INNER STRUCTURE OF M 51

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The exceptionally regular grand-design structure of M 51 has been in the focus of interest while studying the origin and properties of spiral arms in general. It has been a popular test case both for the Lin-Shu hypothesis (Lin and Shu, 1966) that views the spiral arms as intrinsically produced, rigidly rotating density waves, and also for the tidal approach (Toomre, 1969) which stresses transient density waves excited by external perturbations. For M 51 the latter view is well motivated by the presence of the prominent companion NGC 5195.

The most succesful model for M 51, in terms of Lin-Shu waves, is by Tully (1974), who chose the pattern speed in the manner that places the Inner Lindblad Resonance (ILR) at the inner terminus of the optical arms at $30''$. However, near-IR observations (Zaritsky *et al.*, 1993) have shown that stellar spirals trace additional $1\frac{1}{2}$ revolutions inside $30''$. This challanges the density wave fits assuming a single constant pattern speed. Indeed, to extend the fit inside $30''$ a considerably larger pattern speed would be required, making simultaneous matching of the outer spiral structure difficult. The existence of several modes is in principle possible, but that kind of models do not yet exist for M 51.

The tidal models, initiated by Toomre and Toomre (1972), view the global spiral arms of M 51 as originally kinematic, transient waves that have been amplified by some mechanism. Indeed, previous tidal simulations that include particles' self-gravity (Hernquist, 1990; Toomre, 1995; Salo and Laurikainen, 1999) can produde the main spiral pattern quite well, but their resolution has not been sufficient enough to look inside $30''$. For the generation of tidal spirals Toomre has proposed two different scenarios. In his original view the kinematic distortions of the outer disk evolve into propagating wave packets traveling inward with the group velocity. Later he discarded this scenario for M 51, as the implied propagation time exceeded the short duration of his parabolic model. Instead he demonstrated how *in situ* swing amplification of weak kinematic disturbances could lead to a strong response in the inner disk (Toomre, 1981).

In the current study we employ high resolution 3D simulations with $N = 4 \cdot 10^6$ particles to study the inner structure of M 51. A simple model with exponential stellar disk profile + inert spherical halo is assumed, yielding a total inner rotation curve similar to observed. Our standard disk mass is one half of halo mass, and the disk velocity dispersion corresponds to $Q = 1.5$. The gravity resolution is about $1.5''$ at $r = 25''$. A perturbation from bound companion orbit is assumed (Salo and

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Laurikainen, 1999), but our results for inner structure are insensitive to details of the encounter geometry. The main question is: are tidal waves capable to penetrate to the central region, or is their role just to modify a pre-existing spiral mode, as suggested by Lin and Bertin (1994).

When evolved in isolation, our simulation disk displays quite interesting behaviour. The central disk (within about 50″) shows m=2 spiral waves, whereas the outer disk exhibits weaker multi-arm structures. This is in accordance with the expected strength of swing amplification for various radiae and m-values. However, the m=2 spirals occur in a recurrent fashion, which is not easily explained by just having amplified N-particle noise. Similar recurrent spiral instabilities have been seen in previous simulations with various disk models (Sellwood, 1990), but these were not retained unless some cooling mechanism was applied. During our simulations lasting 4 Gyrs there are no signs of weakening of these structures, probably because due to large N the heating of the disk is very slow. With increased disk mass the inner spirals exhibit also oval appearence (within the linearly rising part of the rotation curve). However, the disk remains stable against any large-scale bar instability. The radial propagation speeds correspond well the group velocity calculated from the Lin-Shu dispersion relation. Sometimes we can even see the reflection of high speed trailing waves (lacking ILR) from the center as leading ones. Although no actual modes are set up, these strong recurrent wave packets generate significant inner spiral structure in our isolated M 51 disk.

During the perturbation a strong response of the outer disk is seen, while a few hundred Myrs later, corresponding to the present time, tidal arms reach almost to the center. The initial, almost immediate response is likely to owe its strength to *in situ* swing amplification. However, this direct excitation occurs at relatively low frequencies, placing its ILR quite far, at 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 tidal waves initiated by the outer perturbation, as Toomre (1969) originally proposed. Indeed, the propagation speed is consistent with the expected group velocity.

