A Neutral Hydrogen Survey of NGC 2685

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Received April 1, 1979

Summary. NGC 2685 has been surveyed in the 21-cm line of neutral hydrogen in the velocity range \( V = +730 \) to \( +1030 \) km s\(^{-1}\) using the Westerbork Radio Synthesis Telescope. The basic data are a three-dimensional array of brightness temperatures with a half-power resolution \( (\Delta x \times \Delta y \times \Delta V) \) of \( 49'' \times 57'' \times 27 \) km s\(^{-1}\) and an r.m.s. noise of 0.9 K. The radio continuum showed nine background sources, two of which may be variable.

The data are presented as two single-channel maps (Fig. 2) and as a column density map and two velocity-position cross sections (Fig. 3). These reveal two kinematic systems with different rotation axes, which correspond to the helix-like structure and the faint outer ring, respectively. Most of the \( \text{H} \text{I} \) is associated with the latter. From the \( \text{H} \text{I} \) kinematics and the optical geometry a spherically symmetric mass model is constructed, which is consistent with the optical spectroscopic observations as well (Fig. 4 and Table 2). The systematic velocity is \( +870 \) km s\(^{-1}\) (heliocentric), the \( \text{H} \text{I} \) mass \( 2 \times 10^8 \) \( M_\odot \) and the total mass \( 76 \times 10^9 \) \( M_\odot \), assuming a distance of 17 Mpc.

The results are discussed in terms of accretion of intergalactic gas. The outer ring may be quite old (more than \( 10^9 \) yr) or possibly a remnant of the formation period of the galaxy. The helix-like structure may be the result of a much more recent accretion event. Although this model accounts for some of the general properties of the galaxy, understanding the detailed morphology is still a challenging problem.

Key words: galaxies – accretion – 21-cm line – NGC 2685

1. Introduction

NGC 2685 is referred to by Sandage (1961), not without reason, as "perhaps the most unusual galaxy in the Shapley-Ames catalogue". The obvious peculiarities cause him and others to refer to it alternatively as a 'spindle' and a 'pancake'. Several suggestions have been made regarding the origin of these peculiarities. Burbidge and Burbidge (1959), who favor the pancake model, suggest that magnetic fields may be responsible. Sérsic (1973) favors the spindle model and proposes a mechanism based upon the hypothesis of a variable central mass or fission of the central mass into two elements. Along similar lines Arp (private communication) points out "a group or chain of peculiar and interacting galaxies about 28' north following and two moderately large galaxies about 9' south preceding NGC 2685". These galaxies are roughly aligned with the spindle and he suggests that "they are associated and probably ejected". More recently it has become acceptable to consider interactions of galaxies with their environments, and Toomre (1977a) suggests that we may be seeing the accretion of an intergalactic gas cloud or a gas-rich dwarf. This suggestion is the basis of the interpretation given here.

Despite its obvious interest, kinematic data on NGC 2685 have been slow to accumulate. Aside from data on the systematic velocity (references in de Vaucouleurs et al., 1976) the first detailed optical spectroscopic data were published by Demoulin (1965); these indicated that the helix-like structure rotated around the long axis of the galaxy. Subsequently the same author (Ulrich, 1975) found that gas within 10' of the nucleus showed rotation similar to that of the "helix". Finally Schechter and Gunn (1978), extending work by Humason of almost 40 yr earlier (Adams and Seares, 1939), observed stellar velocities within 20" of the nucleus and showed that they were consistent with what would be expected of a lenticular galaxy seen edge-on.

The first detection of the 21-cm line in NGC 2685 was by Balkowski et al. (1972), and the most reliable global line profile currently available was published by Gallagher et al. (1975). Before the present observations, the only information on the \( \text{H} \text{I} \) velocity field was a suggestion of the rotation direction derived by Knapp et al. (1977) from an off-center line profile. The present observations were discussed briefly at the 150th meeting of the American Astronomical Society (Shane, 1977) but are presented here for the first time in detail.

