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Orbiting Extragalactic Bodies and the Evolution of Exponential Profiles in Galactic Disks

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Abstract

In order to investigate the effects of band structures – coplanar, corotating groups of extragalactic satellites – on the evolution of galactic disks, simulations were performed using an adapted MATLAB point-scattering code developed by Dr. Curtis Struck and Dr. Bruce Elmegreen. The code, originally designed to investigate the effects of disk-bound clumps of matter on the formation of exponential density profiles in galactic disks, places non-interacting star particles in a galactic gravitational potential and disturbs them with gravitationally attractive perturbing bodies. The code was modified to create fully 3-dimensional extragalactic orbits constrained in a band structure at an angle from the disk and simulation runs were performed for total band masses between 3.864×10^7 M_o and 3.864×10^9 M_o. It was found that extragalactic band structures influence galactic evolution in three significant ways: they drive non-transient spiral waves, they cause varying degrees of vertical evolution, and they contribute to the formation of exponential density profiles in a highly mass-dependent manner.

Keywords: Galactic Disk Evolution, Extragalactic Satellites, Scattering

1. Introduction

Galaxies are the fundamental building blocks of the universe's large-scale structure. Understanding their structure and evolution allows us to learn more about the universe as a whole, and our knowledge of the universe's large-scale structure similarly informs research at the galactic level. One major interaction between these two scales is the phenomenon of infalling matter - such as dwarf galaxies derived from cosmological galaxy filaments - which becomes bound into orbit around a galactic disk. This results in what I have termed a 'band structure': the phenomenon of a number of coplanar and corotating extragalactic bodies in orbit around a host galaxy. This formation was first discussed in relation to our own galaxy; Kroupa, Theis, and Boily[1] showed in 2008 that the dwarf galaxies around the Milky Way reside in what they called the Disk of Satellites, a band structure almost perpendicular to the Milky Way's galactic disk. Further work by Pawlowski, Pflamm-Altenburg, and Kroupa[2] in 2012 revealed that not only are the dwarf galaxies around the Milky Way coplanar, but many satellite globular clusters and stellar streams that reside in the halo share this orientation.

In 2008, Koch and Grebel[3] proposed that a similar structure existed around Andromeda consisting primarily of early-type dwarf galaxies; Ibata et al.[4] confirmed this finding to a high degree of confidence in 2013, showing that roughly 50% of Andromeda's dwarf galaxy satellites reside within a common, corotating plane. More recently, in February of 2018, Müller et al. demonstrated the existence of yet another of these structures around Centaurus A.[5]

The implications of these structures' existence, especially in relation to the validity of ΛCDM cosmology, is hotly debated. Their formation, too, is a matter of contention; we are as of yet unsure whether these structures came about through coherent accretion from galaxy filaments or through interactions between large galaxies. That being said, they certainly exist, and questions naturally arise concerning these structures' effects on their host galaxies. Do they have

a significant influence on evolution, disk structure, or other features such as disk density profiles or spiral wave formation? Can we use galactic features to predict the presence or absence of an unobserved band structure?

In this paper, I pursue answers to these questions using a point-scattering simulation code. The paper is organized as follows: in Section 2, I discuss the code used for this investigation. Section 3 details the variety of conditions under which I ran the simulation, and Section 4 presents the results of these runs. Section 5 discusses the implications of my results and considers avenues of future investigation.

2. Code

The simulation code used in this work is primarily based on a code written by Dr. Curtis Struck and Dr. Bruce Elmegreen.[6] The original code was designed to investigate the interaction between disk-bound scatterers and exponential density profiles in galactic disk. It places a number of 'star' particles in a gravitational potential that includes both disk and halo contributions and uses fixed-orbit massive disturbers to scatter the star particles through gravitational interaction. All gravitational interactions are handled using one of two integrator functions, both of which rely on MATLAB's *ode23* – an explicit four-stage $2^{nd}/3^{rd}$ order Runge-Kutta ordinary differential equation solver[10] – for numerical solutions. For further information on *ode23*, please see reference 10; for further information about the simulation code, please see reference 6. I modified the code, removing the 2-dimensional disk-bound scatterers and replacing them with a number of massive, extragalactic disturbers arranged in fixed, 3-dimensional, coplanar, corotating orbits: a band structure. The band is constrained radially and azimuthally, having a radial width of ~ 1 kpc centered on a band radius of 8.5 kpc and an azimuthal width of ~ 22.5° centered on a band angle of 33.75°. The band itself consists of 20 disturbers of identical mass distributed randomly within the band constraints and following fixed Keplerian orbits. In the code output figures, 1 time unit is 9.8 Myr, 1 radial distance unit is 0.5 kpc, and 1 mass unit is 1.932×10^6 M_o.

