INTERACTING GALAXIES: THE KINEMATICS OF NGC 4038/39 AND THE HI BRIDGE BETWEEN M81 AND NGC 3077

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1. THE KINEMATICS OF NGC 4038/39

Computer simulations of galaxy encounters (Toomre 1974 and references therein) have strongly supported the idea that the luminous bridges and tails in many multiple galaxies are a result of gravitational interaction. The need for an observational test of the kinematics of these models has prompted observations of NGC 4038/39 (the "antennae") in the 21 cm line of neutral hydrogen (HI) with the Westerbork Synthesis Radio Telescope (WSRT) at an angular resolution of 100"×150" ($\alpha\times\delta$). A detailed description of the observations and data reduction is given elsewhere (van der Hulst, 1977). Neutral hydrogen is definitely associated with the tails as was already indicated by the filled aperture observations of Huchtmeier and Bohnenstengel (1975) at the lower resolution of 8ʹ.7. The distribution of HI column density is shown in Figure 1 superposed on a print of a plate obtained by F. Schweizer with the 4 m telescope at Cerro Tololo. Owing to the low declination of the object (-19^{o}) the WSRT map is affected by several sidelobes; the main effect is an attenuation of extended east-west structures, for which reason the HI along the southern tail in Fig. 1 shows a gap. Computer experiments and a comparison with the filled aperture observations show that the WSRT data are entirely consistent with an HI distribution which is uniform along this tail and increases with about a factor 2 at the extreme end, where the tail is very blue and small HII regions are present (Schweizer, elsewhere in this volume). The tails contain 2.9×10^{9} $M_{\odot}$ of HI (assuming a distance of 20 Mpc), 85% of which is in the southern and more prominent tail. About 1.1×10^{9} $M_{\odot}$ of HI is associated with the galaxies which are not spatially resolved at the present angular resolution.

The comparison of the velocity information with the model of Toomre and Toomre (1972) is shown in Figure 2. The left diagram shows the geometry; the spatial coordinates are given in units of the perigalactic distance. The middle diagram shows the radial velocities of the test particles in the left diagram. Velocities to the left and the right of the vertical axis are approaching and receding; the unit is 415 km s^{-1}.

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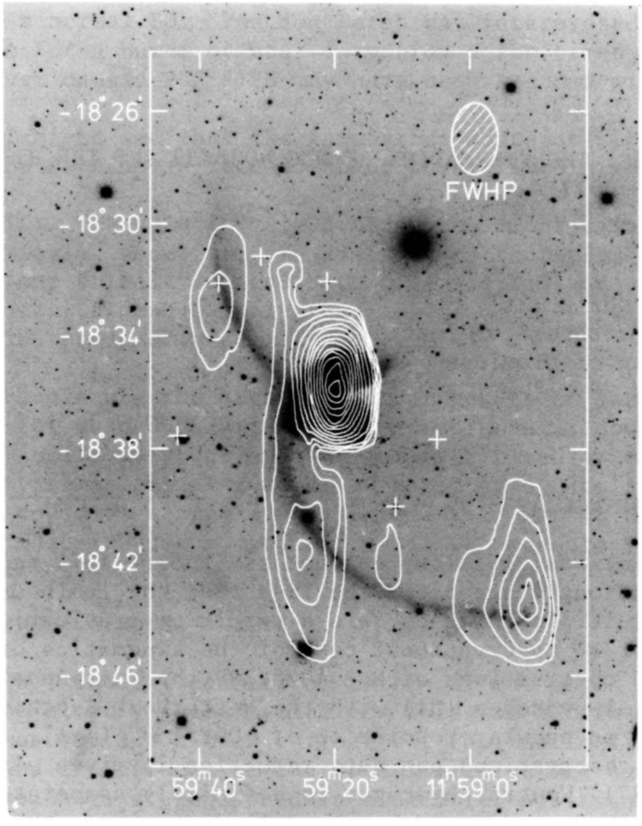

Figure 1. Distribution of HI column density in NGC 4038/39 as measured with the WSRT superposed on a 4 m CTIO photograph. The contour interval is 4.5×10^{19} cm^{-2}. The ellipse denotes the half power beam width.