2. Observations and Reductions; Background Sources

The observations used in this investigation comprise two 12-h runs with the Westerbork Synthesis Radio Telescope (Baars et al., 1974) and the 80-channel 21-cm line receiver (Allen et al., 1974) made in September 1974. The two runs were identical except for the velocity setting of the filter bank (8 channels at fixed intervals of 40 km s\(^{-1}\)). The heliocentric velocities of the center of this bank were +870 and +890 km s\(^{-1}\). Observations were made with the half-length array only, giving interferometer baselines between 54 and 702 m at intervals of 72 m. The system was fully operational during both observations and there was no evidence of significant interference, so that a full 12-h synthesis was available for all baselines and velocities.

In calibrating and correcting the observations and making Fourier transforms to the map plane, standard procedures (Högboom and Brouw, 1974; van Someren Greve, 1974) were

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map center \((x, \delta) = 8^h 52^m, +58^\circ 59'\) (1950)
map size = 1\,288 square
grid interval = 18" square.

followed. The resulting 16 maps, at equally spaced velocities between +730 and +1030 km s\(^{-1}\), have the following properties:
The sum of these 16 maps was searched for continuum sources, making allowance for the presence of line radiation in the neighbour-hood of NGC 2685. Nine sources, all of which had been reported by Willis et al. (1976), were identified. These are listed in Table 1. The excellent agreement of the fluxes for seven of the nine sources suggests that these determinations are internally quite consistent, the formal r.m.s. error being only 1.9 mJy. The two sources noted as suspected variables, 0853+58 W2 and 0854+58 W1, show flux decreases in four years of 39 and 31\%, respectively, or 23 and 5 times the internal error derived from the other sources. Although these two sources are located in the same quadrant of the field, the consistency of the other fluxes and the absence of position-dependent trends in the residuals argue against attributing the discrepancies to pointing inaccuracy. Nevertheless, the limited observational material permits only a tentative suggestion of variability until confirmation is available. Two sources reported by Willis et al. were not identified. No trace of 0850+58 W1 could be found above the noise level, although it was expected at several times this level and was confirmed on the original continuum measurement. Source 0852+58 W1 was masked by an instrumental effect near the field center and could not be identified with certainty. Several weaker sources were noted, but none of these was close enough to NGC 2685 to suggest a physical association or to necessitate subtraction from the H\(\text{I}\) maps.

In order to eliminate grating rings, which could produce confusion in the integrated H\(\text{I}\) map, and to partly compensate for the missing short baseline information, all single-channel maps were cleaned and restored, using for restoration the central peak of the synthesized beam (see Högbom, 1974, for a discussion of this method). The iterative procedure for removing components was carried out until all peaks within the region to be cleaned were reduced below 5 mJy, or about 1.2 \(\sigma\).

The regions of the individual maps which appeared to contain line radiation were isolated with the aid of masks. These were auxiliary maps with ones at all places where line radiation was suspected and zeroes elsewhere.

They were constructed in the following way: 1. Each map was convolved in position to a circular beam of Gaussian form with a half-power diameter of 104" and in velocity to a half-power band-width of 58 km s\(^{-1}\). 2. Examination of the corresponding contour maps showed that the 0.26 K contour (1.2 \(\sigma\)) always enclosed a region of line radiation. In addition there was always a number of other regions above the 0.26 K level scattered about the map; these regions were presumably noise. The preliminary masks were defined so as to include all points above 0.26 K in the line-radiation region and to exclude all of the outlying peaks except those which lay so close to the selected region as to suggest a connection. 3. The masks made in this way were extended as necessary to ensure that at each grid point a single continuous series of velocities was included.

