However, as N-body simulations show a large amount of retrograde motion in the bar rotating frame, it has not been checked that models with much less or without any retrograde orbits could also explain partial counterrotation.

In order to untangle the effects of retrograde orbits in the bar and those of the projection onto the plane of the sky, we have computed rotation curves from self-consistent models of barred galaxies. The extreme amounts of retrograde orbits in these models can vary from 14 to 30%.

2. Self-consistent Models

Self-consistent models are constructed using Schwarzschild's method (1979). Improvements follow those introduced by Pfenniger (1984) and Wozniak & Pfenniger (1996). As we do not plan to reproduce the exact shape of the rotation curve for a given observed galaxy, we prefer to use a general mass model which allows more freedom. The mass model used by Pfenniger (1984) is thus suited to our purpose.

Several self-consistent models have been obtained by extremizing an objective function. Figure 1 shows the velocity fields of three models: 1) Min(E) which minimizes the total energy $E = H + \Omega_p L_z$ (H is the total Hamiltonian and Ω_p the bar pattern speed), 2) Max(E) which maximizes E, and 3) Min($|L_z|$) which minimizes the z-angular momentum $|L_z|$.

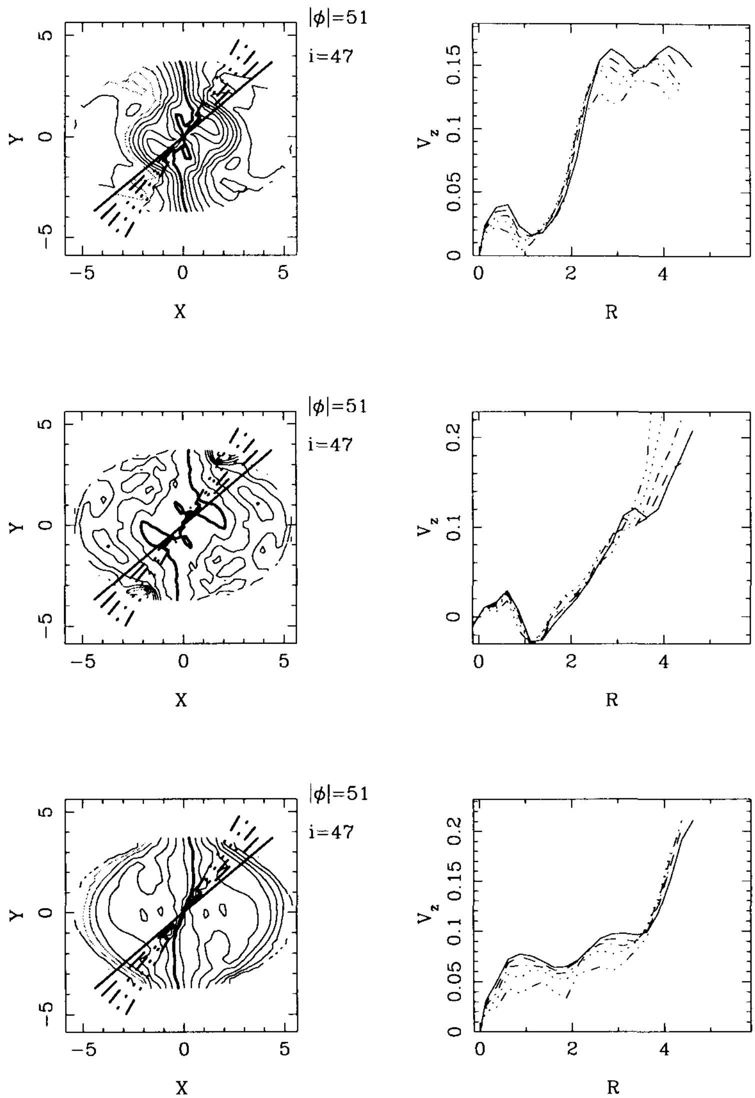

Figure 1. On left panels iso-velocities of the projected velocity fields are displayed for Max(E) (top), Min(E) (middle) and Min($|L_z|$) (bottom) models. Zero velocity curve is the thick line. Five positions of a "spectrograph slit" are also shown. They give LOSV curves displayed on right panels. The bar-disk angle ϕ and the inclination angle i match the values for NGC 2983. Velocities are scaled to the velocity at corotation in the plane of the model.

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3. Velocity Fields

The velocity fields produced by these models have been projected onto the plane of the sky using the position-angle (PA) of the bar and inclination angle of several SB0 galaxies (Bettoni 1989). To illustrate our discussion, we choose the values that match the case of NGC 2983 (Bettoni et al. 1988). In the plane of the model, the corotation (i.e. the end of the bar) is located at $r = 6$. The LOSV curves are obtained from five positions of a simulated spectrograph slit, 0.25 units wide, which corresponds to 1.1″ for NGC 2983. The angles of the slit are -10, -5, 0, $+5$ and $+10°$ with respect to the bar major-axis.

