THE DYNAMICS OF THE SPIRAL GALAXY M81

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The spiral galaxy M81 is a challenging object for testing a density-wave theory. It is of large angular size and favourably inclined to the line of sight; radio observations of neutral atomic hydrogen showing well defined spiral arms with noncircular motions are available (Rots and Shane 1975), and there is evidence from surface photometry for density waves in the old disk population (Schweizer 1976). Can these observations be unified in one density-wave model?

The first step is the construction of an axisymmetric mass model on the basis of a rotation curve. As will be discussed below (see Figure 6), the observed rotation curve derived from the HI measurements is distorted by density-wave motions. After correction for this effect a mass model can be constructed consisting of two spheroids in the central regions ($R \leq 3$ kpc), representing the nucleus and the bulge, and a Toomre disk.

The theoretical spiral pattern of the potential perturbation has been computed with linear stellar density-wave theory (Lin and Shu 1971), including the effects of the finite thickness of the stellar layer and neglecting the gas. A pattern speed Ω_p of 18 km s^{-1} kpc^{-1} was adopted; this value gives the best model with corotation radius 11.3 kpc and inner Lindblad resonance (ILR) at 2.5 kpc. For lower pattern speeds the ILR is so far from the centre that the gas perturbations observed at 3 kpc cannot be ascribed to a density wave. A higher pattern speed restricts too strongly the region where the gas flow can be computed. The velocity dispersions of the stars play an important role. For a disk which is just marginally stable against axisymmetric instabilities, no reasonable values for the pitch angle of the spiral can be achieved. If in the central regions the random motions of the stars are higher by about 70% with a marginally stable disk around corotation, a spiral pattern is obtained which can serve as a basis for the model (Figure 1).

The amplitude of the wave can be determined theoretically (Shu 1970) with a second-order analysis. However, we prefer a more direct method in which the azimuthal brightness variations determined from surface photo-

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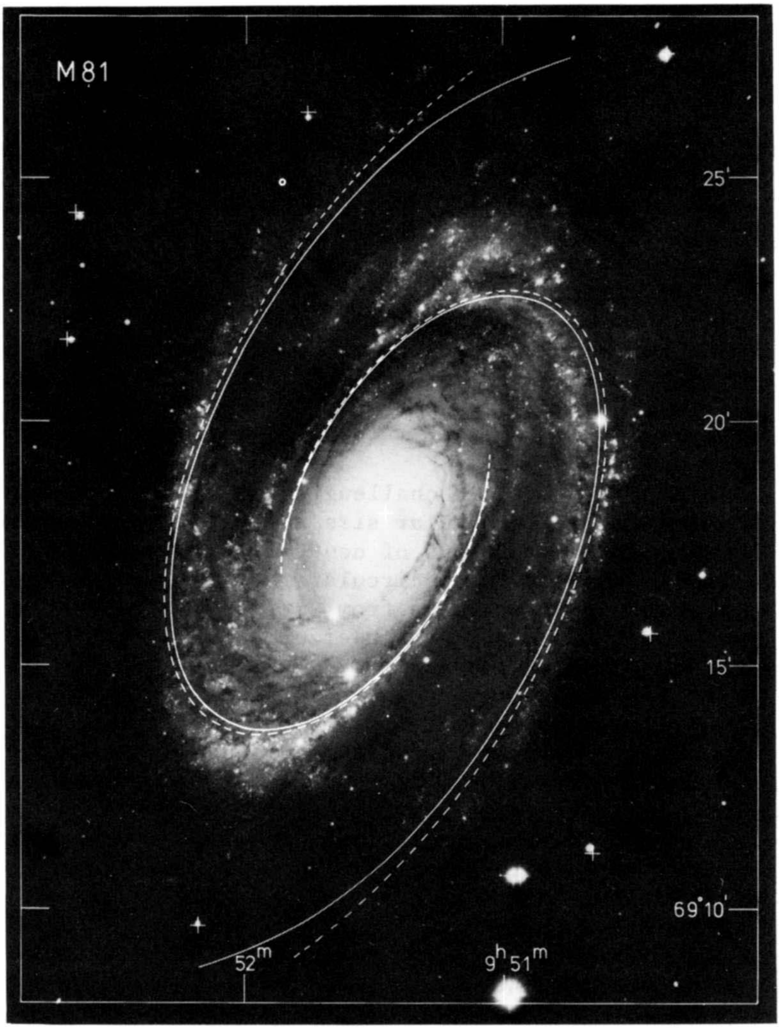