Three features are essential to the model velocities in the tails: (i) the velocity along a tail is approximately constant with a slow decline towards the mean velocity of the galaxies at the tip; (ii) profiles along the tails are narrow; (iii) the tail velocities have opposite sense with respect to the mean velocity. The right diagram shows a position-velocity map centered at $\alpha = 11^h59^m21^s$, $\delta = -18^o36'$ constructed by interpolating the observations onto a line of position angle 40^o, chosen such to obtain close agreement with the coordinate system of the left diagram for the southern tail. Superposed are the model velocities (black dots) after scaling of the dimensions of the model by a factor 0.3 in order to match the observed length of the southern tail. Also the sense of rotation of the original model has been inverted. The model masses are now 2.7×10^{10} $M_\odot$, because the model velocities did not require substantial scaling. The quantitative agreement is quite good and the three crucial kinematical features are well represented by the observations. The broad galaxy profiles of the model are still well separated, because even after the scaling the separation of the model galaxies is a factor 2 larger than is observed. Only at the tip of the southern tail the observed velocities

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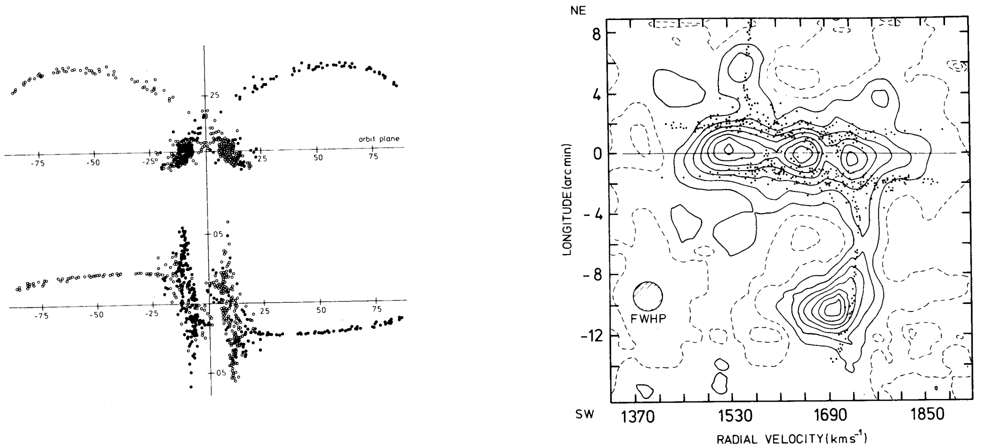

Figure 2. The geometry and velocities (left and middle diagram) of the model of Toomre and Toomre for NGC 4038/39 and the comparison of this model with the WSRT observations (right diagram). The contour interval for the position-velocity map is 0.1 K; the zero and negative contours have been dashed. The circle denotes the position-velocity half power "beam". I thank A. Toomre for kindly providing his model data.

are lower and the profiles broader than the model predicts. This may be a result of integration along the line of sight, the southern tail being seen in parallel at its extreme.

2. THE NGC 3077 HI BRIDGE

The early type spiral galaxy M81 and its two I0 companions, M82 and NGC 3077 are known to have a common HI envelope (Roberts 1972, Davies 1974). The southern part of this triplet, including NGC 3077, has been observed with the WSRT (van der Hulst, 1977) at 50" resolution in order to determine the detailed structure and kinematics of the HI in this region. The WSRT data have been combined with observations from the 100-m Effelsberg telescope (Harten, Mebold and Shane, priv. comm.) in order to incorporate the extended ($\gtrsim$ 15') HI emission which is missing from the interferometric observations. The results are shown in Figure 3, combined with the WSRT observations of M81 (Rots and Shane, 1975) smoothed to the same angular resolution. Superposed are contours of equal radial velocity. The nuclei of M81 and NGC 3077 are indicated by a white triangle and filled circle respectively. The areas in the top left and bottom right corner are blank, because no WSRT observations of these regions are yet available.

