THE GALAXY NGC 4622: LONG-LASTING LEADING ARMS AND RINGS VIA LOW MASS PERTURBERS

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ABSTRACT

There are few candidates for leading arm galaxies. Only NGC 4622 is a confirmed case because it has both leading and trailing arms. In simulations, we successfully reproduce NGC 4622's leading arm and outer pair of trailing arms. A small mass companion (0.01 of the galaxy's mass) passing close (within one-tenth of the disk radius) seems to produce the best match. This very close passage produces a leading arm in our simulations for both direct and retrograde orbit senses. The close retrograde passage seems to match the entire pattern of NGC 4622 a bit better. Moreover, the leading arm from the direct close passage does not last as long. A heavy halo mass (eight times the disk) of the primary galaxy is also necessary to reproduce the present-day features. The massive, distant, and retrograde companions considered in previous simulations produced leading arms but not the sort of outer trailing arms seen in NGC 4622. If tidal encounters only produce leading arms when the inert halo is more important than the disk, leading arms ought to be common if halos are massive. There are only a few other one-armed spirals known with no information yet as to their arm sense. This rarity either indicates that halos tend to be comparable in mass to the disk, leading arms are short lived, or close encounters with small companions are rare. The leading arm is still present in our NGC 4622 close encounter simulations (retrograde) after a billion years, so these leading arms are long lived. Small galaxies are very numerous compared to larger ones so small-large encounters should be frequent. Thus our results may indicate that halos are comparable to disks in most galaxies. Finally, NGC 4622 also provides a different way to make rings in disk galaxies besides bar excitation: the low mass companion itself initiates a leading arm and ring as it passes near the nucleus.

1. INTRODUCTION

1.1 The Rarity of Leading Arms and Halo-to-Disk Ratio

Byrd and Howard (1992) combine simulations with observations of companion galaxies to show that the great majority of spiral galaxies are expected to have tidal arms present in the disk. Observations (de Vaucouleurs 1958) indicate that spiral arms trail the direction of rotation of the disk. Theoretical studies indicate that some tidal encounters can generate a leading arm near the $m=1$ inner-Lindblad resonance with the angular velocity of the companion at closest approach. For example, Athanassoula's (1978) study shows that such an arm can develop from circular retrograde companion orbits. Simulation studies also indicate how leading arms may form. The perturbation of non-self-gravitating n-body disks by unbound companions (Noguchi & Ishibashi 1986) can create leading arms. The self-gravitating n-body studies (Thomasson *et al.* 1989, Byrd *et al.* 1989) show that leading arms are favored when a massive retrograde companion perturbs the disk strongly and the halo mass within the disk radius is significantly greater than the disk mass.

Arguing that retrograde companions should be as common as direct ones and that encounter orientations are random, Thomasson *et al.* (1989) suggest that perhaps 25% of all spirals with major companions should have a leading arm generated via a strong retrograde perturbation. However, this is clearly not the case observationally. Recently, Keel (1991) observationally determined that direct and retrograde companions are equally common in a sample of Karachentsev pairs. The contradiction between the fraction of retrograde companions and the Thomasson *et al.*'s result that these companions should trigger leading arms and the failure of de Vaucouleurs to find leading arms indicates either that most galaxies may have a halo mass close to or less than their disk mass, or, alternatively, that strong retrograde perturbations are rare. If the former indication is correct, it will, of course, have important implications for the general dark matter problem, since it is not consistent with the inferences from other observational evidence (see the discussions in Valtonen & Byrd 1986, 1990). On the other hand, perhaps the latter is correct. The strong perturbations by comparable companions found necessary by Thomasson *et al.* are certainly a rare type of encounter. We need actual leading arm galaxies to study to see which of the alternatives above applies.

1.2 One Clear Example of a Leading Arm Galaxy

Fortunately, there is one observed galaxy that shows an unambiguous leading arm pattern, NGC 4622. The feature was first recognized by Byrd *et al.* (1989) on a blue-light,

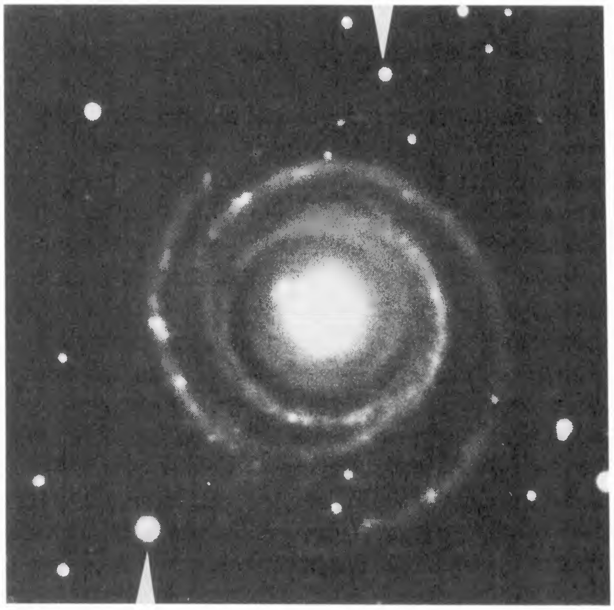


FIG. 1. NGC 4622: *B*-band image in intensity units. The leading arm starts in the center winding counter-clockwise outward. The outer trailing arms wind clockwise outward. The two stars marked with white triangles are about 106 arcsec apart. North is at the top and east is to the left. Photo credit copyright 1975 AURA, Inc., Cerro Tololo Inter-American Observatory (No. 7075-0, 02114).

commercially available, NOAO photograph (Fig. 1). He identified a leading arm inside an off-centered inner ring. Two smooth outer arms break from this ring, winding in the opposite sense, and are likely to be trailing arms. The presence of arms winding in both directions and the nearly face-on orientation (and thus clearly visible spiral pattern) make this galaxy an extremely unambiguous case showing that leading arms do exist. A skeptic, however, could reasonably claim that the single arm pattern in the disk might be an artifact of dust lanes and not exist in the stellar component, which comprises most of the disk surface mass density. Buta *et al.* (1992, hereafter referred to as BCB) clearly established with *BVI* surface photometry images that the arm pattern of this galaxy is indeed present in the stellar I wavelength component of the disk. The leading arm appears to begin at about 15″ radius and extends to the inner ring at about 21″ radius.