Figure 1. The theoretical spiral pattern of the potential perturbation (dashed line) and the shock front in the gas (full line) superimposed on a 200 inch photograph (Photo by Hale Observatories).

metry (Schweizer 1976) are transformed into amplitudes of the potential field perturbations, neglecting the self-gravity of the gas. This transformation can be done on the basis of the mass model, the scale heights of the stellar and gaseous disk, and the pitch angle of the spiral pattern.

The theoretical gas flow has been computed with nonlinear density-wave theory for a one-component gas (Roberts 1969, Shu et al. 1973). Since the amplitude of the wave is higher than the critical forcing, we can expect galactic shocks over the whole region computed in the model (3-8.7 kpc). The shock front has been indicated in Figure 1. There is a small displacement of this front with respect to the minimum of the potential well; the pitch angles are nearly the same except in the outer regions. At the shock front we may expect to find the principal dust lanes, and the agreement with the observed dust lanes appears acceptable. The discontinuity in radial velocity owing to the shock is of the order of 30 km/s on the minor axis. To compare the theoretical density and velocity fields with the hydrogen observations the model fields must be smoothed to the beam of the radio telescope. A special technique called "phase smoothing" (making use of the asymptotic approximation of density-wave theory) has been developed to reduce the two-dimensional smoothing to one dimension. Also the smoothing effects of integration over a gaseous layer of finite thickness along the line of sight can be treated in this way. For M81 the smoothing by a beam with a full width at half power (FWHP) of 25" is more important than the line-of-sight smoothing; however, at resolutions better than about 15" the line-of-sight smoothing may dominate. The smoothed fields are only weakly dependent on the velocity dispersion of the gas and the parameters used for the calculation of the stellar wave except Ω_p.

The smoothed theoretical velocity fields at 25" and 50" resolution are shown in Figure 2 and 3 together with the observations of Rots and Shane (1975). For the observed velocity fields part of the reduction has been redone to improve the velocity determination (see Bosma 1978, Visser 1978). The underlying picture represents the HI distribution at 25" resolution (Rots 1974). In the 25" velocity field the kinks in consecutive contours at the inside edge of the spiral arms are an indication of the shock front. The next important things to note are the secondary turnover points at 3.3 kpc from the centre along the major axis, in the observations as well as in the model. These secondary turnovers are entirely due to the density wave, because the unperturbed velocity field shows only one turnover point at 4.8 kpc on either side of the galaxy. At 50" resolution (corresponding to ≃1/3 of the arm spacing of the theoretical spiral pattern on the minor axis) there are no indications of the shock front; the velocity contours have a nearly sinusoidal shape. The agreement of the model with the observations is good at both resolutions, although the western arm outside 7 kpc shows some deviations. It is not yet clear if this asymmetry in the outer regions can be attributed to tidal interaction with companion galaxies. Also there is the possibility that in M81 more than one density wave is acting at the same time; the coexistence of more than one wave has been postulated on theoretical grounds (Mark 1977). Note that the azimuth of the underlying spiral of the potential wave has been chosen in such a way that the agreement between the observed and theoretical velocity fields is as good as possible, since the phase of the velocity perturbations is important for the correction of the observed rotation curve. The velocity perturbations were also analyzed along the minor and major axes at 25" and 50" resolution (Figure 4). The observational data on either side of the centre have been averaged together taking due account of the antisymmetry. The model velocities are in good general agreement with the observations although there are indeed differences in detail, such as the location of the minimum near 8 kpc along the minor axis. Note the difference in slope at the two resolutions near 7 kpc along the minor axis.