3. Runs

Simulation runs were performed with bands of 20 disturbers lasting 2 Gyr for individual disturber masses ranging from 3.864×10^7 M_o to 3.864×10^8 M_o in increments of 3.864×10^7 M_o as well as a few high-mass runs with disturber masses of 3.864×10^9 M_o. This was motivated by the typical mass range of dwarf galaxies, which lie between 10^7 and 10^9 M_o. I used a run length of 2 Gyr as it worked well as a characteristic timescale; the galactic disk was usually settled in that time, and phenomena that had little effect over 2 Gyr were deemed insignificant compared to other processes.

The simulation was run on my personal machine, using an Intel i7-4800HQ CPU with 12GB RAM and a clock speed of 2.40GHz. The typical runtime was about 250hrs for a 2Gyr simulation run.

4. Results

4.1 Spiral Waves

The presence of a band structure around the host galaxy drives persistent spiral waves in the host galaxy. The formation of spiral waves is not in and of itself notable; spirals were also produced in Struck and Elmegreen's work.[6] However, their non-transient nature is quite remarkable. In both Struck and Elmegreen's work and my previous experiments with non-banded extragalactic disturbers, all spirals produced were transient and usually only present at early times. However, under the influence of a band structure, the galactic disk not only forms spiral waves but maintains them throughout the simulation runtime. **Fig. 1** shows a top-down view of the galactic disk at three points in a run with the same spiral wave present. The run shown was performed using disturbers with individual masses of 3.864×10^8 M_o.

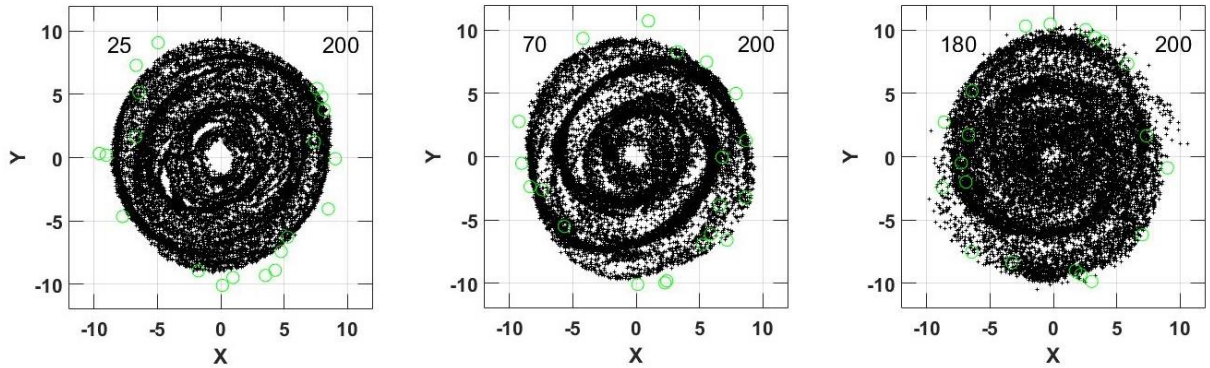

Figure 1: Non-transient spiral waves, at (left to right) 0.25, 0.70, and 1.8Gyr. The wave evolves alongside the galaxy, but does not dissipate, a behavior likely driven by periodic alignments of the band structure disturbers.

At t = 25 (~250 Myr), the spiral has just begun to form; by t=70 (~700 Myr), it is quite distinct, and by t=180 (~1.8 Gyr) it has thickened considerably. You will note that while the appearance of the spiral wave changes – it too evolves as the stars of the disk are scattered – the wave structure remains present throughout the run.

The cause of these persistent spirals seems to be periodic clumping/gapping of the band disturbers. As the disturbers are spread radially, they have different periods, causing periodic alignments and thus a period driving force on the stars in the disk.

4.2 Vertical Evolution

I observed three major phenomena related to vertical evolution: thickening, warping, and realignment of the galactic disk. Thickening is the least exciting of these, occurring when stars are scattered vertically out of the disk, and results in a thicker disk. This is an expected result that was seen in previous work. An example of this phenomenon can be seen in **Fig. 2**. The first frame shows the initial disk; the second and third frames show the disk after 100 and 200 time units (1 and 2 Gyr), respectively, for a band structure consisting of 20 disturbers each with a mass of $1.159 \times 10^8 M_o$.

