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DYNAMICAL INTERACTIONS OF GALAXY PAIRS

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I. INTRODUCTION

As the dynamics of galaxy interactions is too broad a subject to be discussed in any depth in a single review, I will concentrate only on a few topics proposed to me by the organisers. Since a pair should be "two things of a kind", I will not discuss merging and merger remnants. I will also leave out discussions on M/L and hence halo mass determinations. Good reviews covering these subjects, and some of the subjects treated here, have been given by Toomre (1977), Tremaine (1981), White (1982, 1983a), van Albada (1988), Barnes (1990) and others. Here I will briefly review the dynamics of sinking satellites and the effect of companions on elliptical galaxies, then discuss recent work on interacting disk systems, and finally focus on my favourite interacting pair NGC 5194/5195.

II. SINKING OF SATELLITES

a) Non rotating spheroids (Ellipticals or halo dominated galaxies)

A satellite orbiting around a galaxy experiences a drag force which leads to a gradual orbital decay and eventually a merging in a time scale no longer than a Hubble time. This loss of the satellite's orbital energy due to dynamical friction will excite internal motions in the main galaxy. Chandrasekhar's formula (1943), appealing for its simplicity, has often been used for estimating this deceleration. Yet it is in principle valid only for the motion of a point mass through an infinite homogeneous medium, and thus should not apply to satellite galaxies. Nevertheless several authors (e.g. Lin and Tremaine 1983, Bontekoe and van Albada 1987 etc.) have reported a fairly good agreement between their numerical results and the estimates obtained from Chandrasekhar's formula. This should indeed be the case if the distance of the satellite from the center of the parent galaxy is very large compared to the radius of the satellite or if the matter distribution in the main galaxy is self-similar (Weinberg 1989). However one should not conclude from this that dynamical friction is a local effect and in general one should not expect Chandrasekhar's formula to be an adequate approximation to the orbital decay of an extended satellite. A proper and elegant analytical treatment, including self-consistency, has been given recently by Weinberg (1989).

An ideal numerical treatment would include a fully self-consistent description of both the galaxy and the satellite, and a sufficiently large number of particles to eliminate spurious effects like enhanced two body relaxation. This is however not easy to achieve and many alternatives have been used so far including the semirestricted N body method, harmonic expansions for the calculation of the galaxy potential, the direct N body code and the tree code (Lin and Tremaine 1983, White 1983b, Bontekoe and van Albada 1987, Zaritsky and White 1988, Hernquist and Weinberg 1989). To cut a long story short one can say that the subtleties of the various codes, and in particular the treatment of the motion of the center of mass, can influence substantially the results. So it was not until the various approximations in the different numerical treatments were analyzed and understood that a good agreement between the various methods could be reached. Thus the latest attempt by Hernquist and Weinberg (1989) reports an agreement better than 2% between their results and those of Bontekoe and van Albada (1987) and Zaritsky and White (1988).

Weinberg (1989) and Hernquist and Weinberg (1989) argue that the inclusion of self-gravity necessarily requires also the correct treatment of the center of mass shift, since this determines the $m = 1$ Fourier component of the density and potential. They find then an increase of the decay time by a factor of 2 - 2.5 with respect to non-self-gravitating calculations. At first thought one could have expected the self-gravity to enhance the wake of the satellite, thus increasing the drag force and decreasing the decay time. However, the response of the main galaxy to the satellite is not local but global and thus the effect will depend on the phase difference between the satellite and the response of the main galaxy to it. Ideally of course the satellite should also be treated self-consistently since stripping will remove its more loosely bound stars. Compared to numerical calculations, analytical results give estimates of decay rates larger by factors of the order of 50%, due to the neglect of nonlinear effects. This discrepancy appears to vanish for sufficiently small satellite masses (Hernquist and Weinberg 1989).

Scaling the results of the various numerical simulations to the dimensions of real galaxies, one finds decay rates of the order of a few times 10^9 yr. The precise number will depend on various properties like the mass profile and the distribution of velocities in the main galaxy. In this respect we note that most of the simulations run so far have used Plummer profiles, which are less centrally concentrated than the light distribution in elliptical galaxies. Furthermore the inclusion of some rotation could increase the time scale of the orbital decay.

b) Disks

The situation for disks is much more complicated than for spheroids since there are now at least three different mechanisms active (e.g. Tremaine 1981, Quinn and Goodman 1986):

i) Standard dynamical friction as in the case of spheroids

ii) Exchange of energy and angular momentum between the satellite and stars around the Lindblad resonance of the parent disk

iii) Non perturbative "horseshoe" orbits.

