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ASTRONOMY AND ASTROPHYSICS

The Local Mass-to-light Ratio in Spiral Galaxies*

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Summary. Data obtained from Westerbork 21 cm-line studies and optical surface photometry from Palomar Schmidt plates have been combined to calculate the radial variation of the mass-to-light ratio in six spiral galaxies. Although the uncertainties in the modelling procedures are large we conclude that this ratio increases significantly in the outer parts. Local values of M/L may be of the order of 10^2–10^3 there. Part of the variation probably occurs in the disk itself. A few implications of our results are discussed.

Key words: spiral galaxies – mass models – surface photometry mass-to-luminosity ratio

I. Introduction

The mass-to-luminosity ratio in spiral galaxies, in particular its variation with radius, is one of the quantities playing a fundamental role in the discussion of the structure and evolution of these systems. Its determination, however, is not straightforward, and in particular the reported increase of M/L in the outer parts is subject to debate (see e.g. Roberts, 1975; Baldwin, 1975). The different results between various observers can usually be traced back to differences in the adopted models for both the mass distribution and the light distribution.

As an example we combine in Fig. 1 the derived radial distributions of M/L in M 33 from data prior to 1975. These derivations are based on very similar rotation curves and the same photometry; the differences can be traced back to procedures to convert the rotation curve into a mass distribution. All models in Fig. 1 involve a disk component in both the mass and light distribution; in spite of this simplifying assumption rather different results obtain. The discussion of the importance of varying M/L ratios in spiral galaxies centers mainly on questions of the composition of high M/L material (whether it is composed of M-dwarfs, black dwarfs, dead stars, etc.), and the existence of massive haloes around spirals (Ostriker et al., 1974; Einasto et al., 1974). The bulk of this paper will concern a discussion of the modelling procedures.

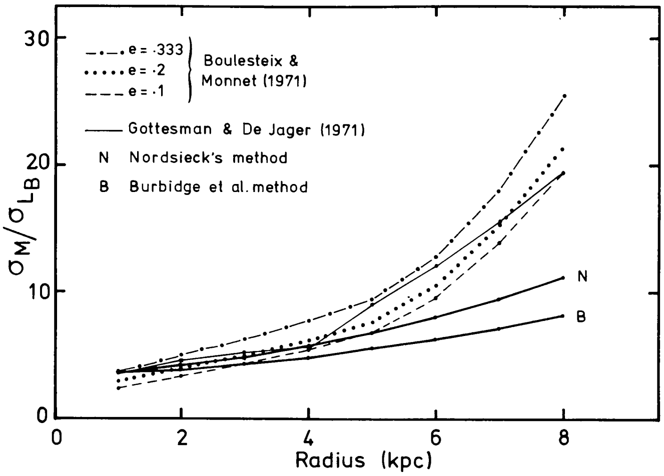

Fig. 1. Radial variation of M/L in M 33. Data are taken from Boulesteix and Monnet (1971), Gottesman and de Jager (1971), and from two calculations based on the rotation curve obtained by Warner et al. (1973): their mass model and our mass model have been combined with the photometry of the Vaucouleurs (1959)

In this paper we use new data on this subject, obtained from the combination of studies in the 21 cm H I line of several galaxies with the Westerbork Synthesis Radio Telescope, WSRT, (Bosma, 1978; Abbrev. B78) and accompanying photographic surface photometry of these galaxies using IIIaJ-plates taken with the 122-cm Schmidt Telescope at Palomar Mountain, PST, (van der Kruit, 1979; Abbrev. K79). Since our data extend to galactocentric distances of about 30 kpc they have bearing on the question of the increase in M/L in the outer parts of these galaxies.

II. Model Procedure and Results

We have collected data on six spiral galaxies, studied both with the WSRT and the PST. A summary of relevant properties of these systems is given in Table 1. The H I observations of NGC 4258 were taken from van Albada and Shane (1976), those of NGC 5383 from Sancisi et al. (1979), while the other four galaxies are discussed in B78. Additional data on the rotation curves in the inner parts of NGC 5033 and NGC 5055 have been taken from van der Kruit and Bosma (1978b). Distances are based on