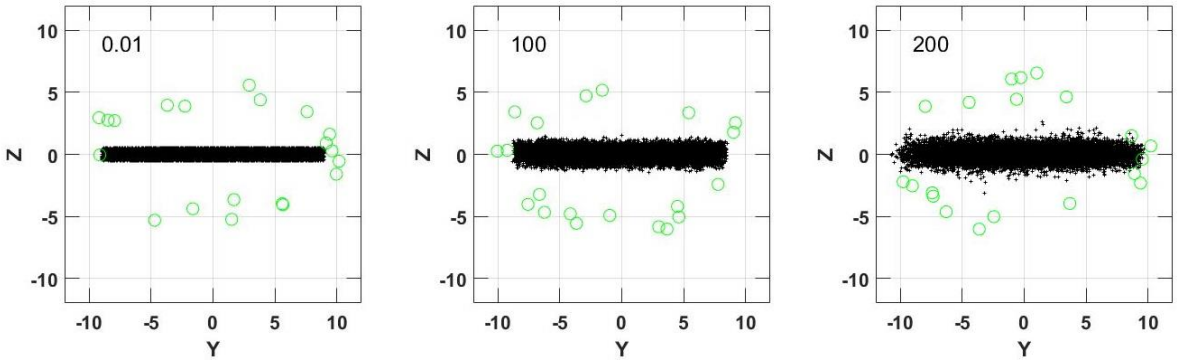

Figure 2: Disk thickening, at three different points in the same run (initial conditions, 1 Gyr, and 2 Gyr). Gravitational interactions between the band structure disturbers and stars in the disk skew stellar orbits along the z-axis. This effect is cumulative, and over time results in an increasingly thicker disk.

Warping is a phenomenon where the gravitational influence of the band structure causes the entire galactic disk to oscillate and bend. This induces significant thickening, and its occurrence and amplitude are both highly dependent on the mass of the band structure. Warping is not observed for low-mass disturbers, becomes apparent around total band masses of $3.5 \times 10^9 M_o$, and grows increasingly violent for larger band masses – eventually drastically thickening the galactic disk. Additionally, the distribution of the band structure satellites can have a major effect; if a number of the satellites have clumped together, the group will create a "bowling ball in a washing machine" effect and instigate a significant, if short-lasting warp. **Fig. 3** shows examples of disk warping. The first frame shows warping for

individual disturber masses of 1.932×10^8 M_o, the lowest mass for which warping was observed. This warp occurred due to a large clump of disturbers in the band. The second and third frames shows warping over consecutive simulation outputs for individual disturber masses of 3.864×10^8 M_o and was caused by a more isotropic satellite distribution.

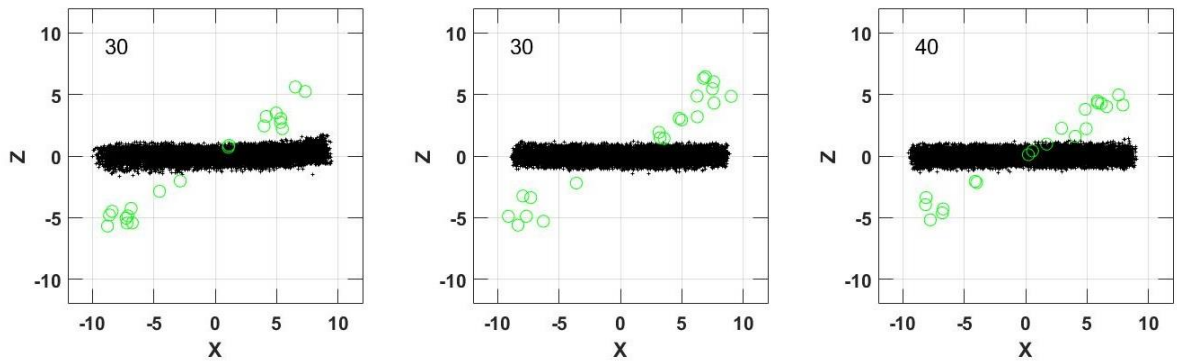

Figure 3: Warping, for two different disturber configurations, wherein the asymmetrical influence of the band structure leads to oscillatory behavior. The left frame shows the effect of a 'clump' of disturbers; the center and right frames are from another run and display the full-disk oscillation caused by a more isotropic band structure.

Realignment of the disk occurs when the total band structure mass approaches that of the host galaxy itself. The gravitational attraction of the band structure overwhelms that of the disk potential, and the entire galaxy is violently realigned to a plane between the original plane of the disk and that of the band structure. Due to the nature of the simulation potential, the behavior we see is not entirely physical; realistically, the band would be realigned as well, and the disk potential would realign itself along with the disk. While not a process we would expect to observe – and one that approaches, if not crosses, the realistic bounds of the simulation – realignment provides an upper limit for band structure masses. If the mass of a band structure is sufficiently high, we should see violent band-disk interaction and a resulting shift in the disk plane; if we do not see these effects, the band mass must be small enough to avoid them. The process of realignment can be seen in **Fig. 4**, which shows the disk at three stages in time for a total band mass of 3.864×10^9 M_o.