Using these masks, the regions of line radiation were eliminated from the unconvolved maps and the remaining line-free maps were averaged. The resulting background map should show any residual continuum radiation or instrumental zero-level effects. Except in regions near NGC 2685, where many channels were

\[315\]

**Table 1.** Radio continuum sources near NGC 2685

<table>
<thead>
<tr>
<th>Name</th>
<th>(a)</th>
<th>(b)</th>
<th>(c)</th>
<th>(d)</th>
<th>(e)</th>
<th>(f)</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>0849+58W1</td>
<td>08 49 35.41 ±0.15</td>
<td>09 05 56.0 ±0.3</td>
<td>30.1 ±0.1</td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>0849+58W2</td>
<td>08 49 41.55 ±0.32</td>
<td>09 04 20.3 ±0.9</td>
<td>14.6 ±0.3</td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0852+58W1</td>
<td>08 52 36.02 ±0.12</td>
<td>09 07 10.9 ±0.0</td>
<td>18.2 ±0.5</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0852+58W2</td>
<td>08 52 36.12 ±0.12</td>
<td>09 07 10.9 ±0.0</td>
<td>18.2 ±0.5</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0853+58W1</td>
<td>08 53 06.28 ±0.16</td>
<td>09 17 41.4 ±0.5</td>
<td>16.8 ±0.3</td>
<td></td>
<td></td>
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<tr>
<td>0853+58W2</td>
<td>08 53 07.08 ±0.16</td>
<td>09 17 41.4 ±0.5</td>
<td>16.8 ±0.3</td>
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<td></td>
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<tr>
<td>0853+58W3</td>
<td>08 53 34.56 ±0.11</td>
<td>09 31 03.6 ±0.1</td>
<td>40.3 ±0.3</td>
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<tr>
<td>0854+58W1</td>
<td>08 54 48.47 ±0.15</td>
<td>09 34 47.2 ±0.4</td>
<td>28.9 ±0.3</td>
<td></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>0854+58W2</td>
<td>08 54 48.47 ±0.15</td>
<td>09 34 47.2 ±0.4</td>
<td>28.9 ±0.3</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Explanation of Table 1:

Data on the nine radio continuum sources found from these observations and previously reported by Willis et al. (1976) are listed. For each source the data from Willis et al., epoch 1970.65, are given in the first line; corresponding data from the present observations, epoch 1974.69, are given in the second line. The errors are estimated essentially as described by Willis et al. In most cases the estimated errors are substantially larger than the residuals, particularly in flux. Since the errors estimates are based upon average calibration quality, this can be explained if the observations of both series were calibrated more accurately, or consistently, than the postulated average observation.

Note E: source reported by Willis et al. as extended.

Note V: suspected variable source源头 discussed in the text.

half-power bandwidth (in velocity) = 27 km s\(^{-1}\)
synthesized beam (half-power, \(x \times \delta\)) = 49" \(\times\) 57"
r.m.s. noise = 0.9 K or 4.2 mJy per beam.
contaminated with line radiation, the r.m.s. noise in this map was about 0.26 K or 1.2 mJy per beam. Near the center of NGC 2685 the noise is comparable to that on a single-channel map and the resultant 3σ upper limit for a source possibly associated with the galaxy is 13 mJy, well above the upper limit of 3 mJy derived by van der Kruit (1971) from continuum observations. Except for the sources mentioned above, no evidence of continuum radiation was found on this map.

A marked instrumental effect, however, was detected, in the form of broken elliptical rings around the field center. Patterns of this sort are generally associated with zero-level errors in the correlator channels or truncation errors in the digital data recording system. Stability of this effect and of the calibration parameters caused the pattern to be similar in all channels, as was confirmed by comparing the results from the observations on two different days. The amplitude near the center of the pattern, which had been displaced by about 4′ from the center of the galaxy in order to avoid confusion with a possible continuum source associated with the galaxy, was about 1 K (4σ).

This effect was removed with the aid of a baseline correction map which was constructed by setting all points outside the identifiable pattern to zero, in order to avoid an unnecessary noise contribution. This correction map was subtracted from each of the full-resolution single channel maps and the results were corrected for primary beam attenuation in order to construct the final maps used in the subsequent analysis. These maps could be multiplied by the corresponding masks when this was required for noise suppression.