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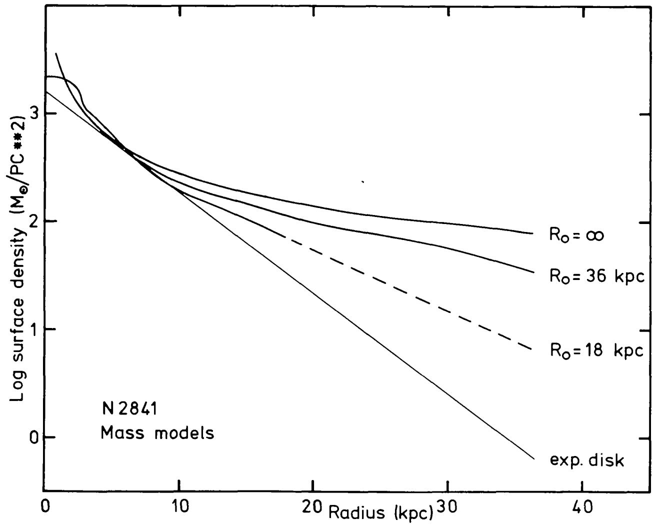

Fig. 2. Radial variation of mass surface densities in various models of NGC 2841

Table 1. Properties of spiral galaxies used in this study

NGC	Type	Distance (Mpc)	R(o) (kpc)	R_{rad} (kpc)	R_{opt} (kpc)	M_{rad}/L_B^o (solar units)	ψ	i
2841	SA(r)b	9.0	8.9	36.1	18.3	28.1	148	68
3198	SB(rs)c	9.0	9.1	25.7	15.7	11.6	36	70
4258	SAB(rs)bc	6.6	14.5	29.4	28.8	7.2	332	72
5033	SA(s)c	14.0	18.6	35.8	24.4	10.9	352	62
5055	SA(s)bc	8.0	12.8	41.1	32.6	9.9	99	55
5383	SB(s)b	31.3	15.4	26.8	26.8	7.4	85	40

$H = 75$ km s^{-1} Mpc^{-1}, $R(0)$ is taken from the RC2 (de Vaucouleurs et al., 1976), R_{rad} is the radius of the last measured point on the rotation curve derived from the 21 cm line data, R_{opt} the radius out to which the optical surface photometry is obtained, M_{rad}/L_B° is the global M/L-ratio obtained from the mass out to R_{rad} (from B 78) and the luminosity derived from the integrated and extrapolated B-magnitude corrected for galactic and internal absorption (from the RC 2), and ψ and i are the orientation parameters (see below).

a) Rotation Curves and Mass Models

The 21-cm line data allow in principle the determination of the rotation curve of a spiral galaxy over almost the entire radial extent. Standard procedures, as e.g. described by Warner et al. (1973) are used to derive the rotation curve and the orientation angles of the galaxy assuming that it follows the ideal picture of having flat disks with the material moving in circular orbits. Most galaxies, however, as discussed in B 78, do not follow this picture but show large scale deviations from axial symmetry in their velocity field. Of the six galaxies in Table 1 two (NGC 4258 and NGC 5383) show deviations from circular motion which most likely are due to bar-like distortions in the disk, three of them (NGC 2841, 5033, and 5055) show indications of a warped H I layer, and one of them (NGC 3198) shows small amplitude effects of both (cf. B 78).

In order to proceed and use the rotation curves and mass models based on them, estimates of the uncertainties introduced by these large scale deviations are necessary. The motions associated with spiral arms and bar-like distortions do affect the determined rotation curve, but detailed treatments as in Visser (1978) and B 78 show that neglecting them results in an uncertainty in the radial distribution of mass surface density due to these distortions alone of the order of probably only 20%. The galaxies with warped H I disks, however, pose a more serious problem in this respect. In B 78, rotation curves have been derived by taking the circular velocity in the rings building up the tilted-ring model to describe the kinematical warp to represent the rotation velocity at the mean radius of the ring. Although arguments can be presented in favour of this assumption, like operational simplicity in view of the unsolved dynamical problem the warps are posing, it is worthwhile to consider a number of extreme cases for one particular galaxy, namely NGC 2841.