1.3 The Environment and Characteristics of NGC 4622

NGC 4622 is a member of the Centaurus Cluster (Sersic & Aguero 1972), with two comparable magnitude close companions: NGC 4616 and NGC 4603D, both at about 7 arcmin. Figure 3 in BCB shows the field around NGC 4622 from SRC-J copy film 322. Only NGC 4616 has a redshift similar to NGC 4622: 4586 vs 4367 km/s (de Vaucouleurs *et al.* 1991) and is clearly a possible suspect for the perturbing companion, as found in the earlier simulation studies. However, for reasons to be discussed later, our prime suspect is a smaller galaxy only 1.85 arcmin to the east (Fig. 3 in BCB). This object is of unknown redshift. Observations which are presently being reduced show that this galaxy is not likely to be a giant E galaxy more distant than NGC 4622. The suspect and NGC 4622 have about the same color, similar to M32, and are bluer than a giant E galaxy.

BCB found that the inner part of the disk where most of the leading arm occurred had no blue features, i.e., no newly formed stars and possibly no gas from which they can form. Using the redshift as a distance indicator and a Hubble constant of 100 km s^{-1} Mpc^{-1} (Buta & de Vaucouleurs 1983), BCB estimate its distance=42 Mpc, which gives an absolute magnitude of $M_T^0(B) = -20.4$. BCB determine several parameters for the inner ring from their fits: the apparent diameter 47″, apparent axis ratio 0.893, and major axis position angle 83°. The angular diameter of 47″ corresponds to 9.6 kpc if the distance is 42 Mpc. The ellipse fit also showed that the center of the ring is displaced 2″.2 west, 1″.4 south of the nucleus, corresponding to a total displacement of about 500 pc. This amounts to 11% of the major axis radius of the ring. The displacement of the nucleus is not along the projected major axis of the ring, but along a position angle of 61°. The disk itself has an exponential scale length of 19.6 arcsec or 4.00 kpc with the distance above.

1.4 Previous Simulations

Struck-Marcell (1990) mentions NGC 4622 as a possible example of the creation of a thick braided ring by a highly tilted passage of a low mass companion, as seen in his impulse approximation, non-self-gravitating disk simulations. Unfortunately, the ESO photograph used by Struck-Marcell shows only the outer trailing arms. The nucleus overwhelms the leading arm and ring. Struck-Marcell's simulation match has a thick braided ring with loops resembling the outer trailing arms and, quite reasonably considering the photograph available, does not produce the leading arm and ring seen by BCB. Struck-Marcell's simulations work extremely well and use little computer time. However, they consider the disk particles to receive an instantaneous velocity impulse from the perturber. The angular motion of the perturber and also the induced motion of the nucleus are absent in their simulations.

The ring and leading inner arm bear a clear resemblance to the more realistic simulation of Noguchi & Ishibashi (1986) and Thomasson *et al.* (1989). In these simulations, the leading arm and ring were excited by the external parabolic passage of a comparable-mass retrograde companion past a disk galaxy that had a large halo-to-disk ratio. The former simulations were not self-gravitating; the latter were and verified that the large ratio was necessary. The leading arm and ring also resemble the retrograde circular orbit perturber studies by Athanassoula (1978).

1.5 The Nature of the Leading Arm and Ring

BCB interpret the leading arm and ring as a set of $m=1$ dispersion orbits. They examine the portion of the disk near the ring yet far enough from the center so that star formation is taking place. In the arm region, $\Omega_p = \Omega - \kappa$,

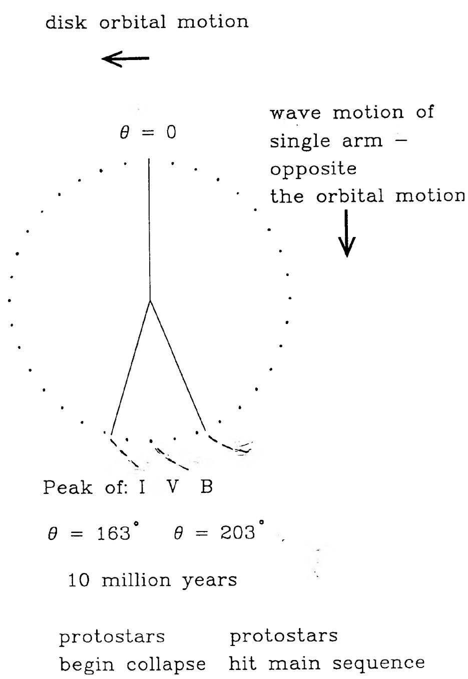


FIG. 2. Direction of orbital motion, leading arm unwinding, old disk stellar density peak, and subsequent blue wavelength light up of main-sequence stars whose formation was initiated by disk gas passing through the stellar peak.