The effect of the two first mechanisms is in the opposite sense, i.e. the first pulls the satellite inwards while the second one moves it to larger radii. This can explain the difference between the results of the analytical work of Palmer and Papaloizou (1982), focusing on the second effect, and those of the N-body simulations of Byrd *et al.* (1986). Quinn and Goodman (1986) stress the importance of self-consistency and of a correct treatment of the center of mass. It is a great pity that self-consistent treatments in which the center of mass of all components is allowed to move freely are not available. Yet existing numerical simulations (Quinn and Goodman 1986, Byrd *et al.* 1986, Valtonen *et al.* 1990, Valtaoja 1990) give us a lot of useful information. Satellites in retrograde or out of the plane orbits have much larger decay time than direct in plane ones, and heavier satellites decay faster than lighter ones.

III. THE EFFECT OF COMPANIONS ON ELLIPTICAL GALAXIES

As shown by the simulations of van Albada and van Gorkom (1977), White (1978), Miller and Smith (1980) and others, colliding spherical galaxies undergo a temporary contraction to about half of their original size, due to the extra inwards force each star feels during the overlap. After the separation the galaxies are larger, more loosely bound and often nonspherical.

Aguilar and White (1985) discussed the exchange of mass during the encounter. For slow collisions, where the relative velocity is smaller than the velocity dispersion in the galaxies, about one third of the mass lost by one galaxy is gained by the other. This fraction increases with decreasing galaxy separation. For distant encounters the exchange is larger for models with more stars on tangential motions, while for nearly head-on encounters it is larger for models with more stars on radial orbits. Thus one can say that the stars captured are those whose velocity vectors do not form a big angle with that of the perturber's.

Miller (1986) and Mc Glynn (1990) studied the effect which an encounter with a big galaxy can have on a small one. Miller argued that a spherical galaxy either suffers very little mass loss (less than one percent) or is totally disrupted. On the other hand the galaxies in Mc Glynn's simulations could loose up to half their mass and still survive. The explanation of this apparent contradiction lies in the density profiles used in the two cases. Miller, using a code with a cartesian grid, modelled galaxies with little central concentration, namely $n = 3$ polytropes. On the other hand McGlynn, using a tree code, modelled more centrally concentrated King profiles. He showed that the central core is little affected even in cases where 30% of the particles in the outer parts were lost. However this number could well depend on the properties of the distribution function used. Thus Miller's results describe the behaviour of less concentrated systems, like halos, and Mc Glynn's of more concentrated systems, like elliptical galaxies.

IV. THE EFFECT OF COMPANIONS ON GALAXIES WITH DISKS

a) Outer parts. Formation of bridges and tails

The now classical work by Toomre and Toomre (1972, hereafter TT) established that gravitational interactions alone can account for the formation of bridges and narrow tails. Using a simple model of test particle simulations they made a comprehensive survey of bridges and tails and of the effect of different encounter parameters on them. They showed that bridges are best seen in interactions with small companions, while tails manifest themselves better in interactions with equally or more massive companions. The amount of matter accreted by the companion is substantial for small angles between the plane of the galaxy and the orbital plane, but decreases rapidly as this angle increases. The effects of retrograde encounters are much less spectacular than the results of direct ones. TT also gave models for four very interesting interacting systems, Arp 295, NGC 4676 (the mice), NGC 4038/4039 (the antennae) and NGC 5194/5195 (M51).

That same year appeared another study on bridges and tails (Clutton-Brock 1972), remarkable not for the comprehensiveness of the survey but for the fact that the simulations reported were actually self-consistent, including both gas and stars. It showed that the gaseous tails could be indeed very thin and long.

