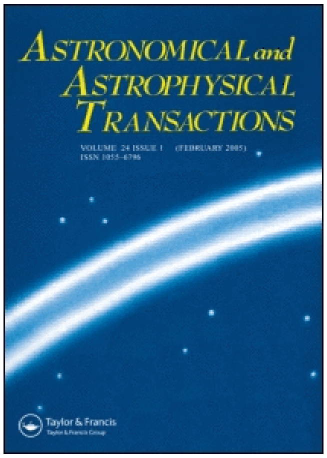

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N-Body models of M51: From extended tail to central spiral structure

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N-BODY MODELS OF M51: FROM EXTENDED TAIL TO CENTRAL SPIRAL STRUCTURE

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Various tidal models for M51 are reviewed, with the main emphasis on comparison with observed morphology and kinematics. Based on our current 3D self-gravitating simulations with up to 4×10^6 particles we propose that the 40° tilt of the extended HI tail, as well the high velocity material north of the companion are best explained in a model with a bound companion orbit. The same simulation models also suggest that the main spiral structure, including the inner spirals within 30″, can be accounted for by a tidal perturbation propagating inward from the outer disc with the group velocity, as originally envisioned by Toomre (1969). During this evolution amplitude variations along the spiral arms arise, much as observed.

KEY WORDS Galaxy dynamics, galaxy interactions, M51 (NGC 5194/95)

1 INTRODUCTION

M51 (NGC 5194) is a nearby, nearly face-on grand-design spiral galaxy, whose regular two-armed spiral structure extends in optical images from 30″ to 300″. Unsurprisingly, the exceptionally regular structure of M51 has received a lot of interest in studies of the origin and properties of spiral arms in general. For example, M51 has been one of the prime test cases for the Lin–Shu hypothesis (Lin and Shu, 1966), which views the spiral arms as intrinsically produced, rigidly rotating density waves: fairly acceptable density wave fits have been constructed for the spiral structure inside 150″ (Tully, 1974). However, IR-observations (Zaritsky et al. 1993) have revealed a pair of tightly wound stellar spirals inside 30″, tracing additional (1/2) revolutions around a central bar/oval at $r \approx 15''$. Although the amplitude of these innermost arms is quite weak, and their pitch angle is smaller than that of the main spirals, they seem to form a smooth continuation of the main structure. This poses a problem to density wave fits, since to extend the fit inside 30″, a considerably larger pattern speed would be required, making simultaneous matching of the outer structure difficult. A possible remedy would be the existence of two quite different intrinsic modes: however, the observed smooth continuation of spirals would then need an explanation. On the other hand, M51 has also been one of the main targets of tidal modeling, initiated by the classic study of Toomre and Toomre (1972). For M51 tidal models are well motivated by the presence of the prominent companion NGC 5195, as well as by many direct morphological and kinematic signs of interaction, the most notable of which is the extended HI-tail (Rots *et al.*, 1990) surrounding the main disc, reaching to a distance of $\simeq 15'$. In the interaction models the bridge and tail represent direct tidal perturbation while the global spiral arms of M51 are viewed as originally kinematic, transient tidal waves which have been amplified by the disc's self-gravity.

In this paper we review briefly the history of M51's tidal modeling, and describe our current simulations which favor a bound relative orbit of the companion. The resolution of these simulations is also sufficient to study in detail the propagation of the tidal wave and address the possible tidal origin of the innermost spiral structure.

2 PREVIOUS TIDAL MODELS FOR M51

Numerical modeling of an individual observed galaxy pair involves a large number of model parameters and assumptions (see e.g. Barnes, 1998). The morphological and kinematic characteristics excited during the interaction also depend, besides the passage geometry and strength, on the properties assigned to the initial galaxy models. In general, it is not guaranteed that a unique model can be found. However, for M51 pair there are a lot of observational constraints. These include, besides the observed velocity difference of about 100 km s^{-1} between the components, for example the straightness of the bridge arm, the existence of an extended tail, and material extension emanating from the companion. The kinematics also set stringent constraints on the models: the velocity field suggests that the extended tail must be strongly tilted (about 40 degrees) with respect to M51's inner disc (Rots *et al.*, 1990). There is also HI emission North of the companion, having velocities up to 250 km s^{-1} with respect to the central velocity of M51.