The most remarkable feature is an HI bridge between M81 and NGC 3077 which appears to be a regular eastward continuation of the outer HI spiral structures at the west side of M81. Farther east this continuation is less evident, though one may tentatively try to identify the double

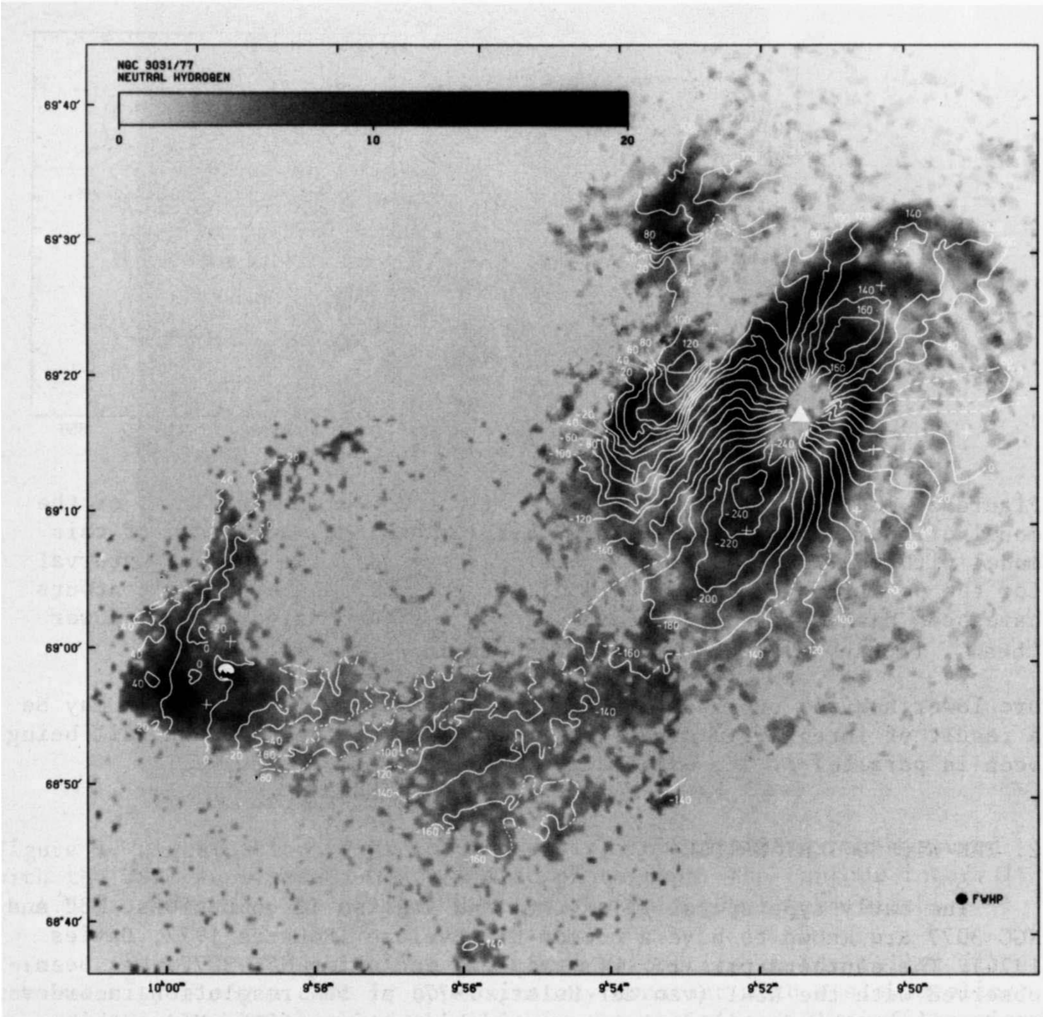

Figure 3. The distribution and kinematics of the HI in M81 and NGC 3077. The grey scale (top left) is in units of 10^{20} cm^{-2}. This diagram has been prepared by A.H. Rots with the Dicomed filmrecording device of the NRAO.

structure in the bridge close to NGC 3077 with the same spiral structure. The HI distribution around NGC 3077 is asymmetric; more than 50% of the HI lies beyond the Holmberg radius, partly in a bright concentration to the south-east of the nucleus and partly in a tail which extends northward. No optical counterpart is found for these features on a print from a deep IIIa-J plate (courtesy H.C. Arp), except for small condensations (Barbieri, Bertola and di Tullio, 1974) coinciding with the bright south-eastern concentration. The amount of HI in the bridge is 5 × 10^8 $M_\odot$; the tail contains 2.3 × 10^8 $M_\odot$ of HI whereas 5 × 10^8 $M_\odot$ is associated with NGC 3077. The HI velocities in the bridge show a regular velocity gra-

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dient which persists across the HI around NGC 3077 and across the tail. The bridge velocities blend smoothly into the differential rotation velocity field of M81.