Gerhard (1981) studied interactions of pairs with the help of two 250 - particle self-gravitating systems, where roughly half of these particles constitute a live halo. He showed that, due to the escaping particles, which carry away a substantial fraction of the internal angular momentum, and to the capture of new particles, which may even be counterrotating, the final internal spin of each disk is smaller than the initial one. Haloes receive angular momentum from the orbital motion. However, unless the orbital plane happens to coincide with the spin planes, the acquired halo angular momentum vector is not aligned with the one of the disk, a factor which could significantly affect galactic evolution. In general one can say that the strength of the interaction depends heavily on the three spins involved, those of the two galaxies and the orbital spin. Mass exchange was found to be more important than mass loss in these experiments. Thus if the perturber is modelled as a point mass, the mass loss calculated is artificially higher then when the perturber is treated as a collection of points. This is in agreement with the results on elliptical galaxies (Aguilar and White 1985) mentioned above.

Barnes (1988) used a tree code to repeat the TT simulation which gave the best fit to the antennae (NGC 4038/4039), in order to see the effects of self-consistency. He observed a strong coupling between orbital and internal energies, so that, at the time when the TT simulation showed the best fit to the observations, the two galaxies had already merged in the self-consistent simulation. At the time when the fit to the observations was at its best the main bodies for the two galaxies were very near each other and the two tails quite thin. The overall fit is good, particularly when one takes into account the fact that no scan of the parameter space for a best fitting model was attempted. Barnes discusses two drawbacks of his model. The first is the failure to match the velocities of the two main bodies. The second is the fact that the assumed orbit was elliptic with $e = 0.5$, while the effects of a previous encounter were neglected. Barnes also simulated the formation of tails during parabolic encounters. Haloes increase the relative velocity of the encounter and change substantially the morphology of the tails, without, however, inhibiting their appearance.

b) The response of the gas

Noguchi and Ishibashi (1986) returned to test particles and to two dimensional simulations including both stars and gas. The rate of gas cloud collisions in their simulations allowed them to estimate the variation of the star formation rate during the encounter and the corresponding change of colours of the galaxy. They concluded that the star formation rate will reach a maximum, of the order of several times the pre-encounter rate, some few times 10^8 years after perigalacticon.

This result was confirmed by Olson and Kwan (1990), who used three-dimensional models in which the change of potential of the two galaxies during the encounter is taken into account. They used more elaborate collision rules, inspired from Latanzio and Henriksen (1988), including coalescence and disruption of gas clouds. For these rules, the interaction increases the rate of disruptions more than the rate of coalescence, the effect being more important for stronger interactions. This should lead to a more disturbed and fragmented interstellar medium in more violently interacting systems. The region of high cloud collision rates is also more centrally concentrated for the stronger interactions.

c) Inner parts. The driving of spirals

Both analytical work and N-body simulations have shown that direct passages may drive two armed trailing grand design spirals (Toomre 1969, 1981; Goldreich and Tremaine 1979, Sundelius *et al.* 1987, Athanassoula 1990, etc). This is in good agreement with observations, which show a substantially larger percentage of grand design spirals amongst binaries and galaxies in groups, than amongst isolated galaxies (Kormendy and Norman 1979, Elmegreen and Elmegreen 1982).

Retrograde encounters may force both two armed trailing spirals and one armed leading ones. The latter comes from the interplay between the companion and an $m = 1$ resonance of the inner Lindblad type, which is the only one possible in the case of retrograde pattern speeds, and the result is an $m = 1$ (one armed) leading spiral (Athanassoula 1978). This is the case even if self-gravity is neglected (Kalnajs 1975, Noguchi and Ishibashi 1986), although its inclusion and the parameters describing the stellar and gaseous component influence the overall form of the spiral. Thomasson *et al.* (1989) modeled the effect of a retrograde companion with the help of N-body simulations and verified the formation of the one armed leading spiral. This was particularly obvious in the case of galaxies with high halo-to-disk mass ratio, where the swing amplification is inhibited and the $m = 2$ (two armed) trailing component is of low amplitude.

Some properties of the driven spirals have been discussed by Athanassoula (1990). She showed that the driven spiral patterns are neither permanent nor stationary and that their structure depends heavily on the properties of the perturbed disk. The initial velocity dispersion evolves drastically with time and is raised by the heating due to the spiral perturbations. In the case of unstable disks, the spiral structure which develops unaided interacts nonlinearly with the forcing and, depending on the relative differences of their pattern speeds and phases, this leads to a temporal increase or decrease of its amplitude.

d) Inner parts. The driving of bars

Noguchi (1987) and Gerin *et al.* (1990) showed that the main effect of an interaction on a bar unstable disk is to accelerate noticeably the bar formation. Thus, all other things being equal, the frequency of bars amongst pairs should be enhanced. This is in fact born out by the observations which show that there are 63% of SBs and SABs amongst isolated galaxies, compared to 81% for binaries (Elmegreen and Elmegreen 1982).