Most of the previous models of M51 have concentrated on the effects of nearly parabolic single passage of the companion, following the landmark study by Toomre and Toomre (1972; hereafter TT72). These test particle simulations were able to account for most of the morphology of M51 known at that time, including the bridge and tail arms, the general shape of the disc deformation, and the tidal debris emanating from the companion (see Figure 1). The companion, with mass 1/3 of the primary, was assumed to move in a highly inclined orbit, crossing the primary disc plane in the north-west quadrant about 100 Myrs ago. The lack of the main spiral structure was attributed to the neglect of self-gravity. Hernquist (1990) made first fully self-consistent 3D treecode simulations for M51, concentrating on parabolic relative orbits. His study emphasized that besides the inclusion of self-gravity, a considerably longer duration of the perturbation is required for the formation of the extended HI-tail. In Hernquist's most successful experiments the time since the

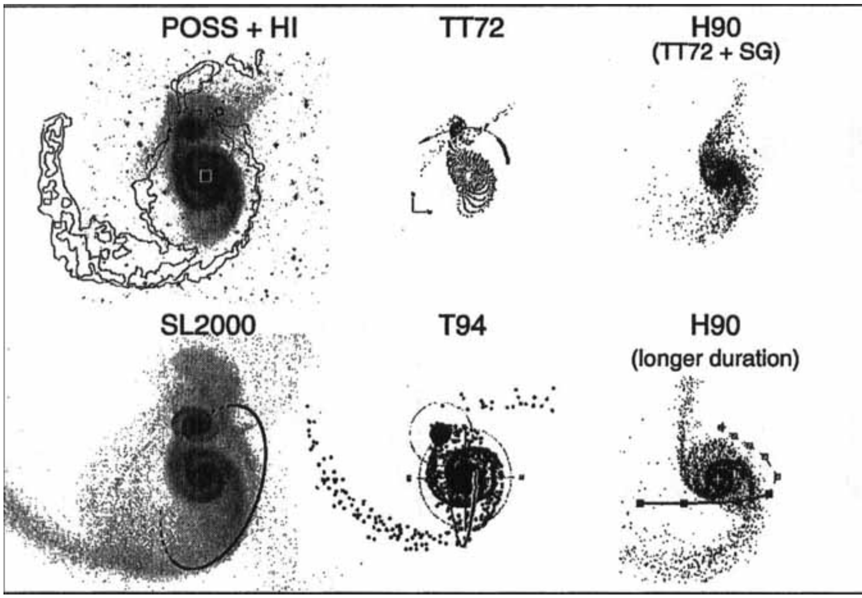

Figure 1 Evolution of tidal models for M51. In the upper left the Rots *et al.* (1990) HI observations are overlaid on the Palomar Sky Survey image. The box in the center indicates the region where the innermost stellar spirals are seen in IR observations (see Figure 7). Other frames display various simulations on the same scale: TT72 test-particle model, Hernquist (1990) self-gravitating TT72 model + model with different crossing direction, and Toomre (1994) self-gravitating model. The frame in the lower left displays our current model (Salo and Laurikainen, 2000a) with a bound perturber. Thick lines indicate the portion of orbit on the side of observer.

crossing was about 2–3 times longer than in the TT72 model, which required pushing the crossing direction to the south-west. Compared to TT72 he also reduced the pericenter distance and increased the companion mass, to one half. More recently Toomre (1994) refined the TT72 original model by including the disc self-gravity and by assuming the crossing to occur nearly south of the primary, with correspondingly increased duration since the perturbation. By adopting the mass ratio of unity, a quite successful morphological match can be obtained, the extended HI-tail being particularly well reproduced.

