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Dynamical evolution of a bulge in an N-body model of the Milky Way

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Abstract. The detailed dynamical structure of the bulge in the Milky Way is currently under debate. Although kinematics of the bulge stars can be well reproduced by a boxy-bulge, the possible existence of a small embedded classical bulge can not be ruled out. We study the dynamical evolution of a small classical bulge in a model of the Milky Way using a self-consistent high resolution N-body simulation. Detailed kinematics and dynamical properties of such a bulge are presented.

1. INTRODUCTION

In the standard ΛCDM cosmology, nearly non-rotating classical bulges which are the central building blocks in spiral galaxies, are generally formed in dry major mergers [1]. As mergers were nearly inescapable in the past and $\sim 2/3$ of the disk galaxies [2] are barred including the Milky Way, the possible co-existence of a bar and a small classical bulge might be rather common in present day disk galaxies, and such bulges might have evolved through their mutual gravitational interaction. In the Milky Way, an upper limit on the mass of a classical bulge ($\sim 8\%$ of the disk mass) has been set by modelling the kinematics from the Bulge Radial Velocity Assay (BRAVA) data [3]. But there is evidence for a metallicity gradient above the Galactic plane [4] which is taken as an indication for the existence of a classical bulge in our Galaxy. Hence, it is important to understand the dynamical interaction between a preexisting classical bulge and the bar in the Galaxy.

2. EVOLUTION OF A CLASSICAL BULGE: STRUCTURE AND KINEMATICS

In order to follow the dynamical evolution of a small, initially isotropic, non-rotating classical bulge, we construct an equilibrium model of a live disk galaxy consisting of 10 million particles using the method of [5]. The disk density follows an exponential profile with a scale length of 4 kpc, total mass $M_d = 4.5 \times 10^{10} M_\odot$ and $Q = 1.4$ at half-mass radii. The bulge-to-disk mass ratio (B/D) is 0.067. Other details of the galaxy model can be found in [6].

A strong bar forms in the disk within 0.5 Gyr and is transformed into a boxy bulge via the well-known buckling instability. During the secular evolution that bar drives a substantial fraction of the energy and angular momentum from the disk are being transferred to the surrounding dark matter halo and the preexisting classical bulge. Based on the work of Lynden-Bell & Kalnajs [7], several authors have emphasized that resonant interaction plays a significant role in the angular momentum transfer. The left panel of Fig. 1 shows the evolution of specific angular momentum gained by the embedded classical bulge. Orbital spectral analysis reveals that the 2:1 resonance (right panel of Fig. 1) plays the

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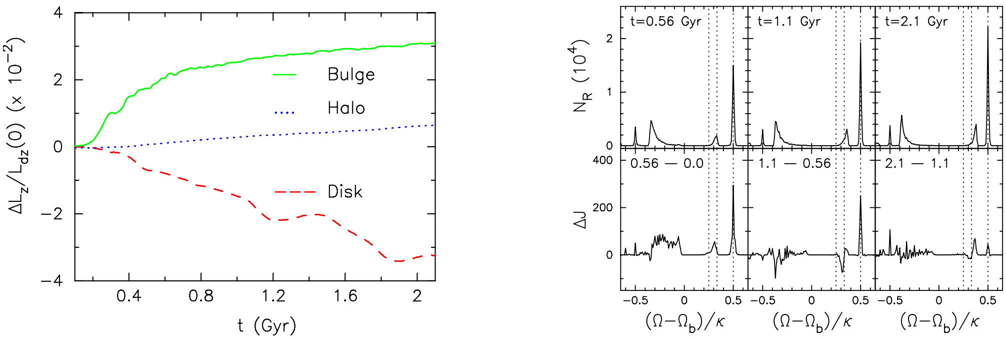

Figure 1. Left: Evolution of the change in the specific angular momentum normalized to disk angular momentum at T=0. Right: Spectral analysis showing 2:1 resonance mainly responsible for transferring angular momentum to the classical bulge from the bar rotating with a pattern speed Ω_b. Other notations bear usual meaning.

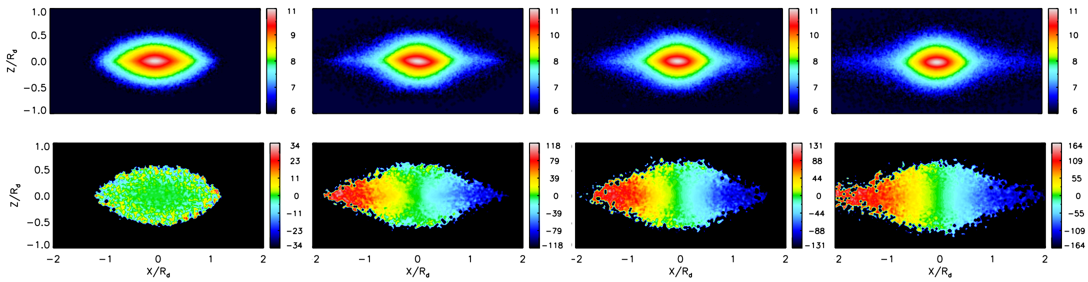

Figure 2. Surface density and velocity maps of the classical bulge alone. From left to right, panels are taken at T = 0, 0.56, 1.1 and 2.1 Gyr. The bulge is initially non-rotating and flattened by the disk gravity.

dominant role in the transfer of angular momentum from the bar to the classical bulge [6]. As a result of the angular momentum gain, the initially non-rotating isotropic low mass classical bulge transforms into a highly rotating triaxial and anisotropic object.

The angular momentum gained by the low mass classical bulge has a profound effect on its structure, kinematics and dynamics. In the upper panel of Fig. 2, we show edge-on surface density maps at four different epochs during the secular evolution in the galaxy. The normalized fourth-order Fourier cosine coefficient obtained by analyzing the density field indicates the presence of non-axisymmetric features developing inside the classical bulge at around $T = 0.56$ Gyr which also marks the bar buckling instability in the disk. At later phases of evolution, the inner regions of the classical bulge become rounder and the outer parts become disky. The corresponding velocity maps on the lower panel of Fig. 2 show that as the bar evolves, the bulge spins up and shows prominent signatures of cylindrical rotation in the inner regions (at $X/R_d < 0.4$). Further analysis (see [6]) have shown that a bar-like structure forms in the inner regions of the classical bulge which may be responsible for making the inner regions rounder through heating [8] and cylindrical rotation seen in the classical bulge. Since cylindrical rotation is considered as a proxy for the boxy bulge, our new results on the kinematics of the classical bulge would open up the possibility that many boxy bulges might have an underlying small classical bulge in barred galaxies, especially the Milky Way.

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