As discussed elsewhere (B 78) the rotation curve of NGC 2841 is fairly flat out to 36 kpc. The warp in that galaxy starts at a radius of about 18 kpc. Several mass models have been calculated for this galaxy. Two of them have been calculated with the method outlined by Nordsieck (1973) for infinitesimally thin disks: one for the outer radius, R_0, at 36 kpc and one with R_0 at 18 kpc. Note that in Nordsieck's method to obtain $\sigma_M(R)$ an estimate has to be made for the contribution to the mass surface density integral of the unknown portion of the rotation curve beyond R_0. This estimate is a compromise between two extreme cases of behaviour of rotation curves beyond R_0: staying flat out to infinity and becoming Keplerian immediately after R_0 (cf. Nordsieck, 1973). It is unlikely that we significantly overestimate this contribution since our resulting mass surface density curves agree well with those derived from fitting the rotation curves with the spheroids and disk models described by Shu et al. (1974), which necessarily represent lower limits to the true mass surface density distributions (cf. B 78). The results are shown in Fig. 2; the dashed line indicates the extrapolation of the $R_0 = 18$ kpc model with a quasi-exponential law. Also included in Fig. 2 are the $1/r$ surface density law for $V_{rot} = 280$ km s^{-1} from $R=0$ to $R=\infty$, and the exponential disk model which has the same scalelength as the light distribution. At the radius of 36 kpc these models differ by a factor 100 in mass surface density.

This state of affairs is discouraging, because we only can make plausibility arguments to justify our choice of mass models. The exponential disk model does not fit the rotation data, since the velocity difference at 36 kpc radius between the observed radial velocity and the projected circular velocity based on this model is 80 km s^{-1}. Note that this velocity difference is always positive for any model velocity curve which is declining instead of flat in the region with $R < 36$ kpc. It can be argued that if z-motions are important in warped disks the sign of the radial velocity component of these motions should be randomly distributed among the galaxies. Since all warped galaxies appear to have flat rotation curves one cannot discard the flatness of the curves because z-motions have not been taken into account: unless the warp problem is contrived a z-motion correction should result sometimes in declining rotation curves, sometimes is rising rotation curves. A similar argument can be presented against the use of the $R_0 = 18$ kpc model. This leaves us with the choice between the $R_0 = 36$ kpc model and the $R_0 = \infty$ one. The $R_0 = 36$ kpc model gives us a fair estimate of the lower limit to the mass surface densities, while the V=constant, $R_0 = \infty$ model should provide an upper limit. We therefore prefer to use the $R_0 = 36$ kpc model for this galaxy so that we underestimate the M/L-values. Note