For purposes of comparison a global line profile was derived by summing all of the points in each of the masked single-channel maps. The result is shown in Fig. 1, where the filled circles represent the observations. The relevant part of the published line profile of Gallagher et al. (1975), corrected to an aperture efficiency of 0.5, is shown as a solid curve. Despite substantial differences in detail, the general appearance of the two profiles is similar. A synthesis telescope does not measure the global line profile directly; it must be inferred from the distribution of radiation, which is assumed to be restricted to a limited part of the primary beam. Both the cleaning and masking procedures are significant in deriving the line profile, and imperfection in either generally leads to an underestimate of the flux. The agreement indicates that this is not serious in the present case, although there is a possibility that the reported single-dish profile is also slightly too low on account of beam attenuation.

3. HI Maps

The reduced data can be represented in the form of sixteen single-channel maps showing line radiation only. Two such maps are illustrated in Fig. 2, the broken and solid contours representing brightness temperature at 120 km s⁻¹ below and above, respective-
Fig. 3. Contour maps of $\text{H}_\text{I}$ surface density and two position-velocity sections. The main panel shows the distribution of integrated brightness temperature, superimposed upon the same photograph as was used for Fig. 2. The contour interval and lowest contour value are 50 K km s$^{-1}$, corresponding to an $\text{H}_\text{I}$ column density, in the unsaturated case, of $9.12 \times 10^{19}$ atoms cm$^{-2}$. The side and bottom panels are velocity-position cross-cuts along the two axes indicated in the main panel. The contour interval and lowest contour value are 1 K. The shaded ellipses indicate the approximate half-power resolution element in each panel.
Table 2. Geometry and kinematics

<table>
<thead>
<tr>
<th></th>
<th>Central condensation</th>
<th>Helix-like structure</th>
<th>Outer ring</th>
<th>Units</th>
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<tbody>
<tr>
<td>Position angle (axis)</td>
<td></td>
<td></td>
<td></td>
<td>Degrees ¹</td>
</tr>
<tr>
<td>Inclination</td>
<td></td>
<td></td>
<td></td>
<td>Degrees ²</td>
</tr>
<tr>
<td>Radius $R$</td>
<td>0.83 ³</td>
<td>2.8 ⁴</td>
<td>11.6 ⁴</td>
<td>($D/D_0$) kpc ⁵</td>
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<tr>
<td>$V_\nu$ measured ⁶</td>
<td>130</td>
<td>107</td>
<td>134</td>
<td>km s⁻¹</td>
</tr>
<tr>
<td>$\Theta_c$ circular</td>
<td>147 ⁷</td>
<td>121</td>
<td>149</td>
<td>km s⁻¹</td>
</tr>
<tr>
<td>$M$ cumulative ⁸</td>
<td>4.1</td>
<td>9.6</td>
<td>59.6</td>
<td>$10^9 (D/D_0) M_\odot$</td>
</tr>
<tr>
<td>Boundaries ⁹</td>
<td></td>
<td>2.0</td>
<td>5.5</td>
<td>($D/D_0$) kpc</td>
</tr>
<tr>
<td>H I mass ¹⁰</td>
<td></td>
<td>0.5</td>
<td>1.5</td>
<td>$10^9 (D/D_0)^2 M_\odot$</td>
</tr>
<tr>
<td>Total mass</td>
<td>6</td>
<td>20</td>
<td>50</td>
<td>$10^9 (D/D_0) M_\odot$</td>
</tr>
</tbody>
</table>

Notes to Table 2:

¹ Measured from north through east.
² Measured between the line of sight and the positive (right hand) rotation axis.
³ Corresponding to an angular distance of 10° from the nucleus. The data in this column are derived from Ulrich (1975).
⁴ Corresponding to the peaks in the H I distribution as shown in Fig. 3.
⁵ Normalized to the assumed distance $D_0 = 17$ Mpc. $D =$ true distance in Mpc.
⁶ Radial velocity with respect to the adopted systemic velocity. For the H I observations this is +870 km s⁻¹ (heliocentric).
⁷ Assuming the same projection angles as for the helix-like system.
⁸ Total mass within a sphere with radius $R$, as derived from the circular velocities.
⁹ Derived from inspection of Fig. 3. The quantities in the last two lines pertain to the zones defined by these boundaries.
¹⁰ Estimated from Fig. 3. No H I could be identified with the central condensation.