The bar instability sets in differently in interacting compared to noninteracting cases. In noninteracting cases the $m = 2$ component is sizeable only within the corotation radius, while in interacting cases there is an important $m = 2$ component outside corotation which travels inwards to enhance the $m = 2$ growing there.

Strong interactions may temporarily enhance (or decrease) the bar amplitude. This depends on whether the bar leads or lags behind the companion at perigalacticum. If the bar leads it slows down while its amplitude increases, and the opposite occurs when the bar lags behind. This can be easily understood if one considers the exchange of angular momentum between the bar and the companion. Finally 3D simulations show that the interaction will cause a thickening of the galactic disk, particularly in its outer parts.

V. NGC 5194/5195

NGC 5194 (M51) has one of the most spectacular spiral structures observed. Deep exposures (e.g. Burkhead 1978) show a faint outer disk, ending abruptly on the western side and giving the galaxy a comma-like structure, as well as feathers or streamers, which, as simulations have shown, are characteristic of gravitational interactions (e.g. Toomre 1978). Tully (1974) obtained a detailed Hα velocity field with Fabry-Perot interferometry, and established that the photometric and kinematical major axes do not agree. Indeed it is very difficult to decide on values for the position and inclination angles of this galaxy (Garcia-Gomez *et al.* 1990). Kinematical studies (Tully 1974; Shane 1975; Goad *et al.* 1979; Rots *et al.* 1990a and b) give position angles around 170°. On the other hand photometric studies (Boroson 1981; Grosbol 1985) as well as spiral structure analyses (Considre and Athanassoula 1982 and 1988) give values around 30°. For the inclination Tully (1974) gives 20°, and all other studies between 30° and 40°. It is not straightforward to assess these values. The motions in the inner parts might be affected by an oval (Pierce 1986; Wright and McLean 1988) while those in the outer parts by the interaction, resulting in nonnegligible departures from circular motions which could influence the kinematical methods. On the other hand the outermost isophotes may well be non circular, as can indeed be argued from the outermost isophotes of some simulations (e.g. Fig. 1; see Athanassoula 1990 for a description of the simulations). As for the spiral structure analysis, it has been so far applied to too few galaxies (16 so far) for all its shortcomings to be clear. So to sum up, the orientation in space of this galaxy is not clear.

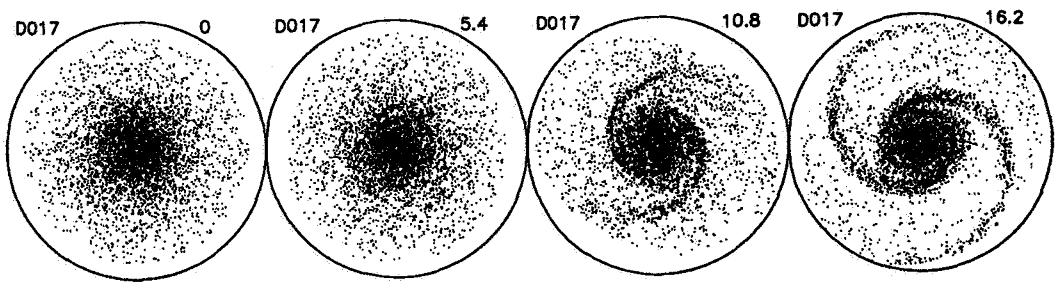

Fig. 1. Response of a disk to a strong external forcing

Rots *et al.* (1990a and b) observed this galaxy in HI using the B and D arrays of the VLA. Their channel maps show isocontours of the shape of the letter S or H, instead of the standard U shape due to differential rotation. They found a long extension in the form of a tail, starting at the SW of NGC 5194 and extending towards the south and then the east. Its total projected length is of the order of 90 kpc and its HI mass roughly $5 \times 10^8 M_\odot$. It does not connect onto one of the two bright arms but rather surrounds the bright disk. Such structures often develop in N-body simulations, and an example from a simulation by S. Engstrom, is given in Fig. 2. This is of course not a model of M51, only an example of a formation of such very long, semi-detached tail. It shows how the continuity of the very long tail to the inner spiral structure is lost with time because of the different motions of the inner and outer parts. The presence of such a tail argues that a longer time has elapsed since the pericenter of the NGC 5194/5195 pair than that proposed by TT and Toomre (1978).