The LOSV of the Max(E) model shows a local minimum near $r \approx 1.2$ and a plateau between $r = 2.5$ and 4.5 which is very similar to the LOSV curves of SB0 galaxies. However, in such a model, the local minimum is positive so that no counterrotation is apparent. The Min(E) model is another case of a wavy pattern. Moreover, counterrotation is present in the region $0.9 < r < 1.8$. Finally, the third model of Figure 1 (Min($|L_z|$)) does not display counterrotation. The wavy pattern depends on the exact PA of the slit with respect to the bar major-axis.

The percentage of mass on orbits with retrograde motion ($L_z < 0$ in the inertial frame) is 23% (Max(E)), 22% (Min(E)) and 19% (Min($|L_z|$)) inside corotation. For comparison, extreme values are 14% (Min(H)) and 30% (Max(H)) that are not displayed. The contents in retrograde orbits is thus quite similar from one model to the other.

4. Discussion

Contrary to the results of Sparke reported by Bettoni (1989), the wavy pattern is not only due to a misalignment of the slit with respect to the bar major-axis. Although in our models the wavy pattern is also amplified if the slit is rotated towards the minor-axis, it does not disappear when the slit is exactly along the bar. Thus beside geometrical effects a physical factor is necessary.

Since the amount of mass on retrograde orbits in Min(E) and Max(E) models are quite similar, it is obvious that differences in velocity fields and rotation curves is only due to the spatial distribution of various families of orbits. In the Min(E) and Max(E) models, most of the mass is concentrated on orbits trapped around the retrograde quasi-circular orbits family. However, for the Min(E) model, the spatial coverage is limited around $r \approx 1.2$ while for the Max(E) model, the same mass is spread over a wider region (up to $r \approx 2.5$). Thus, the local minimum is due to retrograde orbits while the value of the velocity minimum depends on the spatial distribution of such orbits.

The plateau between $r = 2.5$ and 4.5 which appears for the Max(E) models but also for a few other un-displayed models, is mainly due to 4/1, 6/1 and higher order orbits with a loop on the major-axis. Such loops create local retrograde motion in the reference frame of the bar although the mean angular momentum remains positive. Thus, in the inertial frame, the velocity is lowered and then the LOSV curve shows a plateau.

The zero-velocity curve of the Min($|L_z|$) model is less distorted than the one of NGC 4546 (Galletta 1987). However this model is interesting as its DF

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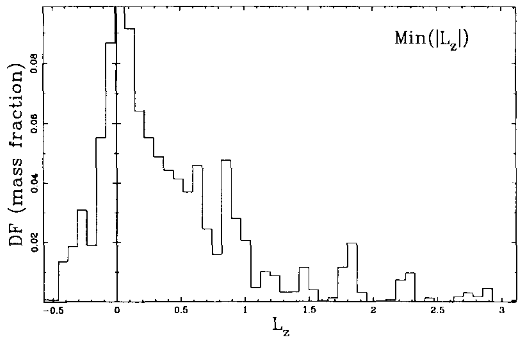

Figure 2. Distribution function of the Min($|L_z|$) model as a function of the mean angular momentum L_z. Each bin represents the mass for the given value of L_z. The total mass inside corotation is 1.

compares very well with the one of N-body simulations (Figure 2). Indeed, our improvements over the Schwarzschild method allow us to obtain the distribution function (DF) in the 4D phase-space.

We have compared the DF as a function of L_z with the particle distribution of the N-body simulation of Pfenniger & Friedli (1991). As for the N-body model, the DF displays a maximum for $L_z = 0$ and a roughly exponential behavior on the ranges $-0.6 < L_z < 0$ for retrograde orbits and $0 < L_z < 1.5$ for prograde orbits. All prograde orbits in this L_z range are elongated along the bar major axis. Between $L_z \approx 0.4$ and 1.0 orbits are trapped by 4/1 and 5/1 families while those trapped around the 6/1 have $1.0 < L_z < 1.5$. From $L_z \approx 1.5$ to 2.0 Lagrangian orbits dominate the DF. Orbits with $L_z > 2$ spend most of their time in the disk and enter in the bar from the $L_{1,2}$ Lagrangian points. Clearly, the "hot" population of Pfenniger & Friedli (1991) is composed of Lagrangian orbits and disk orbits which reach the corotation region of the bar.

Thus, due to the form of the DF, the retrograde orbits with greatest weights have a very small L_z and a small spatial extent so that the rotation curves do not show a clear wavy pattern. Here, the presence of a minimum depends on the PA of the slit with respect to the bar.

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