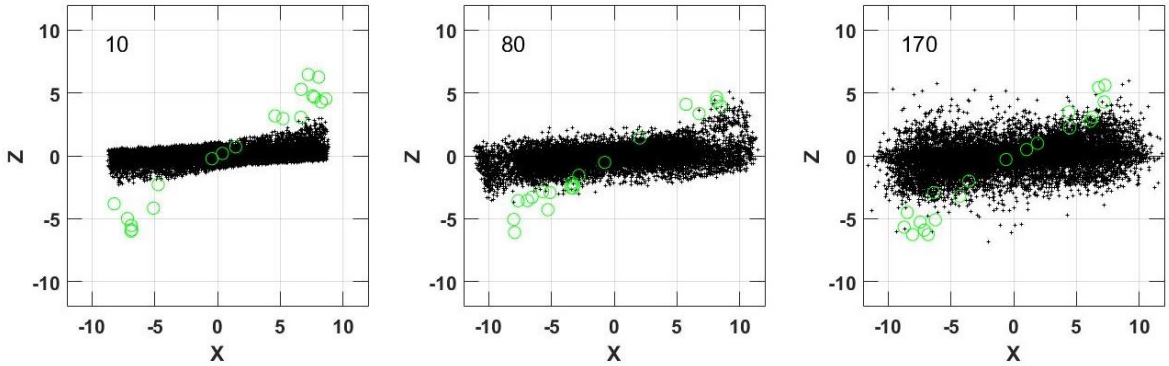

Figure 4: Realignment, at three points of the same run. For a highly massive band structure, the disk finds an equilibrium between the gravitational influence of the band and that of the (due to code restrictions) immutable disk potential. It is to be noted that this is a limiting case, and is primarily useful in recognizing what is or is not realistic.

4.3 Exponential Density Profiles

Most disk galaxies exhibit exponential density profiles; Struck and Elmegreen were able to show that disk bound disturbers are able to create these profiles via scattering.[6] **Fig. 5** is a radial surface density profile created using their original code. The profile takes the shape of a Type II exponential, consisting of two discrete exponentials joined by a sharp break.

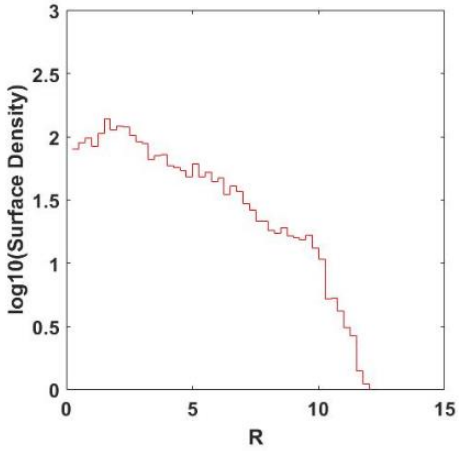

Figure 5: Radial surface density profile created via disk-bound disturbers in Struck and Elmegreen's code.[6] Note the approximately linear section from R≈2 through R≈10, followed by a similar section with a steeper slop from R≈10 to the edge of the disk – this is how a Type II exponential appears on a log-lin plot such as the one above.

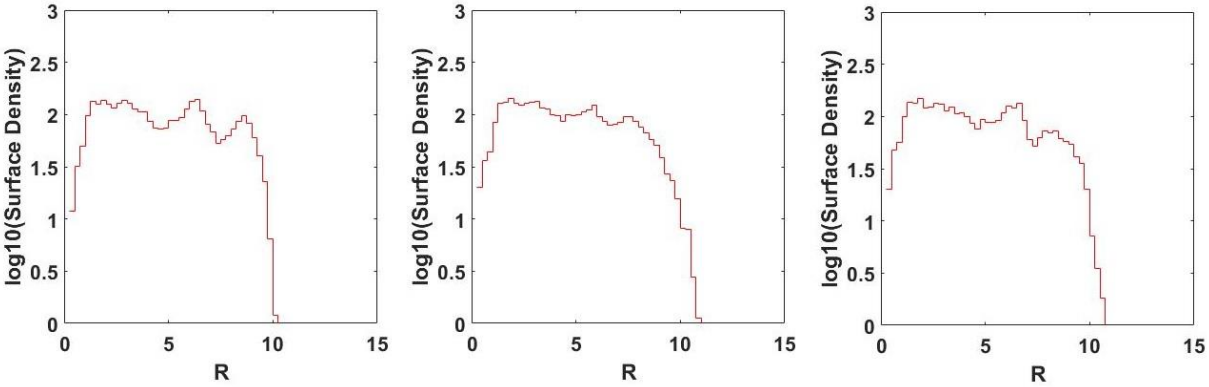

Figure 6: Radial surface density profiles created via band structure disturbers, at 2 Gyr simulation time, for increasing band structure mass left-to-right. Overall, there is less profile evolution than in the disk-bound case – even high-mass bands are likely a secondary or tertiary effect. The bumps at R≈6 are caused by spiral arms.