The velocity field of M51 is shown in Fig. 3 (see also Fig. 7 in Rots *et al.* 1990b).

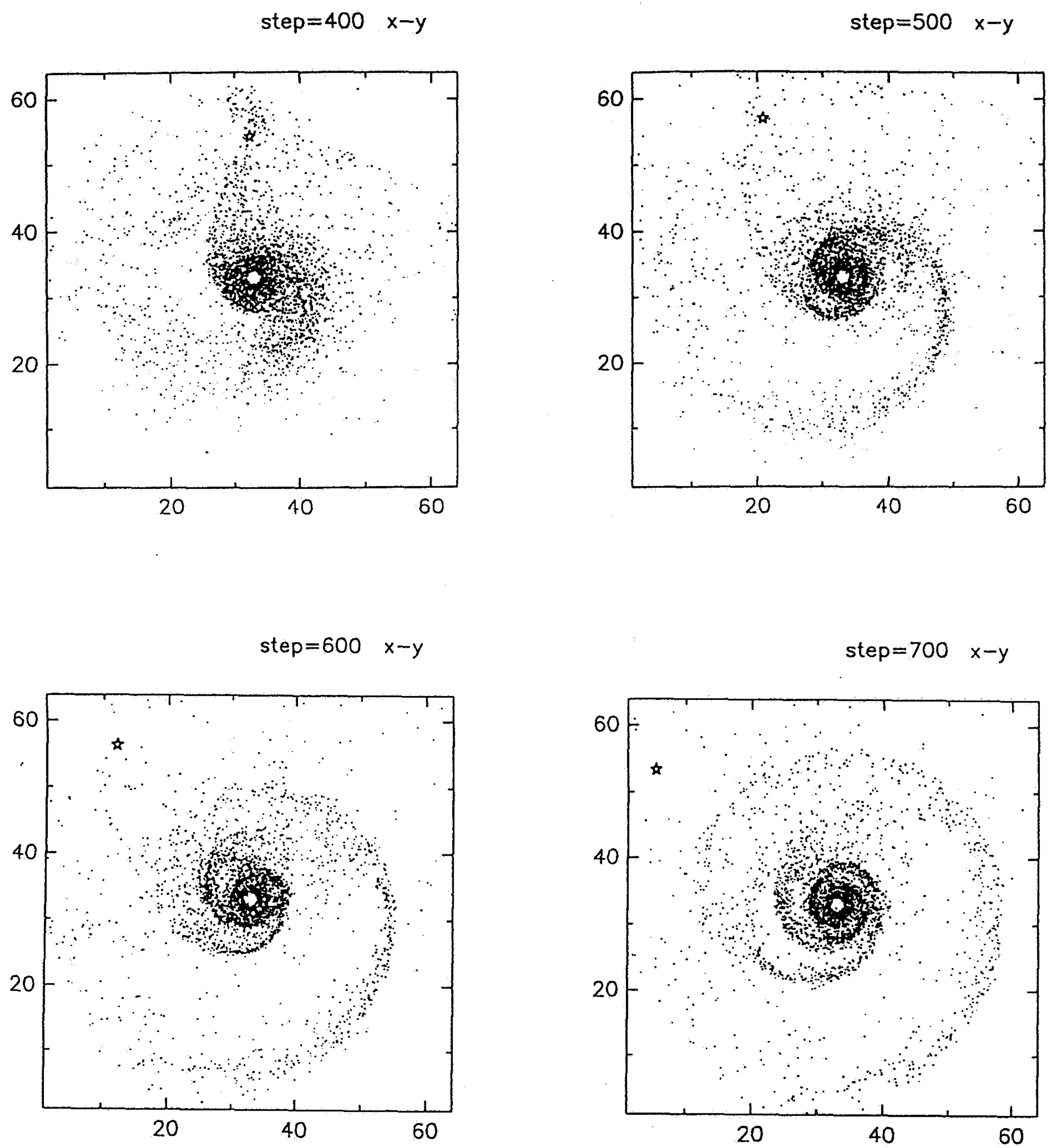

Figure 2. Formation and evolution of a long thin tail, reminiscent of the one observed in M51