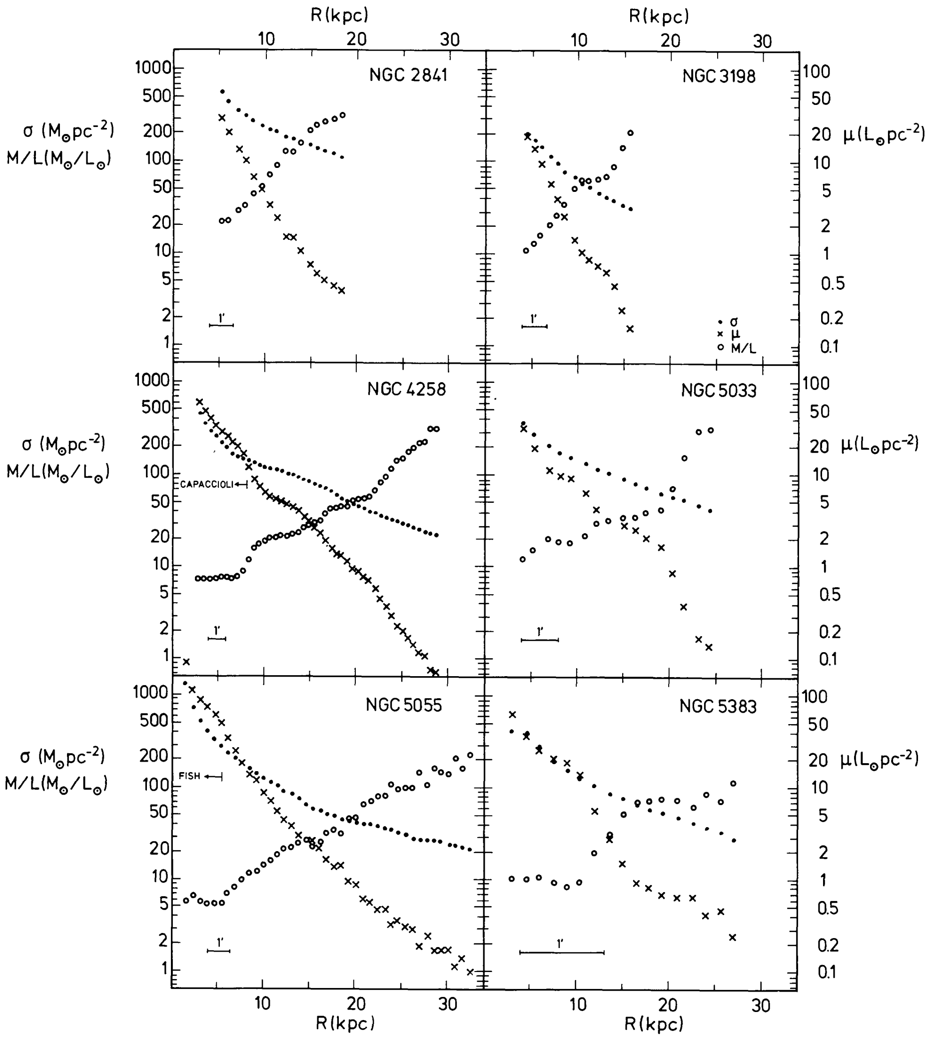

Fig. 3. Radial variations of mass surface density (dots) in $M_\odot$ pc^{-2}, surface brightness (crosses) in $L_\odot$ pc^{-2} and σ/μ_J for six spiral galaxies. The vertical scales are logarithmic, σ and σ/μ are referred to the left-hand scales, μ to the right-hand scales

that this radius is determined by an observational selection criterion; we will discuss the influence of this selection effect in Sect. III.

Regardless of the warp problem we are also faced with the problem of the separation between the disk and the bulge or halo component in the mass distribution. This cannot be done unambiguously at present. In B 78 it is shown that a mass-model can be constructed for NGC 2841 with an exponential disk having the scalelength of the light distribution and a halo component with a $\rho \propto (r^2+b^2)^{-1}$ density law to fit the observed rotation curve out to 36 kpc. For that particular model, which is forced to have a constant M/L-ratio in the disk, the ratio of the halo mass (out to 36 kpc) to the disk mass is about 2.5. Obviously, in this model the halo-component must have a high M/L-ratio, since the light distribution is clearly mainly concentrated in a disk-component. This example shows that although the flat rotation curve indicates the presence of high M/L material, it is not a priori clear whether this is due to a halo component or an increase in the disk of M/L with radius. We will proceed to use mass models based on the thin disk method outlined by Nordsieck (1973) and return to this point in the discussion.

b) Surface Photometry

A detailed account of the main photometric data we will use is given in K 79. In brief, IIIaJ plates (+Wratten 2C filter) have been taken with the PST. The wavelength range of this plate-filter combination is about 3900–5400 Å with an effective wavelength ~4600 Å. The relation of this J-band to the B and V bands is $J=B-0.22\,(B-V)$ (Kormendy and Bahcall, 1974). The plates are calibrated with a series of sensitometer spots and the zero-point of the magnitude scale is derived through Kormendy's (1973) star profile. Extensive checks discussed in K 79 show the magnitude scale to be reliable to $0^{\rm m}.04$ per magnitude-interval in the range 22.5–27.0 mag arc s^{-2} and the zero-point to $0^{\rm m}.2$.

The radial luminosity distributions have been computed by averaging the digitized maps in rings which are circular in the galactic planes. The orientation parameters used (see Table 1) were obtained from the kinematical studies: for the galaxies having oval distortions we used the parameters of the outer parts: for the galaxies having kinematical warps we used the parameters of the inner parts. These orientation parameters agree more or less with those derived from the isophotes themselves. However, for NGC 5055 the position angle of the major axes of the optical isophotes does not change with radius in the region of the warp, contrary to those of the H I column density contours. The irregularity of the isophotes, in particular in the outer NW part, however, prevents us from concluding that the optical disk of NGC 5055 is unwarped, although the warping of the H I disk is certainly not closely followed. In the case of NGC 2841 the photometry does not extend to the warped parts of the disk, and for the other