However, as discussed by Barnes (1998) the understanding of the M51 system is still far from being satisfactory. Especially, the apparently counter-rotating sense of the extended HI-tail, which most likely indicates a considerable tilt with respect to the inner disc of M51, is difficult to account for by the above mentioned models. A possible solution is that the present structure of M51 manifests more than one close encounter, implying a low current eccentricity for the orbit. Already Howard and Byrd (1990) have suggested a bound orbit for M51, based however on 2D models with an unrealistically small companion. On the other hand, a realistic simulation model implying a bound orbital configuration has been previously constructed for

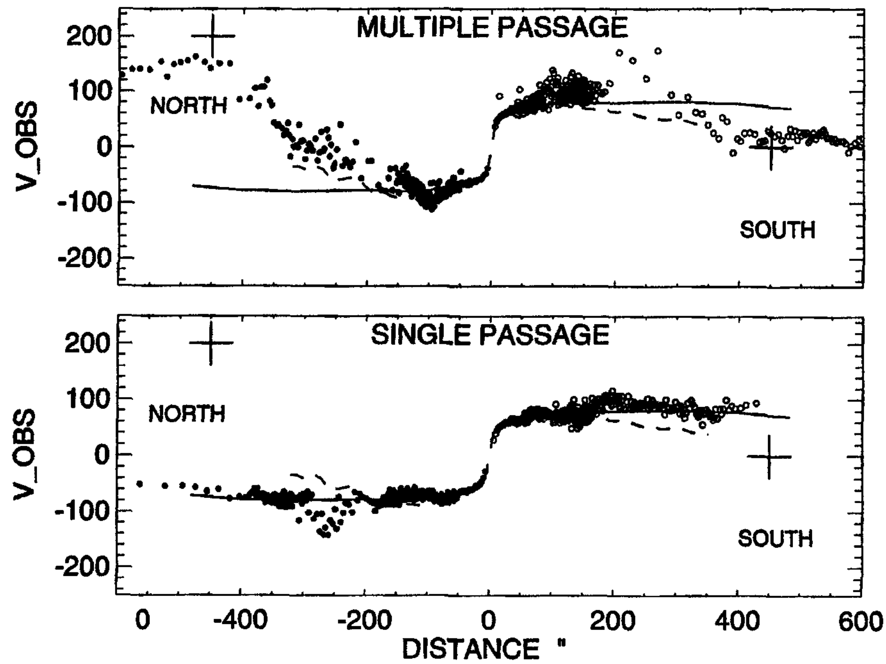

Figure 2 Major axis velocity curve in simulations: symbols indicate velocities in a 30 degree cone about the kinematic major axis ($PA = 170°$, $i = 20°$), while dashed lines denote the $H\alpha$ observations (Tilanus and Allen, 1991). Solid curve indicates the projected circular velocity curve from the simulation mass distribution. Large crosses indicate HI velocities from Rots *et al.* (1990) velocity field.

another M51-type interacting galaxy pair, NGC 7753/52 (Salo and Laurikainen, 1993), accounting for both morphological and kinematic observations.

3 BOUND MODEL FOR M51

We have recently re-investigated the interaction of M51 with its companion NGC 5195 (Salo and Laurikainen, 2000a, b), studying a wide range of orbital geometries. To facilitate an extended survey, a fast 3D spherical-polar grid code (Salo and Laurikainen, 1993) was used. In the simulations both components of the pair are described by self-gravitating exponential star+gas discs embedded in analytical bulge+halo potentials, chosen in a manner that gives a rotation curve in accordance with observation. These runs were also complemented by live-halo experiments, in order to study the long-term orbital evolution due to dynamical friction.

Altogether, two possible classes of relative orbits fulfilling the constraints set by the current projected separation and velocity difference were found: (1) nearly parabolic, single encounter orbits similar to those studied earlier, and (2) bound orbits implying several close passages. In both cases the major perturbation, capable of accounting for M51's prominent grand-design structure, took place when the companion crossed the disc plane of M51 about 500–600 Myrs ago, at a distance of about 20–30 kpc. However, the two classes differ with respect to the direction of this crossing. In the bound model the companion was moving toward observer, and a second crossing occurred about 50–100 Myrs ago, enabling the companion to reach its present position and velocity away from observer (see Figure 1).