The properties of the bridge and the tail (width: 4-8 kpc, length: 25 kpc, peak column densities: 3-5 × 10^{20} cm^{-2} and profile halfwidth: 20-40 km s^{-1}) are very similar to those of the Magellanic Stream (Mathewson, Cleary and Murray, 1974) and the HI filaments in NGC 4631/56 (Weliachew, Sancisi and Guélin, 1977). For the Magellanic Stream three hypotheses have been put forward: (i) the gas is primordial (Mathewson 1976, Mathewson and Schwarz 1976); (ii) the gas traces the wake of the Magellanic Clouds in the hot halo of the Galaxy (Mathewson, Schwarz and Murray, 1977); (iii) the gas has been drawn out of the Clouds by the Galaxy during a past encounter (Mathewson et al.1974, Fujimoto and Sofue 1976, Lynden-Bell 1976, Davies and Wright 1977). Of these hypotheses only the latter is likely to apply to the NGC 3077 bridge. A primordial hypothesis raises a stability problem, because the bridge will disperse within about 6×10^8 years as estimated from its velocity gradient. In a galactic wake hypothesis the bridge and the tail cannot be explained as such at the same time. The good match of the structure and velocities of the bridge with M81 strongly suggests that the gas has been drawn out of M81. Gravitational model calculations (van der Hulst, 1977) for the interaction between M81 and NGC 3077 and between M81 and M82 indicate that either NGC 3077 or M82 can possibly produce the bridge with the correct velocities. A model involving all three galaxies may be required to fully describe the interaction.

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DISCUSSION FOLLOWING PAPER V.3 GIVEN BY J.M. VAN DER HULST

VAN WOERDEN: Does the tidal HI filament around NGC 3077 also have a dwarf-irregular (possibly DDO 66) at its tip?

VAN DER HULST: I would definitely say not; it is way off.

DAVIES: DISTRIBUTED HI IN SMALL GROUPS OF GALAXIES

In cooperation with G.P. Davidson, L. Hart, S.C. Johnson and P.N. Appleton an extensive programme of mapping the 21-cm neutral hydrogen emission in and around small groups of galaxies has been undertaken at Jodrell Bank using the MK IA radio telescope which has a beamwidth of 13'. The group with the most distributed neutral hydrogen emission is the M81/M82/NGC 3077 group. A detailed examination of the data shows two neutral hydrogen "bridges" between NGC 3077 and M81, a bridge between M81 and M82 and a bridge between M81 and the SW cloud. In addition there is a neutral hydrogen tail projecting from M82 in the direction opposite to M81. Velocity gradients are evident along some of these features which indicates that they may have a tidal origin resulting from the gravitational interaction between the galaxies. Some of the gas, the SW cloud for example, may be primordial and may not have ever been bound to any of the galaxies.

Two pairs of galaxies show a simpler intra-cluster neutral hydrogen distribution. NGC 4151 and NGC 4145 show a bridge connecting the two galaxies. The NGC 4725/4727 pair appears to have generated a neutral hydrogen tidal bridge and tail extending from the less massive galaxy.

NGC 1023, an SO galaxy, is in a different category. It has an adjacent neutral hydrogen companion situated at a projected distance of $\sim$ 60 kpc and having a velocity difference of approximately 200 km/s. This appears to be a purely hydrogen galaxy with no detectable optical emission on the Palomar Sky Survey prints. The other members of the NGC 1023 group are at such large distances that they cannot have pulled this gas from NGC 1023.

ALLEN: Concerning the detectability of faint extended features in the region of the bridge between M81 and NGC 3077 on the Westerbork maps: I should like to point out that the maps of this area shown by Mr. van der Hulst are in fact a combination of WSRT interferometer observations and single dish maps made with the 100-meter Effelsberg telescope.