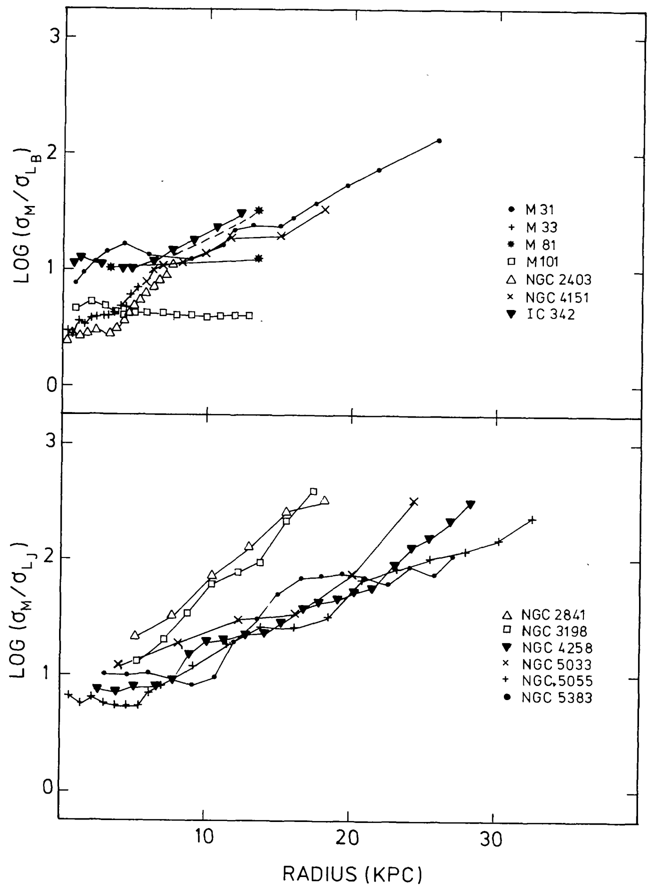

Fig. 4. Radial variations of the local M/L ratio in various galaxies. Only in the case of IC 243 a correction for galactic absorption has been applied ($A_B = 2\overset{m}{.}2$). Note that the luminosities in the upper panel refer to the B-band, those in the lower panel refer to the J-band. Distances are based on $H = 75$ km s^{-1} Mpc^{-1}. The kinematical data in the upper panel are taken from: M 31 (Emerson, 1976; Newton and Emerson, 1977), M 33 (Warner et al., 1973), M 81 (Visser, 1978), M 101 (Bosma et al., 1978), NGC 2403 (Shostak, 1973), NGC 4151 (Bosma et al., 1977), IC 342 (Rogstad et al., 1973). The photometry is taken from: M 31 (de Vaucouleurs, 1958), M 33 (de Vaucouleurs, 1959), M 81 (Schweizer, 1976), M 101 (Okamura et al., 1976), NGC 2403 (Okamura et al., 1977), NGC 4151 (Simkin, 1975 and priv. comm.), IC 342 (Ables, 1971)

galaxies the irregularities associated with the spiral structure prevent an accurate determination of the orientation parameters from the isophote shapes.

We have corrected the annular averages to face-on values adopting again the thin disk approximation. No correction has been made for absorption: galactic absorption is probably negligible at the high latitude of the systems and the internal absorption in the outer parts of spiral galaxies is unknown. The effect of an absorption is to decrease the M/L values, while the assumption of an infinitesimally thin disk rather than spheroids with a finite thickness tends to decrease them too (cf. Fig. 1). Schweizer (1974) has argued that dust reddening in not too inclined spirals is unimportant except in the narrow dust lanes. If we accept this our neglect of the absorption correction seems to be justified. [Note, however, that Mathewson and Ford (private communication) did find evidence for dust in the H I wing of the SMC; also the existence of primary absorption lanes in e.g. NGC 7331 is worrysome].

With regard to the thin disk approximation it should be remarked that the problems are here probably less severe than in the case of the mass distribution. First, the thickness of the disk is unlikely to affect the geometrical correction factor for the observed surface brightness to obtain the face-on surface brightness. Secondly, although bulges apparently extend to large distances at faint levels (as e.g. in NGC 7331; see Arp and Kormendy, 1972) the approximately exponential nature of our observed light profiles combined with the near constancy of the axial ratios of the isophotes as a function of radius, suggests that away from the central regions at least out to R_{opt} the bulge contribution must be small.

The photometry described in K 79 is accurate only in the surface brightness range $\mu = 22.5$–27 mag arc s^{-2}. For three of the galaxies listed in Table 1 published data are available for the inner parts in the *pg* or B band. These are NGC 2841 (Artamonov et al., 1966), NGC 4258 (Capaccioli, 1972), and NGC 5055 (Fish, 1961). We have converted these data to the J-band and included them in our analysis.

c) Results

In Fig. 3 we present the radial distributions of the mass surface density, $\sigma(R)$, obtained with Nordsieck's method from the rotation curves shown in B 78, the optical surface brightness, $\mu(R)$, and their ratio. The surface brightnesses are expressed in units $L_\odot$ pc^{-2}, using $(M_J)_\odot = 5.27$, derived from $M_{pg} = 5.37$ and $B-V = 0.62$; 1 $L_\odot$ pc$^{-2} \equiv \mu_J = 26.84$ (face-on).