where Ω is the orbital angular rate of the disk material, κ is the epicyclic frequency, and Ω_p is the pattern speed of the $m=1$ dispersion orbit created by the companion. BCB determined the position angle of the peak intensity at B, V, and I bands going around a circle at the ring. Sketched in Fig. 2 is the direction of orbital motion inferred from the trailing outer arms. Starting from a zero position angle, BCB found in the orbit direction: first, the intensity peak of the stellar component (I), then further downstream the peak of the V component, and finally, the B component peak representing bright new main-sequence stars. Making a reasonable guess for Ω, the angle between these two peaks correspond to a time lag of about 10 million yr, just the time lag between a protostar's formation during a collision of two gas clouds in the stellar density peak and that object's contraction to the main sequence to "light up" in blue wavelengths as a luminous main-sequence star. The protostar will initially have its peak of emission in the I band, shifting to V and B as it heats up while contracting to the main sequence. This is clear evidence that the leading arm is a density wave. The density peak of this wave turns clockwise in the sketch, opposite the disk orbital motion, as inferred from the outer trailing arms.

2. CODE DESCRIPTION AND SIMULATION STRATEGY

We use simulations to investigate what kind of tidal interaction might produce the coexisting arm types in NGC 4622. We are also interested in the properties of NGC 4622 itself. In particular, we would like to know how important the inert "dark" halo is in this galaxy. Here we first describe the computer code briefly then the orbital and galaxy parameters, which were varied in the search for the best choice. Once we settled on the "best choice," we varied the parameters of the encounter and the halo-to-disk ratio in the galaxy to determine how accurate the encounter parameters were and the importance of dark matter in this galaxy.

2.1 Description of Code

The code is an n-body code, fully self-gravitating, with a disk constrained to two dimensions, and a softened companion whose orbit is confined to the disk plane. The nearly face-on orientation of this galaxy makes the use of a two-dimensional disk realistic for comparison with observations of the morphology. We find little difference in arm shapes between perturbed two- and three-dimensional disk models in our studies of M51 and its companion (Howard & Byrd 1990, two dimensional, and Byrd *et al.* 1991, three dimensional). Essentially, if the disk is thin, vertical oscillations are locally independent of horizontal oscillations of stars. The number of particles in the self-gravitating disk can be varied from a few tens of thousands to 180 000 particles depending on the computer used. The primary galaxy has three components: an inert halo contribution, a "stellar" contribution, and a "gas" contribution. The stellar component and gas component are differentiated by their initial velocity dispersion: near the critical value (for stability under axisymmetric perturbation) for the stars and zero for the gas. The amount of halo material is specified by its relative contribution to the gradient of the gravitational potential in the disk (force per unit mass at that location in the initial disk). When this amount is more than 10 times the disk material, the disk contributes an almost insignificant amount to the galaxy potential. We make no assumption about the three-dimensional shape of the halo although we assume it has a very large velocity dispersion and is thus insensitive to perturbations (i.e., we take it to be inert). The large dispersion would imply it to be much thicker than the disk.

The code uses a finite Mestel disk (Lynden-Bell & Pineault 1978). We use this disk because it has an initially flat rotation curve from center to edge. Such flat rotation curves are very common in spiral galaxies. The Mestel disk has a radial surface density distribution similar to the approximately exponential distributions of surface brightness seen in disk galaxies. Observers commonly describe the disks of SA galaxies in exponential scale lengths. The radius of the finite Mestel disk in our simulations is three exponential scale lengths. This corresponds to 12 kpc in NGC 4622. The time steps are set such that 50 time steps is one crossing time or 1.2 million yr per step if the rotation speed is 200 km/s. Unfortunately, this last quantity is presently unknown observationally. See Howard & Byrd (1990) for code details. The original version of the code was written by Miller (1976) as possibly the first polar grid n-body code used for galaxy simulations and generously shared with most users of such codes today. The present code is a descendent, highly modified and tested against independently written polar and cartesian grid codes.

2.2 Orbital and Model Parameters

Recall that the choice of a heavy halo and a retrograde passage is appropriate to make a leading arm. A ratio of halo mass to disk equal to 16 means the halo dominates the disk dynamics. We tried lower values down to 1 to determine just when the leading arm no longer appears. The remaining free parameters we varied are: the distance of closest approach of the companion to the disk center; the mass of the perturber relative to the galaxy, and the time since the encounter. Finally, we tried simulations with the orbit sense reversed. The simulations were done with the disturber confined to the disk plane. We tried perturber masses from equal down to 0.005 that of the galaxy.

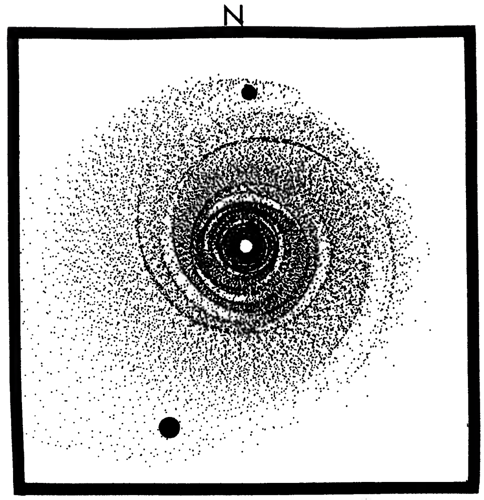
Since Athannassoula's (1978) simulations of a circular bound companion's effects did not result in outer trailing arms, we were interested in either a parabolic or rather eccentric encounter with apogalactic point far from the disk. In our simulations, the halo extends only to the edge of the disk. The angular rate of the perturber at close approach is about the same for both zero energy and bound orbits coming from outside the disk radius, so we considered only parabolic passages for a given distance of close approach. We simulated encounters with this distance ranging from twice the disk radius down to a 1/20 disk radius passage.