VAN WOERDEN: TIDAL INTERACTION AND ACCRETION IN THE GALAXY PAIR NGC 1512 AND 1510

The southern ringed, barred lenticular galaxy NGC 1512 is immersed in a vast amount of hydrogen (van Woerden et al. 1976, P.A.S.A. 3, 68). Its EO-type companion, NGC 1510, at 5' = 20 kpc distance, is 2 mag fainter and has quite blue colours. Disney and Pottasch (1977, A.A. 60, 43) observe an A-type absorption spectrum and strong emission lines; they interpret NGC 1510's colours and spectrum as evidence of recent formation, $\sim$ 500 Myr ago.

Our Parkes observations (Hawarden et al. 1977, M.N.R.A.S., in press) show that the 11 x 10^9 $M_\odot$ of neutral hydrogen is extended over > 100 kpc diameter; from its rotation follows a mass of 2×10^{11} $M_\odot$ for NGC 1512.

Deep photographs with the Siding Spring Schmidt telescope reveal an irregular pattern of arms and filaments, reaching 33 kpc from NGC 1512, and a distortion of the ring. These, apparently tidal, effects indicate for NGC 1510 a mass of 1 - 10% that of NGC 1512. However, if NGC 1510 is young, its luminosity and colours indicate a mass $\lesssim 1 \times 10^8$ $M_\odot$. Also, the Disney-Pottasch coeval model fails to account for the ionization.

Our model proposes that NGC 1510 is a dwarf-elliptical galaxy of 2×10^9 $M_\odot$, which in the last 100 Myr has accreted enough gas to form a young population of $\sim 50 \times 10^6$ $M_\odot$. This model is consistent with the observed colours, absorption and emission spectra, and tidal interaction. The interaction suggests that the inclination of NGC 1510's orbit about NGC 1512 is low. Assuming a velocity of NGC 1510, relative to the surrounding gas, of 100 km/s (the observed radial velocity difference is < 50 km/s), we estimate that $(10 - 100) \times 10^6$ $M_\odot$ of gas would have been accreted.

The low metal abundance observed in the emission lines must, on either model, be due to the composition of the gas disk around NGC 1512.

VAN DEN BERGH: I suspect that many of the problems to which you referred will resolve themselves when good optical classifications based on homogeneous plate material become available.

GALLAGHER: For NGC 6902, if you include the extra light in the outer part of the galaxy, the ratio M_{HI}/L_B is reduced by about a factor of 2 which is normal for an Sbc.

SCHWEIZER: If we accept the idea that NGC 1512 and 1510 interacted tidally rather recently, the observation of a strong burst of star formation in the smaller galaxy agrees nicely with Arp's (1969, A.A. 3, 418) finding that such bursts are a frequent phenomenon. In his sample of six spiral galaxies with companions at the end of one spiral arm, four of the companions show blue absorption-type spectra indicative of strong recent star formation (i.e. spectra with Balmer lines in absorption).

COMBES: TIDAL INTERACTIONS WITHIN THE NGC 4631 GROUP OF GALAXIES

The two galaxies NGC 4631/4656 have been observed in the 21-cm line of atomic hydrogen by Weliachew et al. (A.A., submitted). The isophotes of neutral hydrogen emission show very important distortions; mainly around NGC 4631 we note at least four gas features around this galaxy. A numerical model considering only a restricted three-body problem, has been tried to interpret the distortions in terms of a tidal interaction.

This model shows that at least two of the features, the bridge between NGC 4631 and NGC 4656, and the counter arm almost parallel to the plane of NGC 4631, can be interpreted in terms of a parabolic passage of the two galaxies. The other two features, almost perpendicular to the plane of NGC 4631, are interpreted as being related to a third neighbouring galaxy NGC 4627. The latter does belong to the

NGC 4631 and 4656 group according to its systemic velocity and its optical appearance, showing filaments towards NGC 4631. Due to its much smaller total mass, NGC 4627 has a negligible action on NGC 4631 and 4656 but is greatly being damaged itself. Though NGC 4627 is classified now as a dwarf-elliptical galaxy, it is assumed to have been an irregular or spiral galaxy in the past and to have lost its neutral gas in the recent encounter. This assumption is supported by the presence of rather young stars in this small galaxy.

GIOVANELLI: HI OBSERVATIONS OF THE M51 SYSTEM

Observations in the 21-cm line (in cooperation with M.P. Haynes and M.S. Burkhead), made with the 100-m telescope of the MPIfR and the 92.6-m telescope of the NRAO, have revealed an extended distribution of peripheral HI in the M51 system, well beyond that reported by previous observers. Its characteristics may be summarized as follows:

(1) The projected diameter is 125 kpc for an assumed distance to M51 of 9.7 Mpc.