ly, the adopted systemic velocity of +870 km s⁻¹. On these two maps we see clearly the separation of two kinematic systems, one associated with the faint outer, elliptical ring, which is best seen on the deep exposure in the Hubble Atlas (Sandage, 1961), and the other associated with the peculiar structure of helical appearance. The other single-channel maps do not show these two systems as well separated, because of the rather large synthesized beam, but are not inconsistent with their existence.

A more complete representation may be seen in Fig. 3. The central panel is a map of integrated brightness temperature (or H I column density, if the 21-cm line is unsaturated), and the two side panels are cross cuts along the apparent major and minor axes, as indicated by broken lines, showing brightness temperature as a function of position and velocity. The map in the main panel was made by summing the masked single-channel maps. The side panels were constructed from the unmasked maps.

The main panel shows strong concentrations of H I in the "helix", particularly where it is seen tangentially, and a much more extended distribution corresponding to the outer ring (which unfortunately shows up only very weakly on this reproduction). The lower panel shows the rapid rotation of the "helical" system and the lack of rotation of the outer ring in this orientation, whereas the right-hand panel shows the rotation of the outer ring clearly. The "helix" is not readily identifiable in this panel.

4. Geometry and Kinematics

NGC 2685 appears to comprise three systems, as follows:

1. a central body, contributing most of the light, which, although it has the appearance of a prolate spheroid, has been shown by Schechter and Gunn (1978) to be most probably an S0 galaxy seen almost edge-on. No H I has been identified with this system.

2. The well-known helix-like structure which at first sight appears, probably misleadingly, to be wrapped around a cigar-like central body. Close examination of photographs suggests that the symmetry axis, in fact, be one of coaxial rings or tightly wound spirals in which dust and stellar associations appear to dominate; the present observations show that H I is also plentiful in this structure. Three of the rings are sufficiently complete that it is possible to determine their orientations and axial ratios, and these give, quite consistently, the orientation parameters of the helix-like structure reported in Table 2. Part of each ring is seen in absorption against the central body, eliminating the sign ambiguity. The radial velocities of the extremities of this helix-like structure can be read from the lower panel of Fig. 3 and converted to rotational velocities with the aid of the geometrical parameters. The results are also given in Table 2. These velocities are found at points about 30° on either side of the nucleus. Within 10° of the nucleus, where the helix structure is not evident, Ulrich (1975) finds ionized gas with a similar sense of rotation and a projected velocity at 10° from the nucleus of about 130 km s⁻¹. These gas motions are confirmed by Schechter and Gunn (1978). Under the assumption that this gas belongs to the same structure as the "helix", the corresponding rotational velocity is also reported in Table 2. Three regions in the "helix" have also been observed spectroscopically (Demoulin, 1965). One of these, region A on the np side of the galaxy, is reported to have a relative velocity of +200 km s⁻¹, outside the range of the present H I observations, but at a velocity where nothing is seen in the integrated line profile (Gallagher et al., 1975). The other two, regions B and C...
on the $sf$ side, have reported velocities in approximate agreement with the H1 results.

3. An outer ring, prominent on the deep photograph in the Hubble Atlas, but scarcely visible in Figs. 2 and 3, because of difficulties inherent in the photographic superposition of the contours. The ring has a rather diffuse appearance, although it seems to contain some faint knots which might be regions of star formation. It appears roughly as an ellipse but exhibits some irregularities, in particular a hook-like extension on the $nf$ end, which is reflected in the H1 distribution (Fig. 3). The orientation of the symmetry axis, assuming that it is a circular ring seen in projection, is given in Table 2. The orientation of the long axis is, within the error, the same as that of the inner (S0) structure, although it appears that the outer ring is seen a little more face-on. The planes of symmetry of these two structures need not differ by more than about 15°. Most of the H1 in the galaxy appears to be associated with this ring, although the limited angular resolution makes a quantitative estimate difficult. The radial velocity and associated rotation are reported in Table 2.