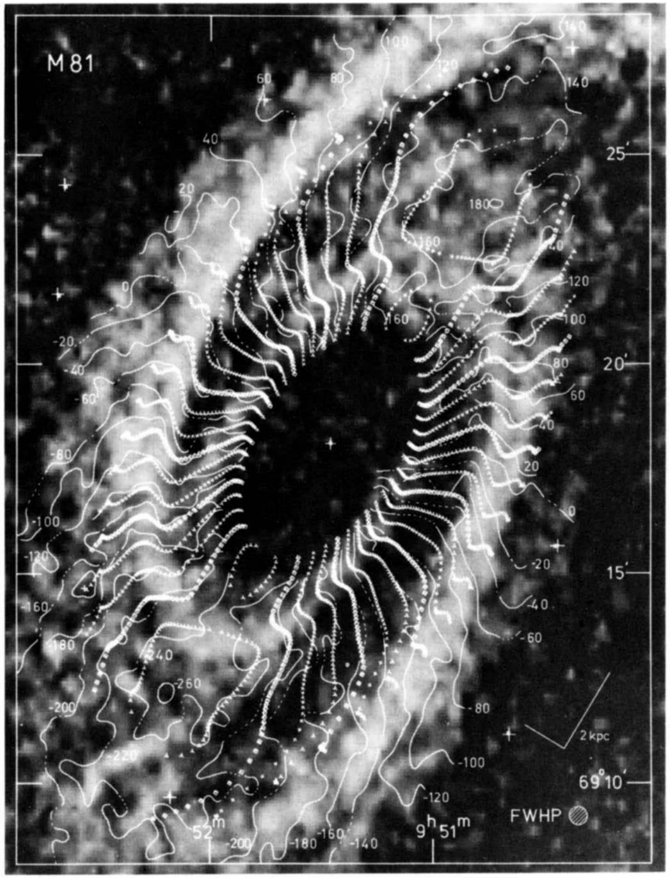

Figure 2

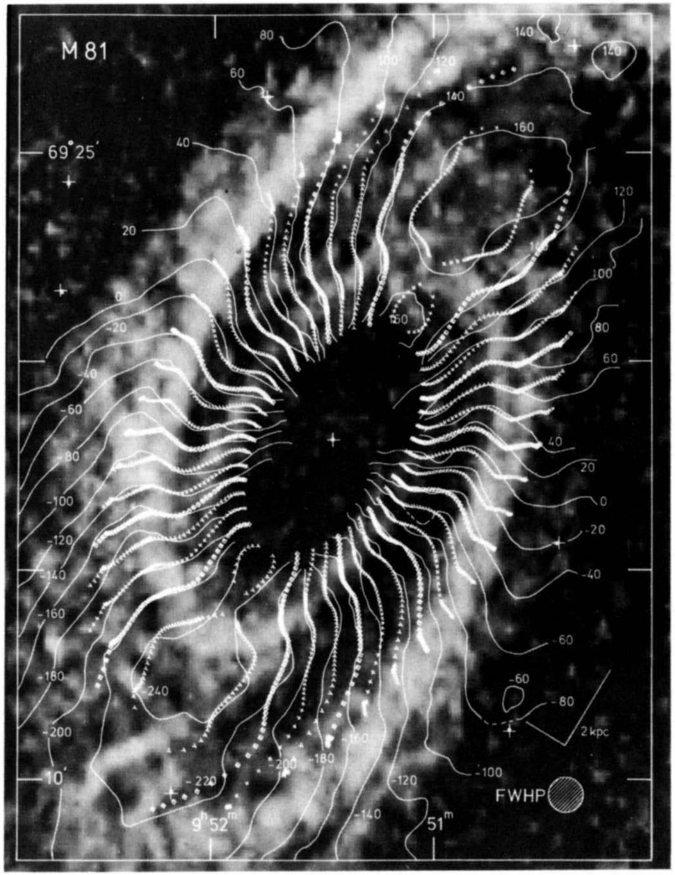

Figure 3

Theoretical (symbols) and observed (full and dashed lines) radial velocity fields at 25" (Figure 2) and 50" resolution (Figure 3) superimposed on a radiograph of the density distribution at 25" resolution (Photo courtesy of E.B. Jenkins). Also the beam and linear scales in the plane of the galaxy are shown. Dashed lines do not represent actually measured velocities, but indicate a possible continuity.

