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M51's SPIRAL STRUCTURE

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The M51 system (NGC 5194/5195) provides an excellent problem both in spiral structure and in galaxy interactions. We present an analytic study of a computer experiment on the excitation mechanisms for M51's spiral arms and whether or not a halo is important for these mechanisms. This work extends previous numerical studies of the M51 system by including self-gravitation in a two component disk: 'gas' and 'stars', and a dark halo. The analytic study provides two new observational constraints: the time ($\approx 70 - 84$ million years ago) and position angle of perigalacticon (300°). By using these constraints and a simple conic approximation, the search for the companion's possible orbit is greatly simplified. This requires fewer N-body simulations than a fully self-gravitating orbit search. Fig. 1 shows the dust lane spiral pattern of M51 overlaid on an optical photograph. The analytically determined direction of perigalacticon is indicated with a line.

We assume a mass distribution in M51 that reproduces the observed flat rotation curve (Tully, 1974). The density distribution of a finite Mestel (1963) disk produces a flat rotation curve without the addition of any other components. The Mestel disk can be embedded in an appropriate inert halo to provide stability against small perturbations. We use a finite Mestel disk with adjustable halo mass to disk mass ratio, $\mathcal{H}/\mathcal{D}$. We fit the photometry of Burkhead (1978) to the Mestel mass distribution to estimate a radius, R_{Mestel}, for the Mestel disk. We find $R_{Mestel} = 15.5$ kpc (distance = 9.6 Mpc). Schweizer (1977) observed NGC 5195 to have a $\Delta V_r = 110$ km/sec for the radial velocity difference between M51 and its companion. By assuming a luminosity mass for NGC 5195 he also found that the mass ratio of $\frac{NGC\,5195}{NGC\,5914}$ is 1/3 to 1/2 . We use this value as a starting point for our simulations. Observations give an inclination between 10° and 20° for M51's disk. This tilt is too small to make any rectification necessary.

The original version of the code was written by Miller (1976, 1978) who used it to study the stabilty of disk galaxies. Sundelius, Thomasson, Valtonen and Byrd (1987) introduced two disk components which evolve simultaneously. One component begins 'cold', *i.e.,* with no velocity dispersion. This will represent disk gas clouds seen in the optical and radio. The other component begins 'warm', *i.e.,* with a velocity dispersion just equal to the critical value for stability against axisymmetric disturbances. This will represent old disk stars seen in the IR.

Each simulation time step = 1 $\Delta T \approx \frac{2\,\pi\, R_{Mestel}\,(\mathrm{kpc})}{314 \cdot V\,(\mathrm{km/s})}$ 10^9 yrs where V is the rotation curve velocity. For an $R_{Mestel} = 15.5$ kpc each time step is $\Delta T \approx 1.5 \cdot 10^6$ yrs.

We used a simple conic routine to obtain a family of orbits consistant with the analytic and observational constraints. We conducted an exhaustive set of simulations and compared the simulated galaxy with the M51 observations. We eliminated those orbits that did not produce the proper match. Orbits with eccentricities greater than 0.6 do not develop the inner structure in a timely fashion. Our best choice orbit has the current x,y position on the sky of the companion correct, the ΔV_r correct, the time since perigalacticon correct, and the azimuth of perigalacticon correct. The morphology matches M51's spiral pattern. We then varied $\frac{\mathcal{M}_{companion}}{\mathcal{M}_{M51}}$ from 0.1 to 0.5. $\frac{\mathcal{M}_{companion}}{\mathcal{M}_{M51}} = 0.1$ seems to work the best. This indicates that the companion may have an abnormal mass to luminosity ratio. By varying $\mathcal{H}/\mathcal{D}$ from 0.0 to 11.0 we determine that these simulations constrain $\mathcal{H}/\mathcal{D}$ to be between 1.0 and 3.0.

Our final set of orbit parameters is:

$e = 0.1$ $\quad i = 50°$ $\quad a = 1.07 \cdot R_{Mestel}$
$\Omega = 280°$ $\quad \omega = 165°$ $\quad \nu = 280°$
$R_{en} = 0.97 \cdot R_{Mestel}$ $\quad \mathcal{M}_{companion} = \frac{1}{10}\mathcal{M}_{M51}$ $\quad \mathcal{H}/\mathcal{D} = 1.0$ to 1.5

time step 119 $\Longrightarrow$ 70 million years since perigalacticon.