(2) The velocity field is quite irregular, extending almost 200 km/s beyond the cutoff of the profile of NGC 5194, and the gas does not co-rotate with the material in the disk of NGC 5194.

(3) The HI mass exceeds 10^9 $M_\odot$.

(4) The contour map of the HI column density at velocities larger than 600 km/s yields a suggestive match with a peculiar optical extension of the system toward the NW, recently traced by Burkhead (1977, preprint).

(5) No positive detection of NGC 5195 may be claimed, in contrast with the result of Rood and Dickel (1976, Ap.J. 205, 346).

Although the M51 system is by no means unique in being surrounded by an extended distribution of material luminous both optically and in the HI line, the obvious peculiarities of the system in combination with the details of the circumgalactic HI make it quite special. Either a primordial or tidal origin is possible. Our low resolution observations do not yield information on the structure of the gas at a scale smaller than about 40 kpc; the distribution may then be an assembly of Sculptor-like clouds as found by Mathewson et al. (1975, Ap.J. 195, L97) and Haynes and Roberts (in preparation). The association between optical and HI luminosity, on the other hand, recalls the case of the Leo triplet (Haynes et al. 1977, B.A.A.S. 9, 361), although the large velocities of the gas and its extension make a tidal origin after a recent pericenter transit, as in the picture proposed by Toomre and Toomre (1972, Ap.J. 178, 623), rather improbable. The possibility that this material may have been swept out from the galaxies in the system during earlier close passages of the history of their affair cannot however be ruled out.

SANCISI: GAS DISTRIBUTION AND VELOCITY FIELD OF THE BARRED SPIRAL GALAXY NGC 5383

In cooperation with R.J. Allen a new, more sensitive 21-cm line study of NGC 5383 has recently been completed with the Westerbork Synthesis Radio Telescope. The results confirm and strengthen the main conclusions from the preliminary observations reported by Allen et al. (1974, The Formation of Galaxies, ed. J.R. Shakeshaft, p. 425) and by

Sancisi (1975, La Dynamique des Galaxies Spirales, ed. L. Weliachew, p. 403).

Hydrogen distribution. Most of the hydrogen is found in the optically bright parts of the galaxy and is concentrated especially in the central region and in the spiral arms. There is apparently little or no HI emission from the bar. HI is detected out to about 3' (∿ 40 kpc) or twice the de Vaucouleurs radius, where the column densities fall to values of about 1×10^{20} cm^{-2}. Clear evidence of related faint optical emission of similar extent in the outer regions of NGC 5383 is shown by a deep IIIa-J plate recently taken by van der Kruit and Bosma (1976, private communication) with the 48-inch Schmidt telescope at Mt. Palomar.

Velocity field. The overall shape of the velocity field is typical of an axisymmetric disk in circular differential motion. The rotation curve is approximately flat within 20 km/s out to the outer parts of the galaxy, indicating an extended mass distribution. In the inner regions near the bar the velocity field clearly shows large scale deviations of order 100 km/s from circular motion: in particular, the iso-velocity contours tend to become parallel to the direction of the bar.

A comparison of the HI velocities with those derived from optical emission lines in the central regions by Peterson et al. (1977, preprint) shows good agreement: the same velocity pattern indicating non-circular motion in the optically derived velocity field is easily recognizable also in the radio map even though the radio observations have much lower resolution.

It is most likely that these velocity perturbations are associated with the presence of the bar.

Southern companion. HI emission has also been detected in the small 16.5 mag SBdm galaxy (U 8877; Nilson 1973, Uppsala Gen. Cat. Gal.) located about 3' to the south of NGC 5383 (12.5 mag). Its systemic velocity V_{Hel} = 2370 km/s is close to that of NGC 5383 (V_{Hel} = 2250 km/s), providing further evidence for a mutual association.

VAN DER KRUIT: Surface photometry by myself and Bosma on the deep plate just showed indicates that the inner region is an ovally distorted lens with the bar along the major axis. The outer structure seems to be the response of the outer disk to the ovally distorted lens. Also, its flat rotation curve indicates that M/L in the outer region must be 10 times higher than in the lens.