The fate of tidal wave reaching central region depends crucially on the strength of the inner, pre-existing waves, which are continuously generated by our disk. If these are strong (as in Figure 1), the tidal wave is not able to penetrate within 20″–30″, but just interferes with the intrinsic patterns. On the other hand, if these are weak or absent, continuous structure can be seen at least down to 10″ (see Figure 2). Also in the former case the patterns can join rather smoothly, as the properties of tidal wave (azimuthal propagation speed and spiral shape; see below) at a given distance match closely those of the intrinsic patterns.

The shape of the transient tidal wave, lacking any overall pattern speed, deviates clearly from the shapes deduced from the Lin-Shu dispersion relation: the radial distance between wave crests is rather determined by the critical wavelength, as found previously in simulations of Donner and Thomasson (1994), although

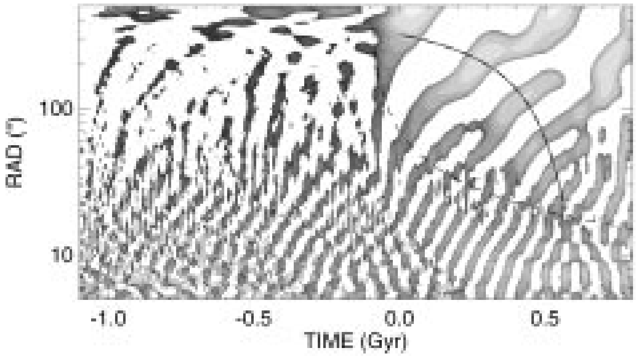

Figure 1. Evolution of m=2 Fourier amplitudes during M 51 simulation. A cosine transform is shown, displaying a density cut as seen along a constant azimuth. Forward (backward) leaning slopes correspond to trailing (leading) waves, while the time-distance between slopes indicates pattern speed. Coherent series of crests correspond to propagating wavepackets. The strong perturbation starts around T=0 when the companion crosses the disk plane of the primary. Strong waves in the upper right are tidal perturbation propagating towards interior: line with arrow indicates expected propagation, while dashed line approximates the boundary outside which tidal perturbation is effective.

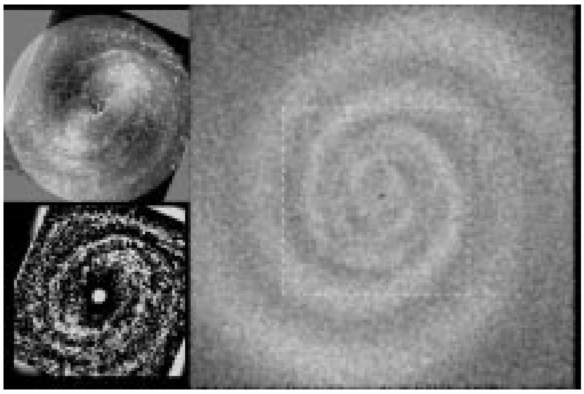

Figure 2. The two small frames show Scoville's IR observations of M 51's innermost $60'' \times 60''$: in the upper frame m=0 component has been subtracted, while in the lower frame deviations from local mean brightness are emphasized. The large frame shows an example of inner structure in simulation, in the same scale. HST observations were obtained from the data archive at the Space Telescope Science Institute.

for much more limited radial range. Also the shapes of the inner packets seen during the isolated evolution follow the critical spirals instead of Lin-Shu shape, eventhough they have a well defined constant pattern speed.

The innermost trailing spiral arms are evident in the Hubble Space Telescope (HST) near-IR observations, made by Scoville. They also show signs of symmetric leading arms embedded in the central oval (Figure 2). These arms cannot be just dust features, because their structure does not follow the dust lanes visible for example in the HST V-image (Grillmair *et al.*, 1997). It is tempting to identify these leading spirals with those seen in simulations when a strong trailing packet is reflected from the center. M 51 has also a nuclear ring with the diameter of about 1.5″ likely to be connected with the ILR of the central oval.

In conclusion, our model suggests that the tidal wave is capable to penetrate to the central regions of M 51. However, the structures excited by tidal wave are essentially similar to those which may develop even in isolation. Nevertheless the interplay with the tidal wave is necessary for the observed continuity of spirals. Note that the model for M 51 studied here matches also the outer morphology and kinematics of the system (Salo and Laurikainen, 1999), thus offering a plausible model at distance range 10″–1000″. In the outer regions ($r > 30''$) any pre-existing spiral is overhelmed by the tidal wave.

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