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FORMATION OF RINGS BY GALACTIC COLLISIONS

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RESUMEN

En este artículo estudiamos la formación y evolución de anillos en galaxias de disco formados por la colisión con una compañera esférica. Este estudio es llevado a cabo utilizando simulaciones numéricas y modelos auto-consistentes. Hemos probado diversas galaxias blanco con diferentes radios de escala y dispersión de velocidades radiales centrales. También hemos probado compañeras con diferentes masas y diferentes radios de escala. Hemos utilizado un gran número de condiciones iniciales para tener colisiones con diferentes velocidades, inclinaciones y parámetros de impacto. Nuestros principales resultados son: (a) las interacciones fuertes (compañeras de alta masa o velocidad de impacto pequeña) resultan en anillos con velocidad de expansión constante; (b) las colisiones que producen anillos son muy efectivas para calentar el disco, aumentando considerablemente la dispersión de velocidad radial; (c) los anillos producidos en las colisiones son ondas de densidad; (d) las colisiones inclinadas y centrales crean anillos inclinados, pero no son eficientes para desplazar el núcleo de la galaxia blanco; (e) las colisiones perpendiculares y periféricas son más eficientes para desplazar el núcleo, así como para producir anillos inclinados que persisten por un largo período de tiempo (algunos 10^8 años).

ABSTRACT

We study the formation and evolution of rings in disk galaxies by the impact of a spherical companion. This study is carried out by using numerical simulations and fully self-consistent models. We have tested a number of target disk galaxies with different radial scalelengths or central radial velocity dispersion, and a number of companions with different masses and radial scalelengths. We also have tested a large number of initial conditions to produce collisions with different velocities, inclinations and impact parameters. Our main results are: (a) strong interactions (high companion mass and/or slow impact velocity) result in rings with constant expansion velocity; (b) our tested collisions are very effective to heat the disk, increasing the radial velocity dispersion; (c) the rings created by collisions are certainly density waves; (d) inclined-central collisions create inclined rings, but they are not effective to displace the nucleus of the target; (e) perpendicular-peripheral collisions are more effective to displace the nucleus, as well as to create inclined rings, which remain inclined for a long period of time (some 10^8 years).

Key Words: galaxies: evolution — galaxies: structure — methods: numerical

1. INTRODUCTION

Some extragalactic systems are classified as ring galaxies due to the presence of a pronounced ring structures surrounding an apparently empty region in which an off–centered nucleus can often be seen. Such systems are relatively rare, because they need some more or less specific collision parameters to be formed – central and perpendicular collisions preferentially result in pronounced rings. Polar ring galaxies are a similar phenomenon, but they will be not discussed here (see Bournaud & Combes 2003).

Lynds & Toomre (1976) and Toomre (1978) have presented a clear picture of what happens during a collision resulting in a ring structure. An extra inwards gravitational force is exerted by the intruder when it approaches the disk and the disk particles are forced to contract. When the companion leaves there is a strong rebound. The disk particles orbits are crowded together and a transient density wave, propagating outwards, is formed. A second or even a third rebound is possible, depending on the companion mass and velocity, as well as the disk radial velocity dispersion.

Several studies were carried on following these precepts. For example, Huang & Steward (1988), Appleton & James (1990) and Athanassoula, Puerari, & Bosma (1997, hereafter APB97), while Hernquist & Weil (1993) and Horellou & Combes (1993) also included gas in the simulations. Mihos & Hernquist (1994) add star formation as well.

In this contribution, we present some results of our new fully self-consistent set of simulations result-

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ing in ring galaxies. The models and computational details are presented in § 2. Due to the short extent of the contribution, we present our main results in § 3. A fully version of our study will be presented elsewhere (Puerari & Aguilar, in prep.).

2. MODELS AND COMPUTATIONAL DETAILS

We have constructed several fully self-consistent models using the *mkkd95* task, which is distributed with the NEMO package (`http://bima.astro.umd.edu/nemo/`). The *mkkd95* task follows the procedure given in Kuijken & Dubinski (1995). Some different disk+halo models were used as targets to understand the effects of the disk radial velocity dispersion and radial scalelength. For the companion, we have used Plummer models (*mkplum* task). Several companions were constructed to check the effects of the companion mass and radial scalelength. We have designed a set of interactions to check the effects of the orbit inclination, velocity, as well as the impact parameter. The full tables with all parameters will be presented elsewhere (Puerari & Aguilar, in prep.).

Our target galaxies have 400,000 particles (200,000 in the disk, and 200,000 in the halo). The companions were always constructed with 50,000 particles. By using these numbers, individual particles have different masses, but we have tested a number of simulations in which all particles have equal mass and the main results remain the same. We have evolved all simulations for a time of $t = 1.0$ Gyears, where the companion crosses the target around $t =$ 0.2 Gyears. In the calculation of the models evolution, we have used the gyrfalcON program (Dehnen 2002; see also the NEMO package). The chosen parameters, mainly the time step Δt, softening ϵ and opening angle θ, ensure an energy conservation better than 10^{-3}.

3. MAIN RESULTS

Our set of simulations contains 47 different collisions, in which we have changed: (a) disk radial scalelength; (b) disk central radial velocity dispersion; (c) companion mass; (d) companion radial scalelength; (e) impact velocity; (f) impact inclination; (g) impact parameter; (h) prograde and retrograde impacts; (i) azimuthal position of the impact.

We have developed a way to show the evolution of the ring structure; instead of using the $x \times y$ plots (and showing some snapshots), we prefer to look the simulations by using $r \times t$ plots (see, e.g., Figures 2, 3, 13, and 14 of APB97). In those plots, we can easily recognize the formation and evolution of the rings (first, second, and sometimes, the third one). We can see if the expansion velocity of the ring is more or less constant or decreases with time. Furthermore, we can easily see what collisions heat the disk and what ones displace the nucleus.

By using these kind of plots, several results can be traced. For example, looking the central-perpendicular simulations, in which only the companion mass is changed (the impact velocity is fixed), we can see that heavier companions result in rings with constant expansion velocity. This behaviour can also be seen by looking the central-perpendicular simulations, in which the impact velocity is changed (the companion mass is fixed): slower collisions result in constant expansion velocity rings. So, we can conclude that strong interactions (heavier companions and/or slower impact velocities) result in rings with constant expansion velocity. Furthermore, when we compare non-central-perpendicular collisions against central-inclined ones, we can see that the last ones are less effective to displace the nucleus than the formed ones.

We have also calculated one-dimensional Fourier transform using the height of the particles as a function of the azimuthal position for each radius at each time. In this way, high $m = 1$ amplitudes represent inclined rings, while high $m = 2$ coefficients represent "banana" structures. We have seen that central-perpendicular collisions have very low $m = 1$ and $m = 2$ coefficients. Central-inclined collisions produce inclined rings, but this inclination tends to decrease with time. Peripheral-perpendicular collisions are very effective to produce inclined rings, and this inclination remains more or less constant with time.

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