3. SIMULATION RESULTS

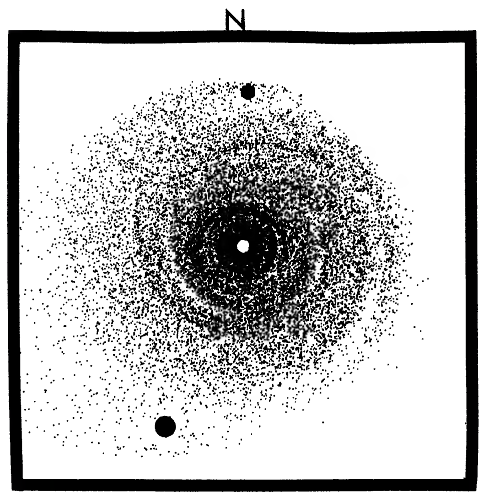
3.1 Companion Mass and Orbit

As mentioned previously, the leading arm galaxy has a neighbor of comparable luminosity and of comparable redshift several disk diameters away (marked NGC 4616 in Fig. 3 in BCB). It seemed to be the most likely suspect. We did a series of simulations of passing companions finding (through a succession of failures) that comparable companions which pass close enough to produce the leading arm in the inner portion of the disk tear away the outer parts of the disk, confirming Thomasson *et al.*'s simulations. Furthermore, any trailing arms in the outer disk probably would not last long enough for NGC 4616 to reach its present large distance.

Eventually, we found that low-mass retrograde or direct companions passing close to the nucleus produce the outer trailing as well as the inner leading arms. In our opinion, a retrograde passage seems to be the best choice for NGC 4622 based on details in the outer arms. These companions have to be remarkably small, a few hundredths of the galaxy mass, to produce the combination of leading and trailing arms seen in NGC 4622. As we mentioned earlier, examination of the ESO Survey reveals a small companion about one disk radius away. This galaxy (of unknown redshift) is consequently our new suspect and is marked "C?" in Fig. 3 in BCB. A system with a similar close-to-nucleus orbit for a satellite is M31 and its tidally stripped companion, M32 (Byrd 1976, 1978). Incidently, from the previously cited studies, M32 is in a direct orbit within M31 and is only 10^{-3} of M31's mass, so there is no danger of this small companion making a leading arm in M31.



(a)



(b)

FIG. 3. (a) Best match of computer simulations to NGC 4622 (Fig. 1). Gas image as described in text. Note the two fictitious foreground stars placed to give scale and orientation relative to those marked in Fig. 1. The rectangular border surrounding the star plot here and on all following figures corresponds to the boundaries of Fig. 1 with N indicating north. Close approach distance/galaxy radius$=R_{en}=2/20$. Mass for the disturber is 0.01 of the galaxy's mass. Halo-to-disk ratio, 8/1. Time step 250. (b) Best match of computer simulations to NGC 4622 (Fig. 1). "Star" image as described in text.

3.2 Matching the Appearance of NGC 4622 with Simulations

Figures 3(a) and 3(b) show a view of our best choice for this fascinating galaxy from our simulations. The image (a) shows the gas arms (with zero velocity dispersion); image (b) shows the stars (with velocity dispersion, Q_T stability parameter of one). These can be compared to Fig.

1, a photograph of the galaxy. To give a sense of orientation and scale, we mark two stars in the photograph which are about 106 arcsec apart and place two fictitious stars in roughly corresponding positions relative to the arms on the simulation frames. We also place the letter "N" indicating north at the top of each simulation frame in this and all following figures. As mentioned earlier, there is observational evidence that NGC 4622 has no H II gas within the inner third of its disk. We can run simulations with gas particles all the way into the center since the self-gravity of the gas in the disk is unimportant compared to the stars over the entire disk in SA galaxies. One can simply use the stellar plot [Fig. 3(b)] for comparison with NGC 4622's disk inside the ring where there is no gas. For the outer disk of the galaxy, the gas creates bright H II regions and is much more conspicuous than the stars in Fig. 1 despite the dynamical unimportance of the gas. We thus compare the outer disk of Fig. 1 to Fig. 3(a), the gas particle plot. The encounter was a zero energy "parabolic" disturber with a mass 0.01 of the primary's mass. The disturber plunges to within 0.1 of the radius of the initial disk ending up to the left about 1.2 times the width of the box from the disk center. The primary has a massive halo eight times the disk. Time step 250 after the start of the simulation seems to be the best time choice.

Note the outer tailing arms, inner leading arm, and the region where the leading arm becomes tangent to a ring with the outer tailing arms coming in from the other side. It is interesting that the leading arm does not appear to be continuous in the simulations but is instead a series of segments going out to the ring segment. Although a foreground star causes problems in seeing the arm near the nucleus, it appears that the leading arm of NGC 4622 does show at least two such segments, as can be seen in BCB Figs. 9(a) and 10. Similarly, we see segments in the outer pair of arms in both the simulations and the galaxy [BCB Figs. 8 and 9(b)]. Also, Fig. 3 in BCB can be compared to the morphology of the outer parts of the NGC 4622 image in Fig. 3(a).