Fig. 2 shows the result from a run with $N_{total} = 180,000$, 30% gas. Both stars and gas are shown. Fig. 2a shows star particles. Fig. 2b shows gas particles. The time step is 125. The great number of particles strengthens all the features and also permits more particles to participate in the outermost features. The scales are not the same. The general agreement with Fig. 1 is good.

These simulations have no collisions among the gas clouds. As an extreme test of the effect of collisions, we ran a simulation with gas collisions using the same parameter set out to time step 119. Fig. 3 shows the results. This is a run with N = 15,000 (100% gas). The general results are the same. The direction towards perigalacticon is indicated with an arrow. Overlaid on this Figure are the dust lanes arms from Figure 1. The match is excellent.

The orbit is rather small, yet the success of the tidal arm match argues that this passage strongly disturbed a quiet disk. The latest radio observations (Rots, *et al.* 1990) of M51 are especially interesting. They may resove this problem. Fig. 4 is a tracing of the observations from a figure in Rots, *et al.* (1990). The companion is marked with a large 'X'. Their HI observations show a long, curving arm that extends well away from the optical regions of the system. The dust lanes in Fig. 1 fit within the disk contours of Fig. 4. In Fig. 4 the far-side arm appears separate from the extended arm. Shown beneath Fig. 4 is a scaled to match copy of Fig. 3.