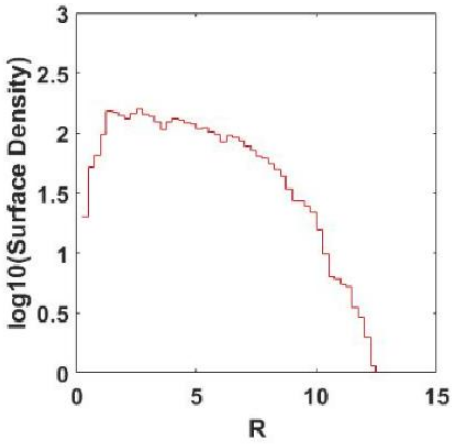

Figure 7: Radial density profile for extreme band mass at 2 Gyr simulation time. Such high masses drive the creation of a Sersic profile, but are beyond the realistic bounds for band structure mass.

Disturbers in a band structure are also able to contribute to the development of exponential profiles in the host galaxy's disk; however, this ability is highly mass dependent. **Fig. 6** shows, from left to right, the disk surface density profile at 2 Gyr for low, middling, and high-mass band structures. The low-mass case used 3.864×10^7 M_o disturbers; the middling and high-mass cases used 1.932×10^8 M_o and 3.864×10^8 M_o disturbers, respectively.

The band structure's presence has less influence on this process than that of disk-bound disturbers; at low masses we see barely any effect at all, and even high-mass cases only produce slow profile evolution. In the high-mass case, the band structure's effect is secondary in nature; it aids the evolution of an exponential profile – and given enough time will indeed cause exponential profile formation – but disk-bound disturbers greatly outpace the effects of a band structure. At extreme masses, we do see exponential density profile formation on timescales rivaling that of disk-bound disturbers as seen in **Fig. 7**, the radial density profile at 2 Gyr with a disturber mass of 3.864×10^9 M_o. Specifically, the radial density profile takes on the form of a Sersic function – another common model for disk density profiles. However, these extreme masses reside past the threshold for violent realignment and as such do not provide a reliable mechanism for exponential density profile formation.

5. Discussion

One of the major implications of this work is a possible evolutionary route for S0 galaxies via warping brought on by a band structure. An S0 (or lenticular) galaxy is a morphological type that lies between spiral and elliptical galaxies, possessing the disk of a spiral without significant spiral waves. Additionally, S0 galaxies possess a large bulge and are generally thicker than spiral galaxies.[7] There is no current agreed-upon mechanism for S0 formation, though numerous theories have been proposed. In my work, many of the simulation runs where the galactic disk underwent significant warping resulted in an S0-like galaxy; further work is required to investigate this possibility, but it is an intriguing consequence of the kinds of vertical evolution produced by band structures.

Another significant result is constraints on band structure mass that we can compare to observational data. Low-mass band structures provide minimal vertical scattering, where as high-mass band structures cause violent changes in the disk, and we can use these telltale signs to constrain the nature of possible band structure observations. There are other galaxies, such as NGC 3109, for which we suspect the presence of a band structure; observations indicate a small number of satellites exhibiting the coplanar and corotational characteristics necessary for such a structure, but due to the small number of observations the existence of a band structure is uncertain.[8] The behavior exhibited by the galactic disk in the presence of a band structure allows us a new lens by which to confirm the presence or absence of such a structure through observations of the host galaxy instead of more difficult observations of its dwarf companions. Finally, the ability of band structures to drive persistent spiral waves is intriguing and necessitates further investigation. As discussed, the spiral waves observed in this work came about through periodic alignments of band structure disturbers – disturbers that followed fixed orbits in my simulation. A major question then presents itself – if the disturbers no longer follow prescribed orbits, instead behaving as real bodies interacting with the galactic potential, will the lack of rigidity and introduction of precession effect this result? Further work is required to answer this question, but preliminary results suggest that these more physical band structures are still able to produce persistent spirals in the disk.

6. Acknowledgements

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7. References

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