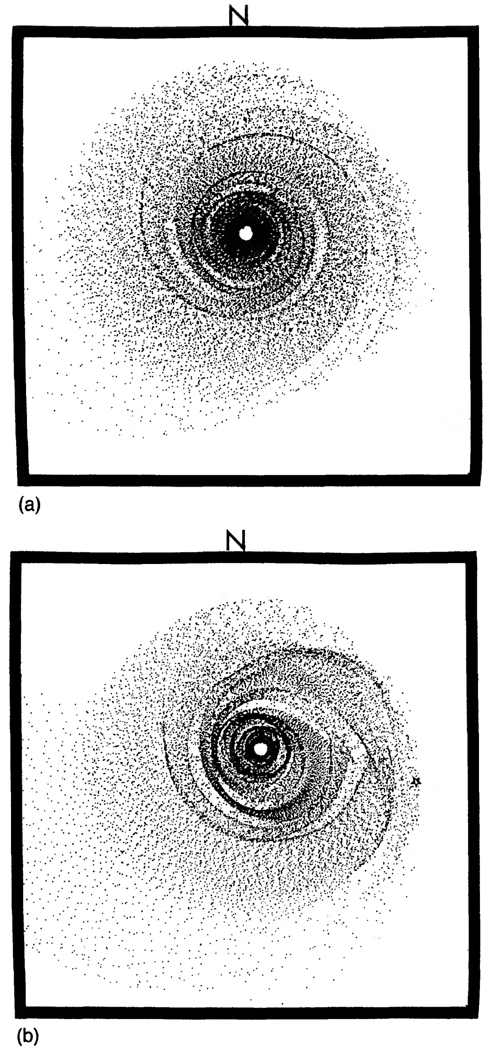


FIG. 4. (a) Effect of different close approach distances, $R_{en}=4/20$. (b) Effect of different close approach distances, $R_{en}=1/20$ disk radii.

3.3 Precision of Model Parameters

We vary the parameters around our best choice to give an idea of how sensitive the fit is to different model parameters. There is a separate figure for each parameter variation, larger and smaller. These parameter values are chosen so that a significant difference appears or to show insensitivity, if that is the case. All the pairs are to be compared to the best choice frame in Fig. 3(a). We do this for minimum encounter distance, perturber mass, halo to disk ratio, and time step in the simulation. The sequence shown in Figs. 4(a), 3(a), and 4(b) displays the effects of different close approach distances. The values are 4/20, 2/20 (our best choice), and 1/20 disk radii, respectively. If the close approach is too large (4/20) the inner leading arm is too weak. If the close approach is too small (1/20) the outer arms are excessively disturbed with "kinks."

Figures 5(a), 3(a), and 5(b) show simulations with different masses for the disturber. The values are 0.03, 0.01 (our best choice), and 0.005 of the galaxy's mass, respectively. If the perturber is too massive, the outer arms are too irregular and merge into one another. For disturber masses too small, the inner leading arm and the outer arms are too weak.

Figures 6(a), 3(a), 6(b) show the effect of varying the halo to disk ratio. The values for the figures are: 16/1, 8/1 (our best choice), and 2/1, respectively. Clearly, at 2/1 the inner leading arm is practically absent and the outer trailing arms show bends not present in the actual galaxy. Increasing the halo-to-disk past 8/1 to 16/1 does not improve the match but it is just as good as our best choice.

To understand what these results mean, we should recall that the flat rotation curves of many spiral galaxies do not in themselves indicate relatively massive halos for the visible disk region. For example, the halo importance can be varied to whatever one likes in our model with the initial rotation curve being flat. This inert halo is thought not to be supported by rotation like the disk but instead by a high

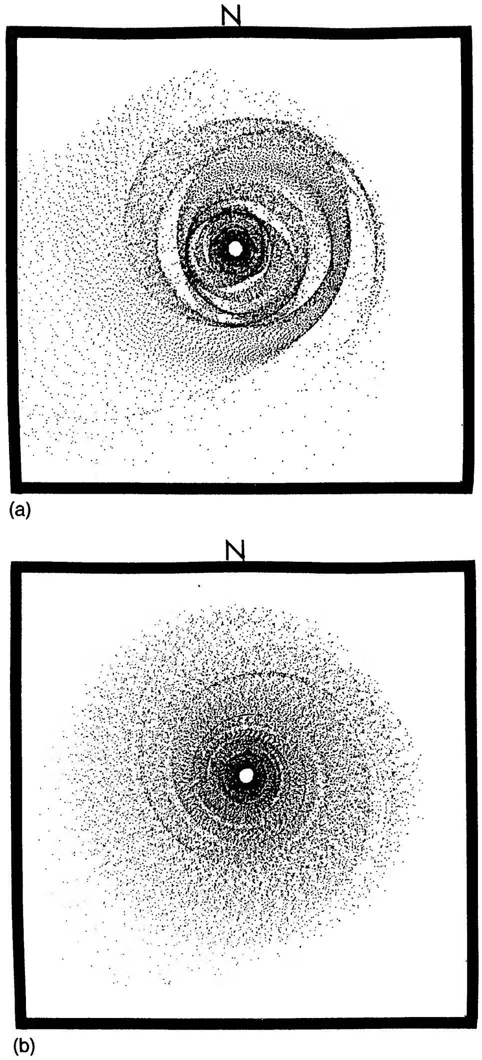


FIG. 5. (a) Effect of different mass for the disturber, 0.03 galaxy's mass. (b) Effect of different mass for the disturber, 0.005 galaxy's mass.