The structure of the whole galaxy is clearly too complicated to permit construction of a detailed mass model on the basis of the available data, so we must be content for the present with a very rough approximation. For this purpose we may adopt a spherically symmetric mass distribution. The masses interior to three radii, corresponding to the three columns in Table 2, are listed. For the purpose of the computations a distance $D_0 = 17$ Mpc is adopted, corresponding to the systematic velocity referred to the galactic standard of rest and a Hubble constant of $55$ km s$^{-1}$ Mpc$^{-1}$. The dependence upon the true distance, $D$, is shown explicitly in the table. The density distribution is represented by an exponential function, with an additional mass, $3.9 \times 10^9 (D/D_0) M_\odot$, added in the center in order to represent the optical observations within $10^5$ of the nucleus. For the purpose of the model this mass is assumed to be distributed uniformly over a sphere with radius $830 (D/D_0)$ pc; the details of the mass distribution in the innermost $1$ kpc are of little significance in the interpretation of the H1 kinematics. The exponential component has a scale length of $2.85 (D/D_0)$ kpc and a mass of $72.3 \times 10^9 (D/D_0) M_\odot$. The mass distribution, shown as mass interior to radius $R$, and the corresponding rotation curve are illustrated in Fig. 4. The initial rise in the rotation curve represents the optical data (Ulrich, 1975), which are not plotted individually, while the two points derived from the H1 observations are shown as open circles. The H1 regions B and C of Demoulin (1965) are plotted as triangles. The reported velocities, with respect to the systemic velocity, have been multiplied by sec 28° in order to correct for the inclination of the axis of the "helix". Other projection effects, which, if included, would move the points radially away from the origin, have not been taken into account. The stellar velocities along the major axis, relative to the systemic velocity, as reported by Schechter and Gunn (1978), are plotted as filled circles. No correction for projection has been applied. All neglected effects, the projection correction, the non-circularity of the stellar orbits, and integration along the line of sight, will tend to reduce the measured velocities with respect to the circular rotation curve, so that these velocities are consistent with the proposed model.

The total H1 mass derived from these observations (see Fig. 1) is $2.1 \times 10^9 (D/D_0)^2 M_\odot$, in excellent agreement with the corrected value of Gallagher et al. (1975) of $1.9 \times 10^9$, giving, for the entire galaxy, an H1 to total mass ratio of 0.026 $(D/D_0)$. Examination of Fig. 3 suggests that about one quarter of the observed H1 is associated with the "helix" and the remainder with the ring. From the mass distribution shown in Fig. 4 the total masses associated with these two zones, placing the inner boundary of the "helix" at $2(D/D_0)$ kpc and the boundary between the helix and the ring at $5.5(D/D_0)$ kpc, from inspection of Fig. 3, are $2 \times 10^{10}$ $(D/D_0) M_\odot$ respectively, and the corresponding H1 to total mass ratios are 0.025 and 0.03. These ratios, however, refer to averages over the corresponding radial zones. The ratios in the regions of the "helix" and ring themselves will be considerably higher. The most luminous material is much more strongly concentrated to the center, so that we must conclude that most of the matter in the outer part of the galaxy is in the form neither of H1, unless very cold, nor of the kind of stars which provide the major part of the luminosity. Thus the radial distributions of mass, light and neutral hydrogen are not greatly different from what is commonly found in spiral galaxies.