Figure 5 shows the arm profiles (HI-surface density as function of spiral phase) at 25" resolution for different ranges in radial distance for model and observations (Rots 1975). For $8 \leq R \leq 10$ kpc the model curve is less certain since this is in the neighbourhood of the second harmonic resonance. The region of the higher harmonic resonances occurs beyond 8.7 kpc; no solutions could be found here. Hence the observations have here been averaged over a wider range in R than the numerical data of the model. The secondary compression at phase $\simeq 60^\circ$ may be an indication of the second harmonic resonance. To obtain the best fit of the density profiles with the model phase shifts of -15°, -18° and $+7^\circ$ have been applied to the theoretical profile in the upper, middle, and lower panel, respectively. We have no satisfactory explanation for this phase shift, and this appears to be a drawback of the model. When the amplitudes (i.e. the maxima) of the observed profiles of the two arms are averaged together, the agreement with the model appears reasonable. The asymmetry of the profiles of the eastern arm (phase 0°) for $R \geq 6$ kpc is well represented. The general agreement for the region $4 < R \leq 6$ kpc is less satisfactory. This may be due to a poorer definition of spiral structure in the inner regions.

Since we constructed a symmetrical density-wave model, we cannot account for the observed asymmetries in the HI-density and velocity fields. In general the eastern arm shows a better agreement with the model.

Finally we shall discuss the effects of the density wave on the observed rotation curve. A rotation curve determined from the velocity fields in Figures 2 and 3 in some standard way (e.g. Rots 1974), turns out to be quite different from the rotation curve used for the axisymmetric mass model. This is demonstrated in Figure 6 which shows the rotation curve representing the axisymmetric mass distribution, the observed rotation curve at 25" resolution and the model curve. In practice we have determined the "axisymmetric" rotation curve from the observations by iteration.

The results may be summarized as follows:

i) A self-consistent model for the spiral galaxy M81 can be constructed inside ≃9 kpc on the basis of density-wave theory as formulated by Lin, Shu and Roberts;

ii) For an acceptable spiral pattern the random motions of the stars must be higher than those required for a marginally stable disk in the more central regions, assuming that the present choice of the pattern speed is justified;

iii) The amplitude of the stellar density wave as determined from surface photometry is consistent with the amplitudes of the observed density and velocity perturbations of the gas;

iv) Indications for the existence of shocks can be recognized as strong gradients in the velocity field if the beam of the radio telescope is of the order of 1/6 of the arm spacing on the minor axis;

v) Density-wave motions can be clearly detected if the beam is 1/3 of the arm spacing;

vi) The arm profiles are more or less consistent with the nonlinear density-wave theory after considering the smoothing effects of the

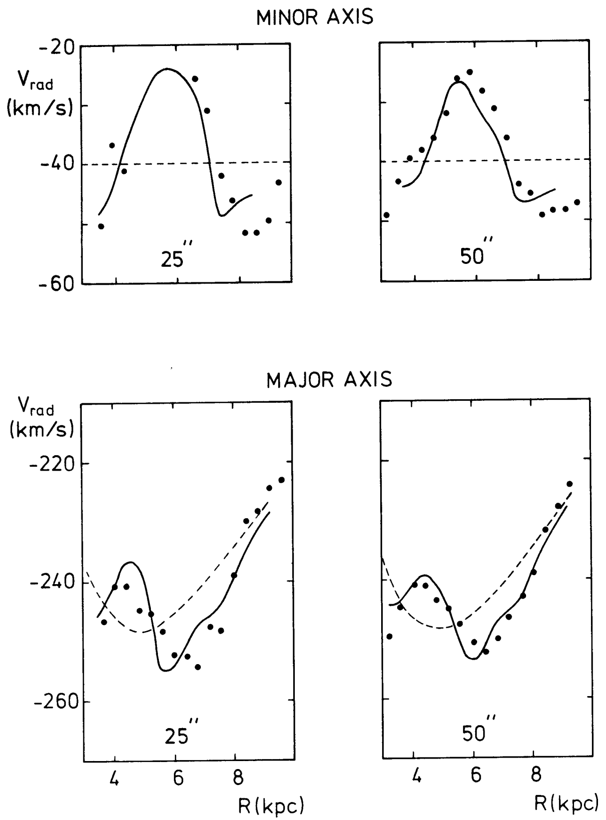

Figure 4. Radial velocities along the minor and major axes at 25" and 50" resolution for the model (full lines) and the observations (dots). The radial velocities of the axisymmetric model are represented by a dashed line.