We compared these two possible orbital classes in detail, with special attention to their kinematic implications. Both bound and parabolic models rather well explain the inner disc velocity field of M51. However, the observed high HI velocities to the north of the companion can be induced only if a recent passage took place, inducing a stream of gas from the main galaxy. Moreover, the bound model is able to account for the observed S-shaped major-axis rotation curve, even though the mass distribution remains close to the initial one with a nearly flat outer velocity curve (Figure 2). Most importantly, in the bound model the extended tail is tilted by about 40–50° with respect to the inner disc, to the opposite side with respect to the sky-plane. This agrees with the estimated tilt by Rots *et al.*. Since the direction of the tilt is determined mainly by the direction of the companion velocity vector in the southern crossing, single passage models yield an opposite tilt as compared to that required by the observations. Not surprisingly, the recent passage in our model also explains the direction of the tidal debris from the companion, as in TT72.

The original motivation of TT72 to favor a single passage was the fear that earlier passages in bound orbits would imply excessive dynamical heating so that the currently observed sharp features could not form. However, during recent years a large amount of evidence for extended halos has accumulated, implying that the past history is likely to be strongly affected by dynamical friction. In our live halo simulations the companion was followed through several disc plane crossings, taking place at successively shorter distances due to shrinking of the orbit by dynamical friction. In spite of the long tidal history the present morphology of M51 with its most important observed kinematic properties can still be well matched (Figure 3), provided that the previous, more distant perturbations have been weak enough. This seems to be possible, provided that M51 has at least a modest extended halo containing a few times the mass within the region of the visible disc.

4 INWARD PROPAGATION OF TIDAL WAVE

The details of the tidally induced spiral arm formation were studied in simulations with N up to 4×10^6 particles. The grid resolution and gravity softening were chosen in a manner that any artificial two-body relaxation should be insignificant, while a good gravity resolution is obtained throughout the system (resolution $\sim 1''$ in the region of innermost spirals). To have realistic stability properties, the inner rotation curve closely matches the observed steep rise within the innermost $15''$. The Toomre parameter $Q = 1.5$, and disc comprises 1/3 of total mass inside $400''$.

When evolved in isolation, our simulation disc develops weak multi-armed outer structures, much like those seen in late type spirals. The central disc (within about

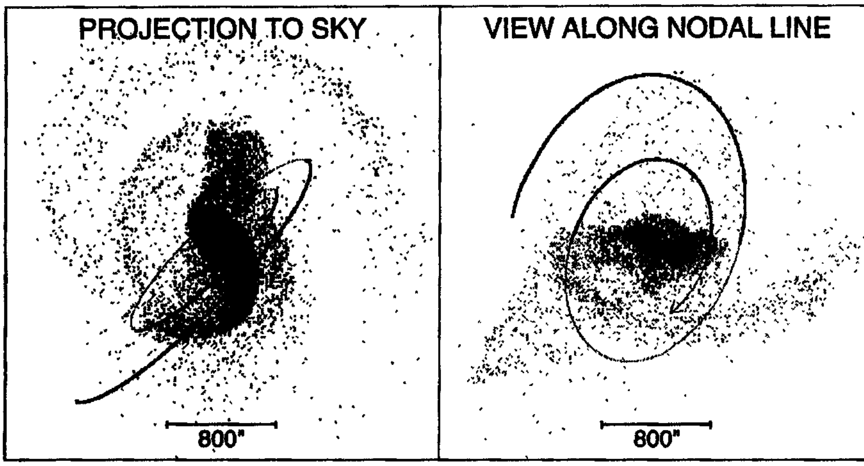

Figure 3 Example of a multiple encounter simulation including a live halo for M51, following the companion through several disc plane crossings. The mass of the extended halo is about 2 times the mass in the disc region.

50″) shows recurrent $m = 2$ spiral wave packets, which however lack any continuity with the outer structures. This behavior is in accordance with the expected strength of swing amplification (Toomre, 1981). During isolated simulations lasting 4 Gyrs there are no signs of weakening of these structures, probably because the heating of the disc is very slow due to large N. With increased disc mass the inner spirals also exhibit an oval appearance within the linearly rising part of the rotation curve. However, the disc remains stable against any large-scale bar instability. The radial propagation speeds of individual wave packets correspond well to the group velocity calculated from the Lin-Shu dispersion relation.