5. Origin and Evolution

Aside from the suggestion by Sérsic (1973), which turns out to be hard to reconcile with the more recent observations, and brief comments by Toomre (1977b) and Gunn (1977), little has been published regarding the possible origin of the peculiar structure in NGC 2685. In contrast to Sérsic, who proposes a mechanism dependent upon a large-scale disturbance of the central mass concentration, I shall, following Toomre (see also Knapp et al., 1977), consider here the possibility that this structure has formed as a result of accretion from intergalactic space. The simultaneous presence of two apparently quite independent gas systems, in addition to the main stellar mass concentration, suggests formation in two separate events. Recent evidence (Lo and Sargent, 1979) indicates that massive intergalactic clouds without accompanying stars are rare, at least at the present epoch, so that the accreted gas may have belonged to a gas-rich dwarf, as suggested by Toomre (1977b). Since the gas will be swept away from the stars at an early stage of the encounter, the distinction cannot be made on the basis of these observations. It is only the behavior of the gas cloud
which is of importance here. The details of this accretion process have been discussed extensively by Silk and Norman (1979).

The initial configuration, according to this scheme, is a highly flattened elliptical or a lenticular galaxy, seen almost edge on. The first accretion event was an encounter with one or more intergalactic clouds (with or without accompanying stars) producing, ultimately, the outer elliptical ring. Such rings are not very uncommon; M83 (Rogstad et al., 1974) and NGC 4278 (Gallagher et al., 1977) are examples. They may be the normal terminal configuration of an accretion event where the specific angular momentum of the accreted matter substantially exceeds that of the accreting galaxy. Once the intergalactic cloud has been captured (by dynamical friction, for example, as discussed by Toomre, 1977a), random motions in the gas will quickly be damped out (Knapp et al., 1978) so that the accreted gas will lie in a plane, which is, in general, not the fundamental plane of the galaxy, or in a series of concentric rings with different radii and axes. Even if a planar configuration is reached, it will evolve into an assembly of non-coaxial rings through differential precession (Kahn and Woltjer, 1959). The rate at which this will happen will depend upon the degree of flattening of the galaxy and the inclination of the disk. Finally, a certain amount of viscosity between these non-coaxial rings will lead to a gradual damping of the precession and alignment of the ring axes with the symmetry axis of the galaxy. It seems probable that this will take place quite slowly, since the interaction between the rings may not be strong, but the rate will depend upon the non-circularity of the particle orbits and the physical state of the gas. At present the ring seems to lie roughly in a plane which is tilted 15–30° with respect to the fundamental plane of the galaxy (see Table 2), suggesting that, unless the accreted matter happened to have an initial angular momentum this closely aligned with the rotation axis of the galaxy, the alignment process is well underway. In the absence of a refined dynamic model of the galaxy and a better understanding of the physical conditions in the gas, it is difficult to estimate the age of the ring, but several rotation periods, or about 10^8 yr (see Table 2) seems a reasonable lower limit. It is not clear how any upper limit can be established on the basis of presently available data. It is quite possible that the ring is a remnant of the original galaxy formation process which has succeeded in surviving to the present time.

The H I mass quoted in Table 2, 1.5 × 10^8 M☉, is, for various reasons, a lower limit to the total mass of the ring. 1. The faint luminosity indicates that star formation is taking place, albeit at a modest rate. 2. Some part of the gas may be present in molecular or ionized form, although the low rate of the star formation and the absence of pronounced associations of young stars suggest that no large quantities of gas are present in the form of cold cloud complexes. 3. Some of the original gas may have lain inside the present inner boundary (5.5 kpc radius) and been swept up by the second accretion event, to be described in the following paragraph. Even the lower limit given above is rather high for the mass of an intergalactic cloud (Silk and Norman, 1979) or the gas content of a dwarf, suggesting that the ring may be of primordial origin or the result of more than a single accretion event.