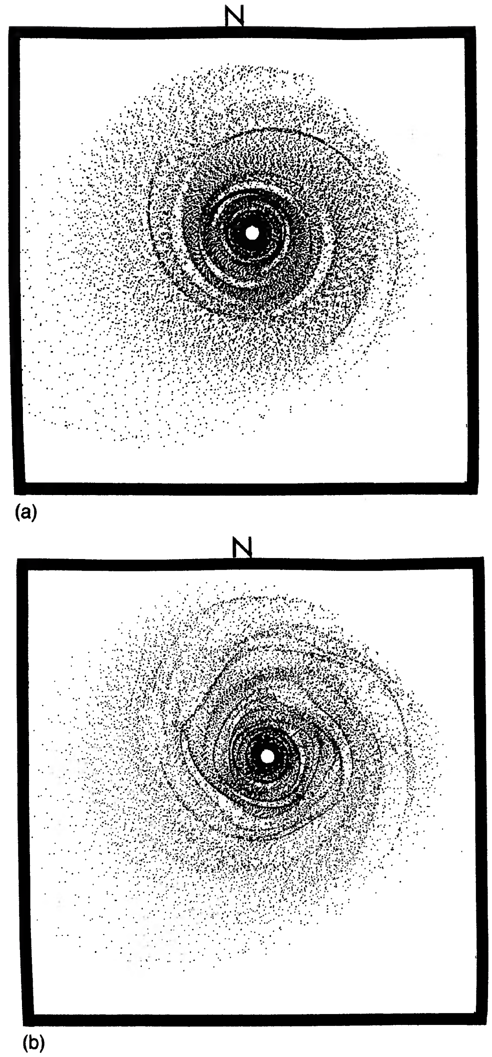


FIG. 6. (a) Effect of different halo-to-disk ratios, ratio 16/1. (b) Effect of different halo-to-disk ratios, ratio 2/1.

internal velocity dispersion. It is thus very stable against perturbations and can by its gravitational field help stabilize the disk. However, for a ratio less than one, the disk is very sensitive to tiny perturbations. A perturbed disk will violently become a barred disk with a large velocity dispersion. One wonders whether galaxies with extremely massive halos do exist. The mere absence of a bar is not enough to tell us more than that the ratio is not less than 1.0. We now see one can profitably use the arm pattern as a halo to disk indicator. By simple comparison of the above variation with the galaxy arm pattern, we can conclude that NGC 4622 has indeed a massive inert halo contributing at least 8 times the disk material to the gravitational potential. Self-gravitation is of little importance in NGC 4622's disk.

Figure 7 is a time sequence of the events in the arm formation which also shows how finely specified the time step is in our simulations. Figure 7(a) shows step 15 before anything has happened with the perturber (marked with a star) and the galaxy falling toward one another. Figure 7(b) is step 55 nearly at close approach. Note that no arms exist yet. Figure 7(c) shows step 75 when trailing arms begin to appear. The leading arm starts to appear by Step 175, which is Fig. 7(d). Figure 3(a) shows step 250, our best choice. At 50 steps earlier than 250 or 50 steps later, the appearance is not a good match to NGC 4622. Finally, the leading arm lasts a long time. Figure 7(e), shows that it persists to step 900, about a billion years after the start of the simulation. This time interval is about three rotations of the disk edge. We see that the outer arms are wrapped almost to nonexistence by step 900.

Our best choice plunging orbit is retrograde. We tried a corresponding close direct encounter and got a disk that looks much like our best choice (see Fig. 8). We think that the outer trailing arms of the retrograde passage match the outer arms of NGC 4622 a bit better. However, both retrograde and direct passages resemble NGC 4622 pretty well. We can understand this by noting that for extremely