In the southern part of the tail we observe velocities between 460 and 360 km/sec, i.e. values similar to those observed in the northern, not the southern part of the disk. A very simple, kinematical, explanation for this can be seen in Fig. 4. The upper left panel shows a greyscale plot of the velocity field of a Toomre disk to which is appended a tail partaking to the same motion. The disk and tail are on the same plane, with 0° position angle (PA) and 20° inclination. However numerical simulations show that the tail of interacting systems is often on a different plane from that of the disk (see e.g. Fig. 14 of TT). If we assume that the plane of the tail has an inclination of $-20°$, then the velocity field changes, as is shown in the upper right panel, and we get in the southern part of the tail similar velocities to the northern part of the disk, as in M51. Still in this simple example the PA of the maximum velocity in the tail is the same in the tail as in the disc, while in M51 the PA of the maximum velocity is roughly at $-20°$ in the disk and $-50°$ in the tail. A shift of the position angle can be found either by a twist of the line of nodes, or, as shown in the lower two panels of Fig. 3, by adding an inwards or outwards radial velocity component.

As could be expected the modelling of such an interesting object has proven to be both appealing and popular (e.g. TT, Appleton *et al.* 1986, Hernquist 1990, Howard and Byrd this volume). Hernquist made a self-consistent replay of the model favoured by TT. He showed that, in good agreement with what has been discussed above, a nice two arm spiral structure develops in the inner parts of the self-consistent disk. The outer structures bear some resemblance to those of the test particle simulation, but at an early time, when the companion is still not on the right projected position. Even when the companion reaches the right position the long HI tail has not developed yet.