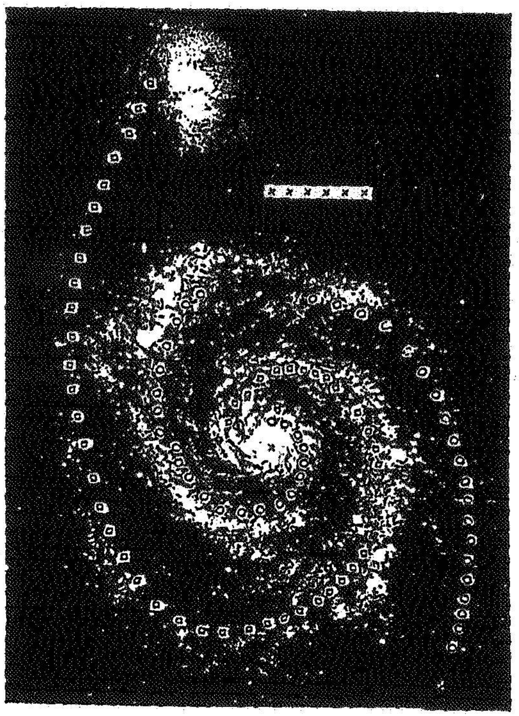

FIG. 1

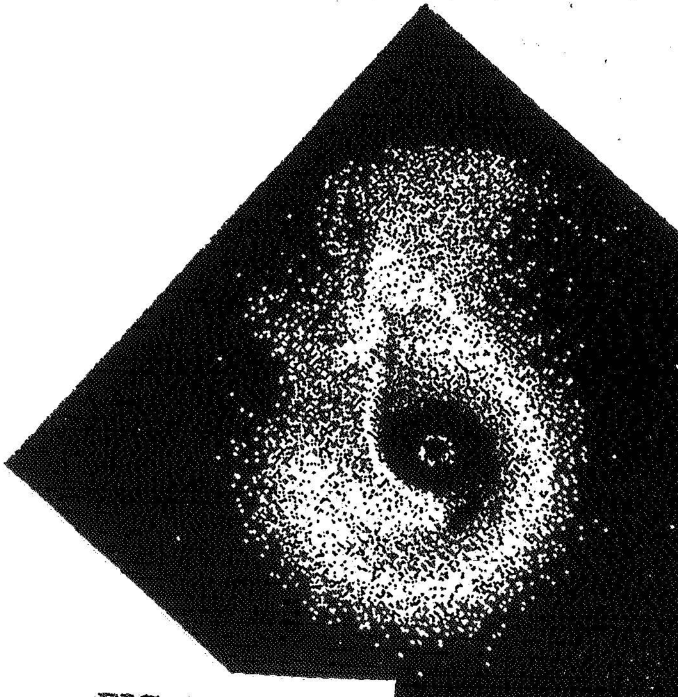

FIG. 2a - STARS

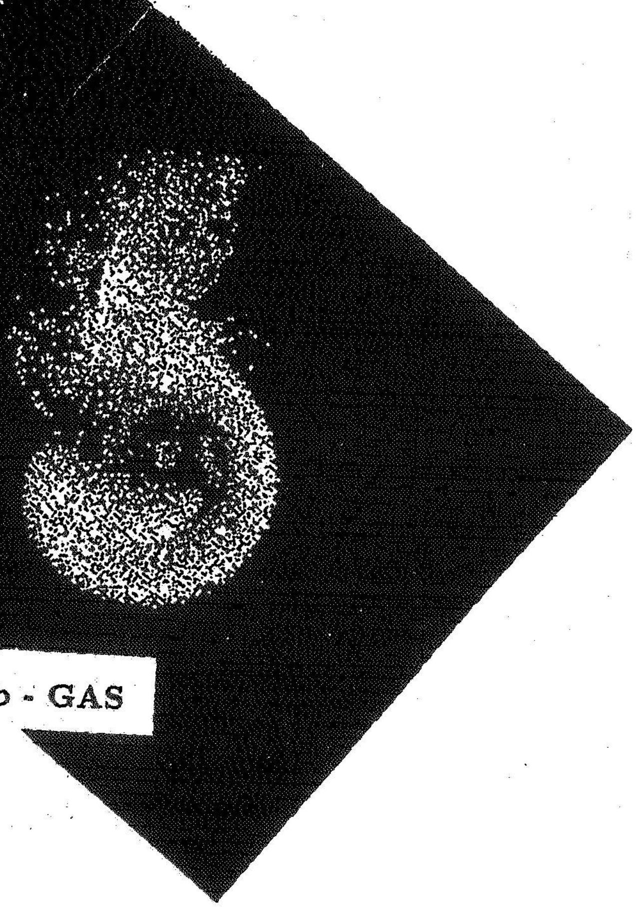

FIG. 2b - GAS

Fig. 1 scaled to match Fig. 2

The clump north of the companion seen in Figure 4 appears in our 180,000 and 15,000 particle simulations (Figs. 2b, 3). We interpret the orbit we found as the osculating conic orbit to NGC 5195's path as it decays towards a final merger with M51. This decay will result from the gravitational interaction of the companion with the halo and disk of M51 and the tidal breakup of the companion itself by M51. Decay time estimates imply less than three orbits before the final merger. We speculate that the extended HI tail is a remnant of the previous disk crossing.

The grand design spiral structure in M51 appears to result from the recent (70 million years ago) passage of NGC 5195. The outer spiral arms behave like material arms, *i.e.,* the gas clouds stay in the arms as the arm winds up. The inner spiral pattern behaves like a density wave triggered by the tidal arms, not directly by the companion. Collisions in the disk gas clouds are not *required* to produce the tidal arms. Instead, the tidal effect of the companion is the dominant driver of the gas. The simulations set limits to $\mathcal{H}/\mathcal{D}$ from at least 1.0 and perhaps a bit larger.

We propose three regions/types of spiral 'structure' in M51: (1) the Rots *et al.* extended HI tidal arm; (2) the tidal arms from the most recent passage; (3) the inner excited density wave.