In the runs with a perturber, a strong $m = 2$ response of the outer disc is seen when the companion crosses the primary disc, and 500 Myrs later, corresponding to the present time, the tidal arms reach almost to the center. Contrary to the outer tail and bridge features, the induced main spiral structure is almost independent of the details of the perturbation geometry (Figure 4). The initial, almost immediate response at $r > 100''$ is likely to owe its strength to *in situ* swing amplification. However, this direct excitation occurs at relatively low frequencies (10 km s^{-1} kpc^{-1}), placing its inner Lindblad resonance (ILR) quite far, at a distance of about 100–200″, and contrary to Toomre (1981), can hardly account even for all the optical spiral structure. Rather, the further evolution seems to be governed by the inward propagation of the tidal wave initiated by the outer perturbation, as Toomre (1969) originally proposed. Interestingly, during this inward evolution the tidal wave is separated into different packets with increasingly larger pattern speed, which accounts for their ability to propagate inside the ILR of the original wave (Figure 5). The superposition of these separate packets also leads to amplitude variations, resembling very much those actually seen (Figure 6). Also the speed of

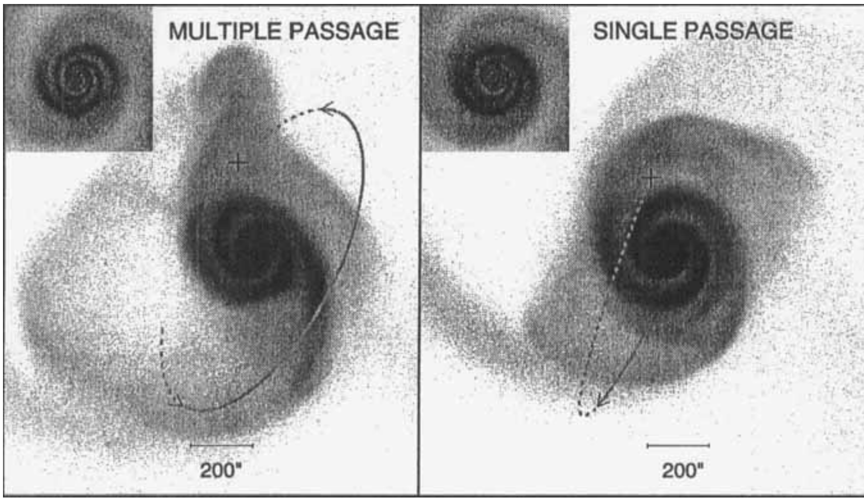

Figure 4 Large-N simulations for M51. In both type of models the tidally generated spirals are rather similar in the region inside 100″ (see the inserts). The duration of the perturbation, counted from the southern disc plane crossing is about 500 Myrs. Note the changes of the arm curvature, especially in the multiple encounter model, resembling the 'straight' arm segments pointed out for M51 in Chernin (1999): however, in the model shown no gas dynamical effects are included.

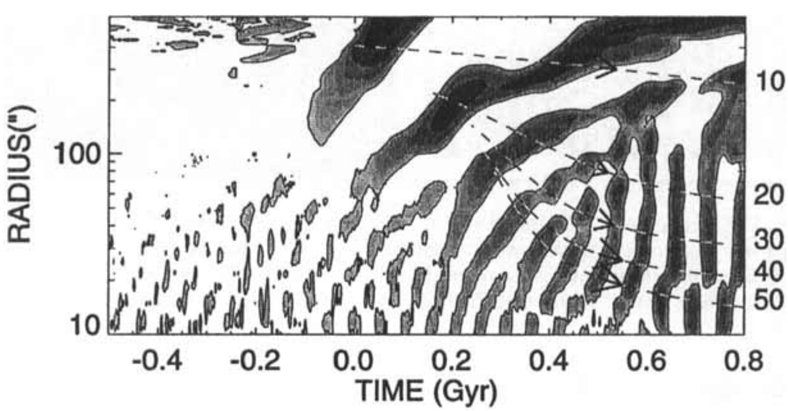

Figure 5 $m = 2$ Fourier amplitudes during M51 simulation. A cosine transform is shown, displaying a density cut as seen along a constant azimuth. Forward leaning slopes correspond to trailing waves, and the time-distance between slopes indicates pattern speed. Coherent series of crests correspond to propagating wave packets. The strong perturbation starts around $T = 0$ (companion crosses the disc plane of the primary), current time corresponds to $T \approx 0.5$. Lines indicate radial propagation for LS-wave packets with different pattern speeds, starting from their corotation.