The helix-like system makes NGC 2685 unique among bright northern galaxies, although two southern galaxies with somewhat similar features are known, the familiar NGC 5128 (cf. Toomre, 1977b) and NGC 4650, which has recently been photographed by Laustsen (Woltjer, 1978). The possible explanation of the “helix” in NGC 2685, as suggested by Toomre, is that this also is the result of an accretion event, more recent than that which may have caused formation of the outer ring. In this case the intergalactic cloud (now of approximately the mass predicted by Silk and Norman, see Table 2) or a gas rich dwarf is seen as falling into the galaxy almost parallel to the rotation axis. Braking by dynamical friction may have been aided by the sweeping up of gaseous material already present in the inner part of the galaxy, as suggested by the fact that the outer boundary of the “helix” coincides with the inner boundary of what currently remains of the ring (see Fig. 3 and Table 2). The resulting angular momentum vector appears to lie nearly in the plane of the galaxy. In this particular case, differential precession will be ineffective in bringing the gas into the plane of the galaxy (cf. Gunn, 1977), but dynamical friction with the stellar disk and interaction with stellar winds will lead to a loss of specific angular momentum and an inward spiraling of the gas. The time scale for interaction with stellar winds is, for the whole cloud, about 5 × 10^8 yr (Faber and Gallagher, 1976), but it should be much shorter for that matter which lies initially closest to the nucleus. The emission lines observed by Ulrich (1975) within 10° of the nucleus, which show the same rotation as does the “helix”, presumably arise from gas which has nearly reached the nucleus. Despite the other speculative features of the hypothesis presented here, this seems to be quite direct evidence for gas being fed into a galactic nucleus. This is one of the requirements of certain theories of non-thermal radio sources (see, for example, Rees, 1976), the other being the presence in the nucleus of some super-massive object upon which the inflowing gas can be accreted. Despite a rather strong mass concentration toward the center (Table 2 and Fig. 4), the absence of a non-thermal radio source stronger than about 3 mJy (van der Kruit, 1971) suggests the absence, as yet, of such a super-massive object. No evidence of enhanced star formation in the nucleus has been found (Heckman, 1978), so that we must conclude that the feeding of gas into the nucleus is only just beginning. It is interesting to speculate how long this can go on without inducing more dramatic effects. Are we perhaps witnessing the formation of a new NGC 5128?

The concentration of the gas in rings (or spirals), some of which appear to be almost complete, can be explained only if the gas has been present long enough to have been drawn out by differential rotation, suggesting a minimum age of at least two rotation periods, or 3 × 10^8 yr. The near uniqueness of the morphology argues that the life span of this configuration is short, probably considerably shorter than the 5 × 10^8 yr upper limit quoted above.

Self-gravitation and viscous damping must be important in determining the structure, as shown by the sharp delineation of the rings and the high densities which are implied by the prominent dust lanes and the large regions of active star formation. In this respect the physical conditions in the “helix” are in sharp contrast with those in the outer ring. The total mass of the “helix” is probably substantially greater than the H I mass quoted in Table 2, although still making only a small contribution to the total mass in its radial zone.

The morphology of the “helix” presents the above hypothesis with a serious problem. One might expect to see a series of concentric, but not necessarily coaxial, rings, provided the axes lay close to the plane of the galaxy. In fact, the best photographs create the impression of rings which are coaxial but not concentric! How differential rotation, or any other process, can draw out material into rings which are not concentric with the mass center is a problem which any complete theory of NGC 2685 will have to face. The first step toward its resolution may be a more detailed kinematical study of the rings.
Acknowledgements. The observations described here were made at the suggestion, and with the cooperation, of Dr E. Bajaja. I am indebted to Dr T. M. Heckman, Dr C. A. Norman, and Prof. J. H. Oort for many valuable suggestions and particularly to Prof. A. Toomre, whose colorful description of the accretion process was the basis of the interpretation presented here. I am also indebted to Dr H. Arp for making available the photograph used in Figs. 2 and 3 and to Prof. J. Gunn for describing his observational results to me in advance of publication. The Westerbork Radio Observatory is operated by the Netherlands Foundation for Radio Astronomy with the financial support of the Netherlands Organization for the Advancement of Pure Research (Z. W. O.).

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