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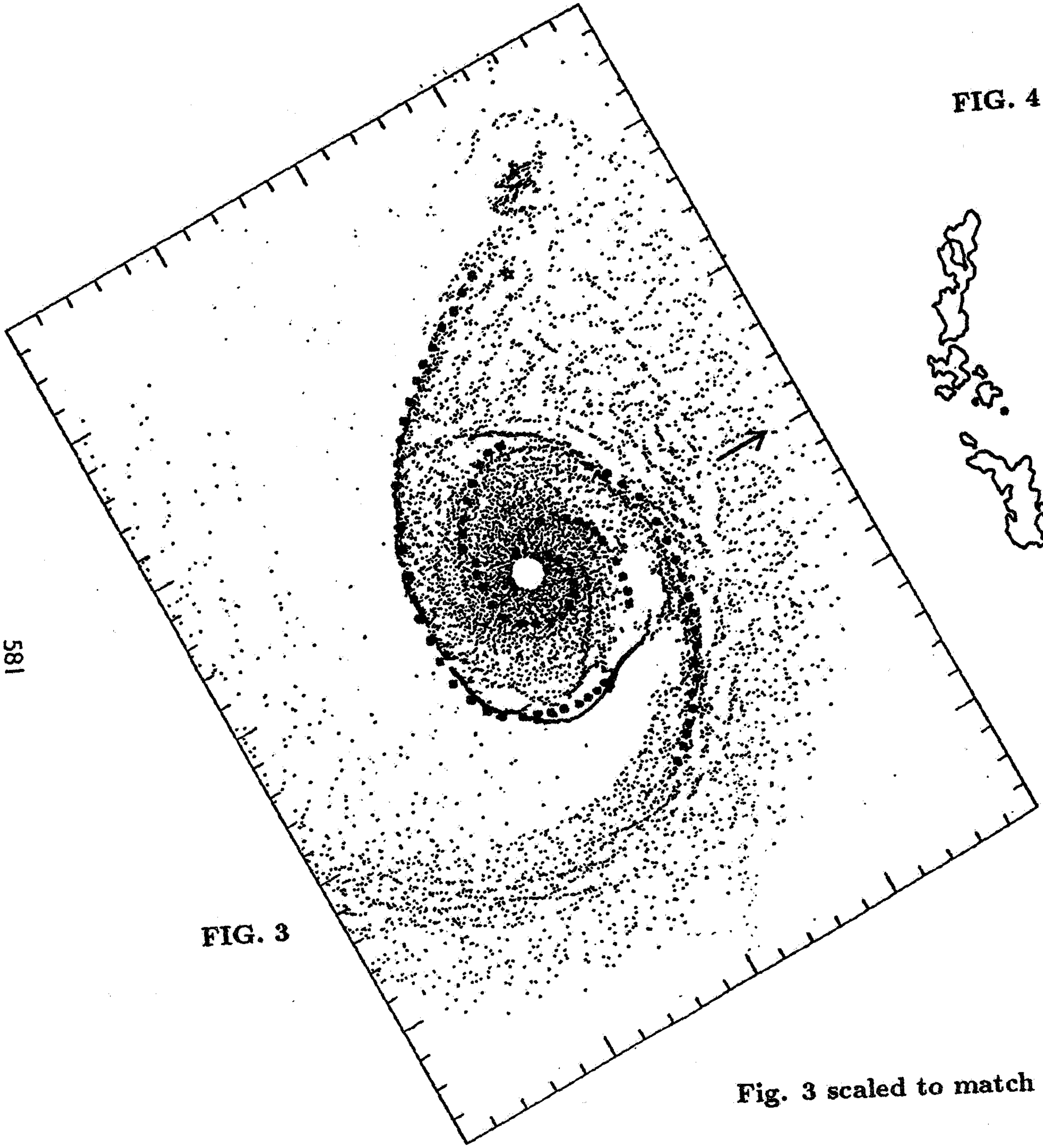
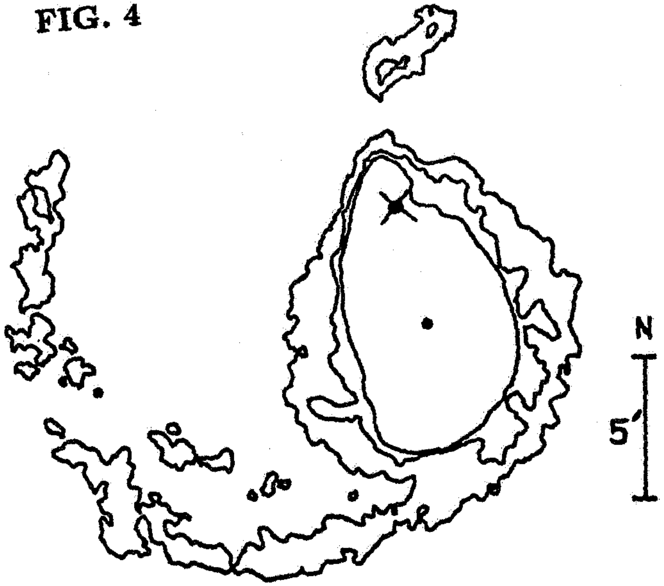


FIG. 3

FIG. 4



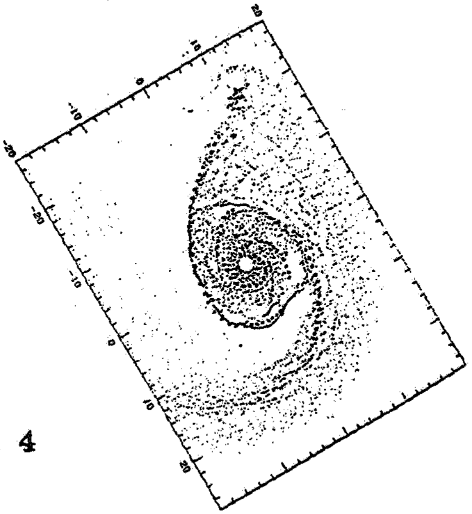


Fig. 3 scaled to match Fig. 4