In Fig. 4 we show in the upper panel similar data from various sources in the literature. The rotation curves and mass models for these galaxies have been determined with the same method as described above (see B 78). Note that for some galaxies the rotation curves are not extended to the outer parts despite of the detection of H I there: in the cases of M 81 and M 101 the velocity fields are highly asymmetric in the outer parts and only the curves for the inner parts have been taken, leading to an underestimate of $\sigma(R)$ and hence σ/μ. The photometric data are inhomogeneous of quality and refer to the B-band. Except for IC 342, no correction has been applied for galactic absorption and no corrections for internal absorption were applied. The σ/μ data of Fig. 3 are collected in the lower panel.

For the large galaxies we find that the local mass-to-luminosity ratio in the outer parts is at least ten times larger than in the inner parts. From the discussion above it follows that this increase is significant. Distance errors result in changes in slope and vertical shifts of the σ/μ-curves, but do not change the factor of total variation.

III. Discussion

If we restrict ourselves first to the case of disk-models for the mass distribution, we note that of the remaining uncertainties only the neglect of internal absorption works towards an increase in the local M/L-ratio. We find it however difficult to accept a much larger absorption correction in the outer regions than in the inner regions. If the matter is concentrated in a disk, the M/L must increase sharply with radius. As discussed, there is an observational selection effect determining the radius of the last measured point on the rotation curve, R_0. It could very well be that the rotation curves are flat beyond R_0; this will increase the M/L-ratios in the outer parts even more. Since the curve of the cumulative mass distribution, $M(R)$, keeps increasing, while the curve of the cumulative light distribution, $L(R)$, converges at about R_{opt} the local values of the M/L-ratio in the outer parts could be very high (10^3 or more). This result holds for all the galaxies in our sample, independent of Hubble type and the presence of a bar or a warped H I disk.

The discussion of mass models in Sect. 2 and the convergence of $L(R)$ shows that high M/L material must exist, but that the main uncertainty is whether the increase of M/L occurs in the disk or is due to a halo with high M/L. It is not possible to distinguish these cases from the present data, but it might be useful to consider work on binary galaxies to find possible constraints on halo masses. White and Sharp (1977) have argued that if (super-)massive haloes exist around spirals the first encounter between two of them will be the last one because dynamical friction cause them to coalesce; the statistics on presently observed binaries are incompatible with this. Van Albada and Freeman (1978) find for the spiral-spiral pairs in Turner's (1976) sample a global M/L_B-value of 13.5 ± 3 (corrected to $H_0 = 75$), in good agreement with the global M/L_B-value of 11 ± 4 obtained by Bosma (1978) from fitting the observed rotation curves of 25 spirals with the models described by Shu et al. (1971). This would imply that the haloes are probably only up to three times as massive as the disk.

Not much can be said about the composition of the high M/L-material. It could be composed of M-dwarfs (cf. Roberts, 1975), but the low velocity dispersion of the M-dwarfs in the solar neighbourhood suggests that these stars should then be in the disks of the spirals. The question of the stability of such disks has then to be raised. Part of the material might well be in a halo having roughly the same mass as the disk, but at present not much is clear about the way such haloes play their role in the global structure of spiral galaxies, especially in the spiral structure problem and the warp problem.

Although we cannot exclude a constant M/L-ratio in the disk (cf. Sect. II) it is possible to construct a consistency argument for an increasing M/L-ratio in the disk with radius. This argument is based on three notions: 1. the apparent constancy of the local mass-to gass mass ratio discussed in B 78, 2. the radial abundance gradients (Searle, 1971; Shields and Searle, 1978; Webster, 1977), and 3. an increase in the color index in the outer parts of NGC 5055 discussed in K 79. Although the interpretation of all three notions are to some extent uncertain they all suggest that in the outer parts of the disks there are fewer massive stars than in the inner parts, which is in turn consistent with an increase in the M/L-ratio. Finally, we note that for the two galaxies having lenses in their luminosity profiles: NGC 5383 and NGC 4258 (cf. van der Kruit and Bosma, 1978a; Capaccioli, 1973 and Fig. 3) the M/L-ratio is increasing abruptly at the edge of the lens. This result implies that the stellar population in the disk (the lenses are probably disk components) is changing abruptly at the edges of the lenses.

In conclusion we have shown for several spiral galaxies that the local mass-to-luminosity ratio increases with radius. The main uncertainty in the interpretation is the question whether this is due to a dark halo or an increasing M/L of the disk material with radius. It seems that the latter possibility is at least partly responsible for the observed trend.

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