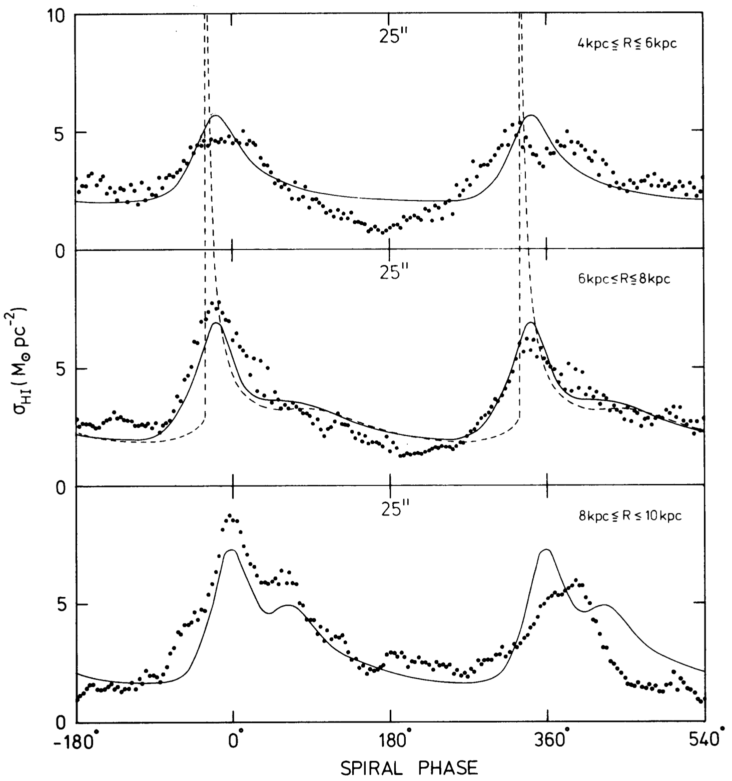

Figure 5. HI-surface densities as function of spiral phase for the observations (dots) and the model (full lines). The dashed line in the middle panel represents the unsmoothed shock profile.

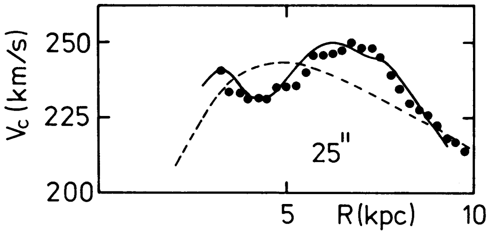

Figure 6. Distortion of the rotation curve by the density wave. The full line is the model curve, observations are represented by dots, and the "axisymmetric" rotation curve is indicated by a dashed line.

beam. A phase shift was needed to get the maxima of the profiles at the right place;

vii) Smoothed density and velocity fields are weakly dependent on the parameters used for the calculation of the stellar wave except Ω_p;

viii) Density-wave motions can cause considerable distortions of the rotation curve; correction for this effect is then required for the construction of mass models from observed rotation curves.

A more detailed discussion will appear in a future paper (Visser 1978).

Acknowledgements

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DISCUSSION FOLLOWING PAPER II.3 GIVEN BY H.C.D. VISSER

MARK: Visser and I felt that it would be good to complement his talk with some preliminary results where we compare the observed wave amplitude of Schweizer with the relative amplitude as suggested by the theoretical calculation of spiral modes. For a reasonably realistic model of M81 which includes about 25% of bulge matter, we find that the amplitudes as observed by Schweizer compare very well with the amplitude distributions in the two dominant spiral modes.

TOOMRE: How did you get the amplitude?

MARK: Our relative amplitudes as stated give the values of the amplitude at one radius relative to that at other radii. The absolute value is not predicted by present theory but one chosen for the best fit of the observations. This run of amplitudes is already very suggestive.

VAN DEN BERGH: Recently a number of people have suggested that the optical peculiarities of M82 might be due to a recent encounter with M81. Do you see any evidence for such an encounter in the velocity field of M81?

VISSER: The major axis of the velocity field is not a straight line, but is curved in the outer regions. This indicates that in the outer regions the disk may be warped, which might be due to an encounter with M82.

"I think you should include numerical simulation in the category of observation too."

A.J. Kalnajs in Discussion II.4