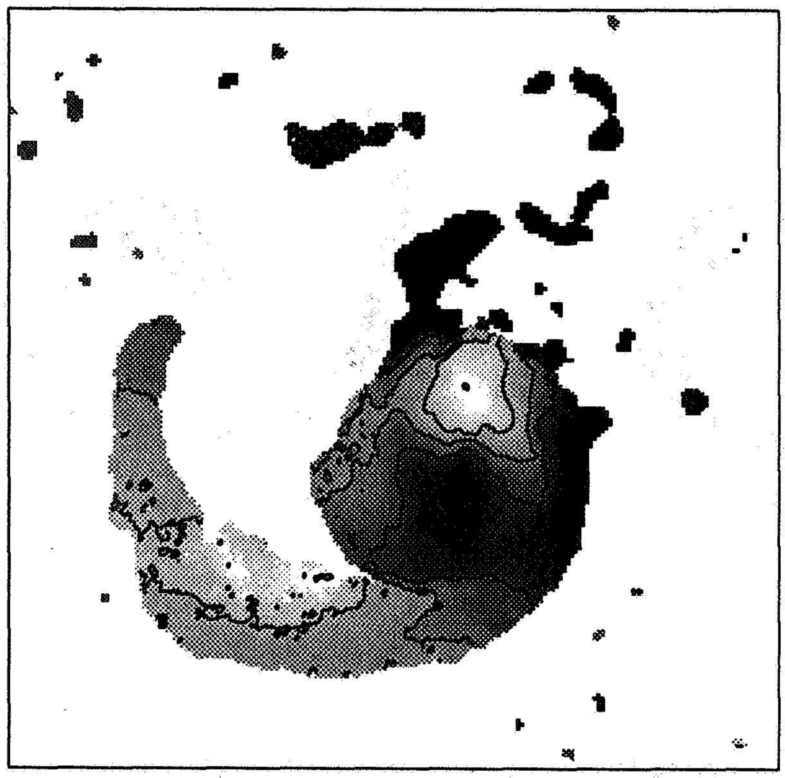

Figure 3. Velocity field of M51

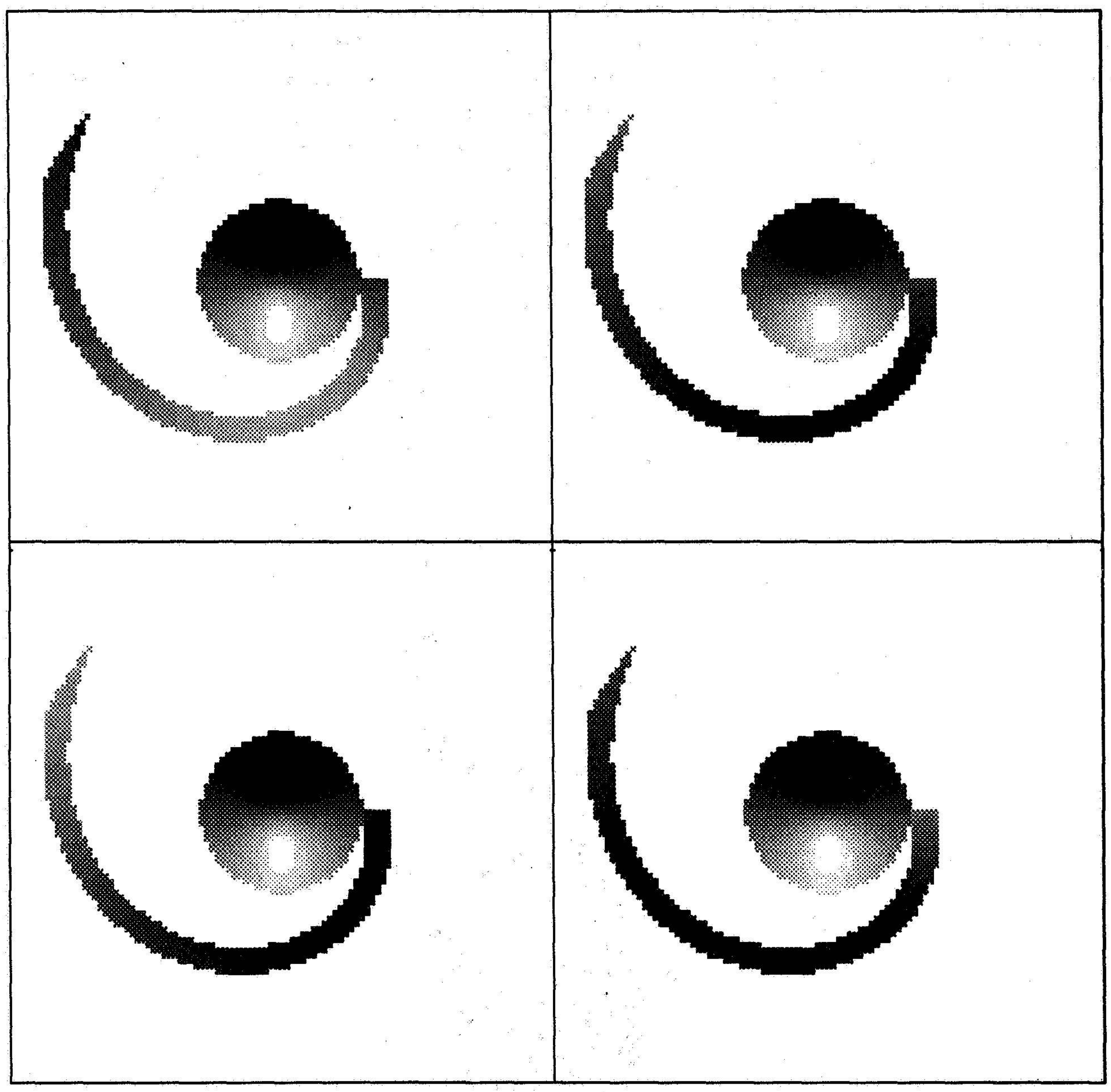

Figure 4. Simple kinematical model of the velocity field of a galaxy with a tail

Given the CPU time necessary for each simulation, it is not easy to make a full parameter survey, as done by TT. Yet Hernquist made, for parabolic encounters, a parameter search including several values of the orbital inclination, argument of the pericenter and impulse strength, thus giving precious insight to their effect. To get a better representation of the inner spiral and of the outer northern arm, one may need to try different models of the unperturbed M51 disk. If this had already a spiral before the encounter, a possibility that should not be neglected, then the problem becomes more complicated. Indeed the preexisting spiral would then interact with the forcing and the result would depend on their relative pattern speeds and phases (Athanassoula 1990). One could then expect secondary spiral features, breaks in the arms and/or evidence of more than one pattern speed. Whether this eventuality is the case or not, the interaction of M51 and NGC 5195 promises the modeler still many exciting moments.

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