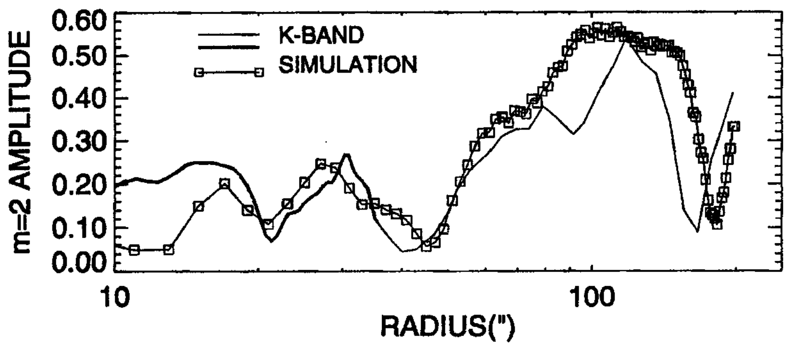

Figure 6 Comparison of the observed radial dependency of the $m = 2$ Fourier amplitude (Rix and Rieke, 1993) with that seen in simulations. Amplitude variations seen at $r = 20''$ and $40''$ result from the interference between the separate components of the inward propagating tidal wave.

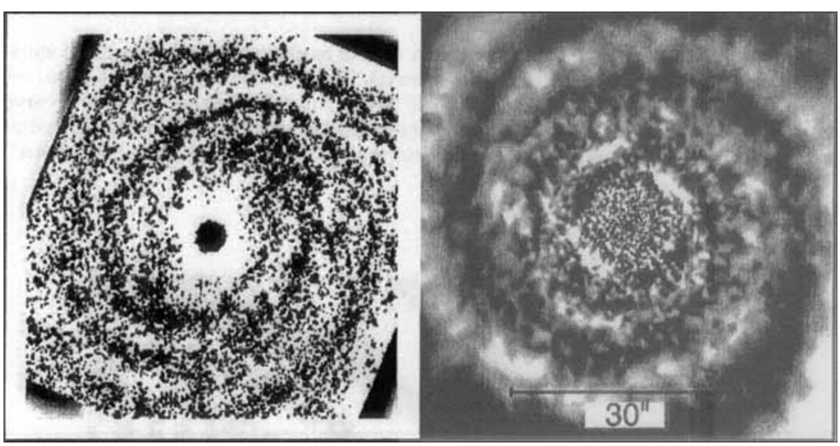

Figure 7 The frame on the left shows the Scoville and Evans (1998) HST K-band observations; deviations from local mean brightness are emphasized. The frame on the right shows the inner structure in the simulation, on the same scale. HST observations were obtained from the data archive at the Space Telescope Science Institute.

radial propagation is consistent with the expected group velocity for traveling short waves (Figure 5).

The fate of the tidal wave reaching the central region depends crucially on the strength of the perturbation and on the inner rotation curve. With our nominal perturbation (perturber mass 1/2, disc mass fraction 1/3) the continuous arm structure extends well inside $30''$ (Figure 7); for a more massive disc even a central oval is seen. For a too small perturber or weak disc, the tidal wave disappears before penetrating to central regions. On the other hand, if the inner slope of M51 rotation curve were shallower than observed, the direct perturbation would lack an ILR and would be able to penetrate to the center, which would lead to the formation of global bar structure, rather than a tightly wound spiral structure.

5 CONCLUSIONS

We have presented a tidal model for M51 which can account for the current structure, from the central spiral arms inside 30″ to the extended HI tail at 900″.

1. Based on the kinematic comparisons a bound current relative orbit is favored, resulting from an orbital decay from a much wider initial orbit due to the influence of dynamical friction.
2. The perturbation responsible for the spiral structure occurred about 500 Myrs ago, after which the perturbation propagated to the inner region. This long duration of the perturbation is consistent with the group velocity of the wave.
3. Amplitude variations along the arms rise naturally in the tidal model, as an interference between separate components of the tidal wave.
4. The requirements for a tightly wound innermost structure are a strong enough perturbation (companion mass about 1/2) and a steeply rising inner rotation curve.

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