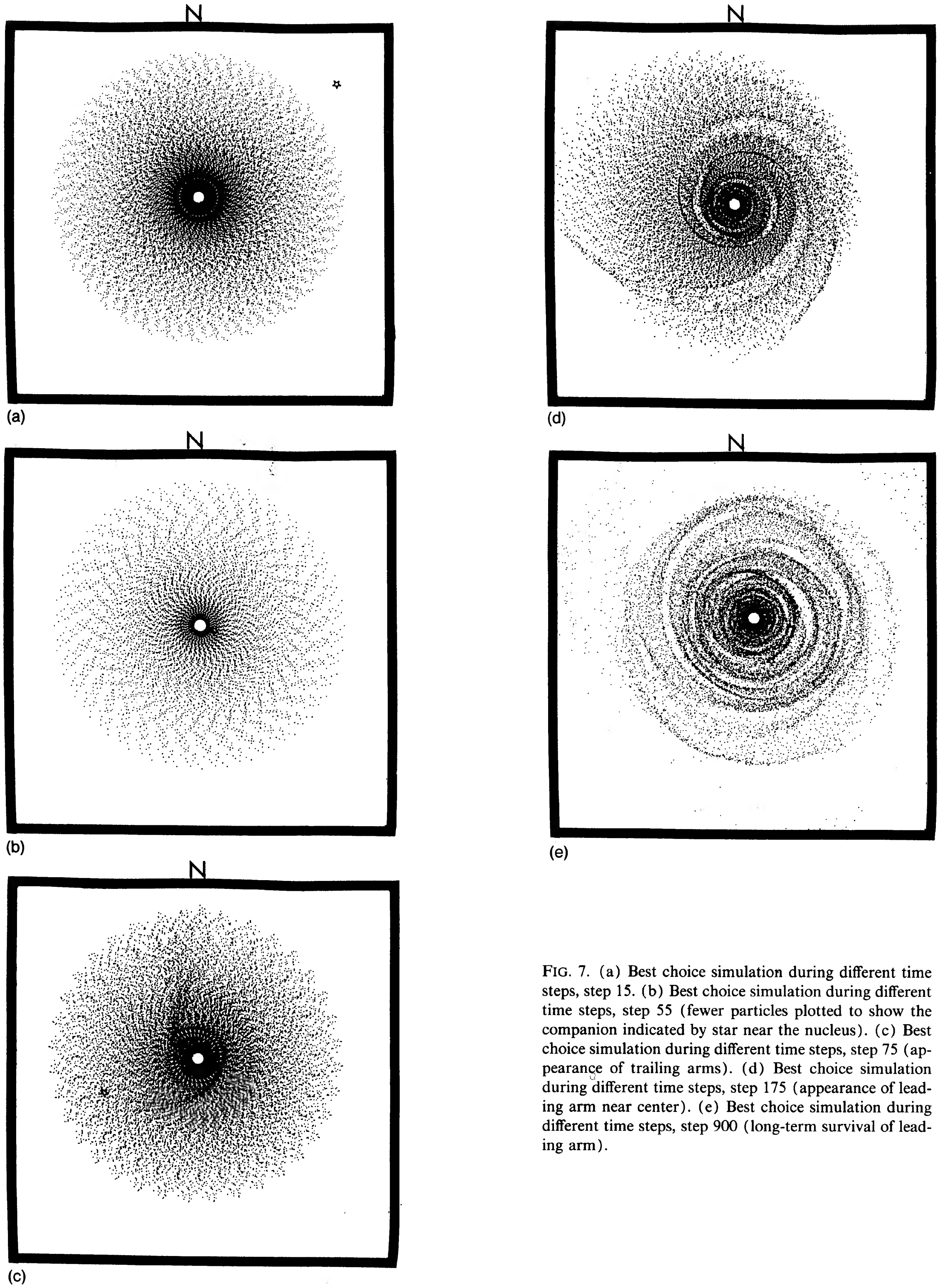


FIG. 7. (a) Best choice simulation during different time steps, step 15. (b) Best choice simulation during different time steps, step 55 (fewer particles plotted to show the companion indicated by star near the nucleus). (c) Best choice simulation during different time steps, step 75 (appearance of trailing arms). (d) Best choice simulation during different time steps, step 175 (appearance of leading arm near center). (e) Best choice simulation during different time steps, step 900 (long-term survival of leading arm).

close encounters that the $m=1$ component of the companion's potential is strong for such close passages. In contrast, a passage beyond the disk edge would be primarily in the $m=2$ component and result in a pair of trailing arms unless the companion is retrograde. For the very close passage, the $m=1$ component will impulsively give velocity perturbations to the disk particles which then result in a turning, leading arm. Thus small mass perturbers passing near the nucleus can make leading arms, rings, and outer trailing arms regardless of orbit sense as long as the halo is dominant! Incidently, the leading arm created by the close direct passage does not last as long as the leading arm from

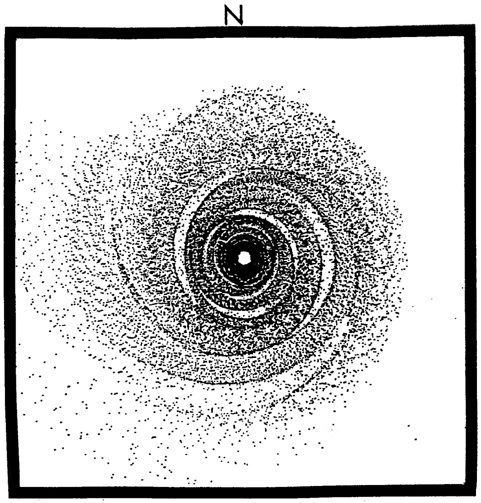


FIG. 8. Best choice simulation matching Fig. 3(a) except that the orbit is direct. Note the resemblance to Fig. 3(a) with some difference in the outer arms.

the close retrograde passage, i.e., by the same time as the retrograde Fig. 7(e), the direct leading arm has disappeared.

Finally, we need to mention a few other points. We have no redshift for the suspected perturber, no tilt for the disk, and no available rotation curve for the disk. Our simulations are thus only preliminary. In Fig. 3 our computer companion is about 1.3 times too far eastward of NGC 4622 compared to the photograph of Fig. 3 in BCB. This might be changed by fine adjustment of the time since close approach or of the rotation curve. Small satellites, such as M32, within large galaxies like M31 will probably be destroyed eventually (Byrd 1979). Because of the possibility that the actual perturber was destroyed in the experience and because the redshift of the suspect is unknown, we did not try to get our simulation companion in a projected position exactly matching that of the suspect.

3.4 The Short- and Long-Term Evolution of the Arm Pattern

There are a few other galaxies known that have a central ring and single inner arm like NGC 4622. However, these have only weak or no outer trailing arms (e.g., NGC 4378). It is quite possible that these galaxies represent the long-term evolution of a galaxy perturbed like NGC 4622. The present pattern of NGC 4622 is still young, as we see comparing our long-term simulations and step 250 of our best choice to the photograph of the galaxy. This is indicated by the presence of trailing arms in the outer disk of NGC 4622 and the arm segments in both the leading and trailing arms, features weakened in the long-term appearance of Fig. 7(e).

The reader might wonder how the leading arm and ring is maintained in the latter time frames of Fig. 7. The pattern has grown to look much like that in Athanassoula (1978) created by a circularly orbiting retrograde companion. However, there is little self-gravity in the disk of our best choice simulation so that the pattern cannot affect itself. As we have found, disk self-gravity is the enemy of leading arms. What can be carrying out the excitation? To understand, one has to recall that the disk of the primary galaxy is extended in space and not rigid. As the perturber swings by, parts of the disk nearer the perturber are affected more than those far away. In our case, the perturber actually enters the disk and as it swings by the nucleus, those inner portions of the primary will be affected more than the outer portions of the disk. Via Newton's third law, the nucleus and inner-most disk will be set to oscillating in a retrograde sense relative to the outer disk. In the long term, the net result will be just as if there were a retrograde companion orbiting continually outside the galaxy with a similar pattern created as in Athanassoula (1978). Our present model includes these third law effects in a simple fashion as described in Thomasson (1989). As a further test of this hypothesis, we placed a small disturber in a retrograde circular orbit inside the disk near the nucleus. It produced a leading arm and ring arc outside its orbital radius.

Miller (1992) and Miller *et al.* (1990) have studied oscillations in elliptical galaxies and halos of spiral galaxies as a general phenomenon, without regard to its origin. They find that the galaxies can start oscillating easily and do it for a long time. We find here that the disks of spiral galaxies may provide distinctive morphological signatures of nuclear oscillation.

4. DISCUSSION AND CONCLUSIONS

At the present time, only a few candidates for leading arm galaxies are known, with NGC 4622 being the sole confirmed case because it has both leading and trailing arms. In our simulations, we are able to produce its leading arm and pair of trailing arms quite successfully. The best fit to the observations is shown in Figs. 3(a) and 3(b). Comparing to Fig. 1, the three major features are all present, the inner leading arm, the ring where the leading arm winds out to, and the outer trailing arms. However, we find that a passage very close to the nucleus of a small mass companion seems to produce the best match. This is in contrast to the more massive distant retrograde companions considered in previous simulation papers which produced leading arms but not the sort of outer trailing arms we see in NGC 4622. Both our simulations and the observed leading and trailing arms show segments, confirming that we are on the right track with our small mass, plunging perturber, and the youth of the arm pattern. We also find that the leading arm will last a long time, at least a billion years into the future. If such arms are frequently created, they should be frequently seen, but this is not the case.

Recall that a condition for leading arms was an inert halo that dominates the dynamics compared to the disk. The rarity of leading arms in galaxies might thus be due to a lack of galaxies with dominant halos. However, up to now, simulations indicated that comparatively rare encounters with comparable-mass companions were also necessary for leading arm formation. Byrd and Howard (1992) showed that disk galaxies are subject to ubiquitous perturbations by small mass perturbers. From the discussion in this present article, plunging small-mass perturbers can create leading arms that can be long-lived via their own action and subsequent nuclear oscillation. As we have seen, a disk at all comparable to the halo suppresses leading arm formation. Since so few leading arm spirals are known to date, massive halos thus may not be common at all.

Later in our simulations the outer tailing arms wind up and disappear. We can count ourselves fortunate to see NGC 4622 at the early stage of its life so it has two outer arms as well as a leading arm. This pattern tells us of the type of event that created its "different twist" pattern which, in turn, tells us of the existence of its unusually massive halo. Needless to say, further observational searches are needed for this type of galaxy arm pattern to double check that they are indeed rare. Perhaps many of them are hidden, like that of NGC 4622 was, by overexposed nuclear regions. Also, more elaborate computer simulations are needed to simulate better the mutual effects of close passages of low-mass companions through disk galaxies. Finally, NGC 4622's pattern and our simulations have implications regarding ringed galaxies. Previously, the generation of ringed galaxies has concentrated on the effects of bars in various resonances with disk material. NGC 4622 may have a different way to make a ring and a leading arm with a plunging low-mass companion or an oscillating nucleus.

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REFERENCES

Athanassoula, E. 1978, A&A, 69, 395
Buta, R., Crocker, D. A., & Byrd, G. 1992, AJ, 103, 1526
Buta, R., & de Vaucouleurs, G. 1983, ApJ, 266, 1
Byrd, G. 1976, ApJ, 208, 688
Byrd, G. 1978, ApJ, 226, 70
Byrd, G. 1979, ApJ, 231, 32
Byrd, G., & Howard, S. 1992, AJ, 103, 1089
Byrd, G., Salo, H., & Howard, S. 1991, BAAS, 23, 824
Byrd, G. G., Thomasson, M., Donner, K. J., Sundelius, B., Huang, T.-Y., & Valtonen, M. J. 1989, Cel. Mech., 45, 31
de Vaucouleurs, G. 1958, ApJ, 127, 487
de Vaucouleurs, G., de Vaucouleurs, A., Corwin, H., Buta, R., Paturel, G., & Fouque, P. 1991, Third Reference Catalogue of Bright Galaxies (Springer, New York)
Howard, S., & Byrd, G. G. 1990, AJ, 99, 1798
Keel, W. C. 1991, ApJ, 375, L5
Lynden-Bell, D., & Pineault, S. 1978, MNRAS, 185, 679
Miller, R. H. 1976, J. Comput. Phys., 21, 400
Miller, R. H. 1992, Amer. Sci., 80, 152
Miller, R. H., Roelofs, G. R., & Smith, B. F. 1990, in Paired and Interacting Galaxies, IAU Colloquium No. 124, edited by J. W. Sulentic, W. C. Keel, and C. Telesco (NASA Conference Publication No. 3098), p. 549
Noguchi, M., & Ishibashi, S. 1986, MNRAS, 219, 305
Sersic, J. L., & Aguero, E. L. 1972, Ap&SS, 19, 387
Struck-Marcell, C. 1990, AJ, 99, 71
Thomasson, M. 1989, Research Report No. 162, Chalmers University of Technology, Gothenburg Sweden, ISBN, 110, 5564, pp. 30–31
Thomasson, M., Donner, K. J., Sundelius, B., Byrd, G. G., Huang, T.-Y., & Valtonen, M. J. 1989, A&A, 211, 25
Valtonen, M., & Byrd, G. 1986, ApJ, 303, 523
Valtonen, M., & Byrd, G. 1990, IEEE Trans. Plasma Sci., 18, 38
Valtonen, M., Valtaoja, L., Sundelius, B., Donner, K. J., & Byrd, G. G. 1990, Cel. Mech. and Dynam. Astron. 48, 95