

Truncated stellar discs in the near infrared

II. Statistical properties and interpretation

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Received 26 April 2005 / Accepted 20 December 2005

ABSTRACT

The results obtained in Paper I are used to study possible relationships between the truncation radius of stellar discs in the NIR and structural parameters of the galaxies. The NIR truncation radius is larger for brighter galaxies, being proportional to V_m^c with $c \approx 3/2$, and with V_m being the asymptotic rotation velocity at large radii (when the rotation curve becomes flat), and is lower for higher wavelengths. When it is normalized to the scalelength, the truncation is an increasing function of the central surface brightness and is lower for late type galaxies, although these correlations are weaker. These relations are in agreement with the scenario of magnetically driven truncations.

Key words. galaxies: structure – galaxies: magnetic fields

1. Introduction

Paper I (Florido et al. 2006) presented the result of the observation of 18 edge-on spiral galaxies in the NIR in order to study the truncation of the stellar disc, the main objective being to describe the truncation curve. This curve is defined as the progressive decrease of the photometric profile taking place at large radii with respect to the mean exponential profile obtained at moderate radii. In this paper we study the relationship of truncation to other parameters of the galaxy. We investigate some key properties that could restrict some of the theoretical scenarios that have been proposed: what types of galaxy show truncation and what relation exists between the truncation, radius, mass, luminosity, rotation velocity at large radii, type, central surface brightness and age of stellar population. The results obtained from this study will be merged with those from a previous one (Florido et al. 2001) in order to obtain a larger sample. No merger with other observations in the optical has been attempted, as the assumption of the same behaviour for optical and NIR truncations is not theoretically justified.

In early works by van der Kruit (1979) truncations were found to have sharp cut-offs. In Paper I and in Florido et al. (2001) truncations were found to be smooth. In these latter two papers it was shown that the smooth behaviour of truncations was not due to projection effects, but was real, existing even in deprojected profiles. In some recent papers (e.g. Pohlen et al. 2002; Pérez 2004) this description is replaced by a two-exponential profile with a sharp elbow. There is increasing evidence favouring the two-slope description, at least in the optical. We are not interested here in the shape of the profile (see Paper I); it may even be that the differences between authors are due to a true difference between the NIR and the optical. For the present, it is not our goal to determine whether this discrepancy is real or is a result of the low signal/noise at these very large

radii, especially important in the NIR, and we refer to a “truncation (break)” or simply “truncation”.

In Paper I it was proposed that most galaxies in the NIR seem to have a truncation curve that is proportional to $(R - R_{tr})^{-n}$ where $n \approx 1$, R is the radius and R_{tr} is the truncation radius at which the truncation seems to be complete, as obtained by extrapolation of the data.

2. Theoretical models

There are at present at least four alternatives to explain truncations (or breaks): a) the collapse model; b) the threshold model; c) the magnetic model; and d) the interaction model.

According to the collapse model, which was introduced by van der Kruit (1987), truncations were formed in the collapse of the protogalaxy, and would correspond to the maximum angular momentum of the protogalaxy. The gas beyond the truncation was accreted in later phases of galactic evolution. Ferguson & Clark (2001) presented a model in which the truncation/break is also a result of the initial conditions in the gas.

The threshold model was introduced by Kennicutt (1989). Here, when the gas density falls below a certain threshold, star formation should cease. A recent model by Schaye (2004) improved the dynamic mechanism by which the star formation threshold is established. Van den Bosch (2001) presented a hybrid model combining the collapse and threshold models. Elmegreen & Hunter (2006) reproduce two-slope profiles in a threshold model which includes several local effects of SF.

Kregel & van der Kruit (2004) have shown that the threshold model is better supported by the observations than is the collapse model. The model by Schaye (2004) predicts an increase of R_{tr}/h for small radial scale lengths and an increase of R_{tr}/h for higher central intensities and for low surface brightness discs.

For an extensive discussion of the different models, see the review by Pohlen et al. (2004). See also the discussion in Battaner et al. (2002).

In the magnetic model of truncations (Battaner et al. 2002), a centripetal magnetic force acting on the gas makes an important contribution to the redistribution of stars once they are born. If the gas rotates under the equilibrium of gravity plus magnetic forces versus the centrifugal force, and if the magnetic force is suddenly suppressed in the star formation process, the newborn stars would migrate and eventually escape. Some important modification of the mass distribution of the stellar density is therefore unavoidably expected at the region where the magnetic force becomes non negligible in the dynamics of the gas.

The interaction model is only rarely defended (Noguchi & Ishibashi 1986). Schwarzkopf & Dettmar (2000) found similar properties of truncations for isolated galaxies and for interacting galaxies. However, close inspection of the large amount of data provided by these authors reveals some differences. Interacting galaxies have a ratio $R_{tr}(R)/R_{tr}(K)$ that is always larger than one (R is red, K in the NIR), i.e. the truncation radius is larger at shorter wavelengths (with a mean ratio of about 1.6); however, in non-interacting galaxies, this ratio is closer to unity. Thus interaction effects should not be ruled out.

3. Results

Paper I presented new observations of edge-on galaxies observed in the NIR. In all, 18 galaxies were observed, but 5 of them were too noisy, 4 untruncated (within observational limits) and 2 uncertain. Therefore, only 7 galaxies were available to study truncations. Five of them, namely NGC 522 (Sbc), MGC-01-05-047 (Sc), NGC 2862 (SBbc), NGC 3279 (Scd) and NGC 5981 (Sc), were very clearly examples of this phenomenon. There are also two galaxies in which the truncation is not evident but that can be included in our study. These are NGC 781 (Sab) and NGC 3501 (Sc). We also use three truncated galaxies from Florido et al. (2001): NGC 4013 (Sb), NGC 4217 (Sb) and NGC 6504 (Sbc). Therefore the subsample of truncated galaxies adopted in this study is formed by 10 galaxies, 7 from Paper I and 3 from Florido et al. (2001). As we have data for both sides of the galaxies, and measure at least in two filters (J and K_s), we have $2 \times 2 \times 10 = 40$ points for our statistical subsample.

However, these 40 data points are not independent. Because of the azimuthal symmetry of the galaxies, the results obtained at both sides should be similar (as, in fact, they are) and therefore correlated. Moreover, the closeness of the filter wavelengths, for J and K_s (for a few galaxies, also H), does not permit us to consider the J and K_s points as really independent, except when considering a differential colour behaviour. The fact that we measure in two filters and on both sides permits us to work with smaller errors, but strictly speaking we have only 10 points for our sample, i.e. the number of galaxies selected. Despite the smallness of the sample, we present the more complete data for truncations in the NIR.

A) Truncation versus Hubble type

At first glance, even for such a small number of galaxies, it seems that truncations are found more often in late type galaxies.

This is a suggestion and is not based on statistics, as the number of galaxies is too low and many more observations would be required. However, we take note of this potential discrimination, as it could be coherent with other findings shown later. This suggestion should be considered with caution, also, because

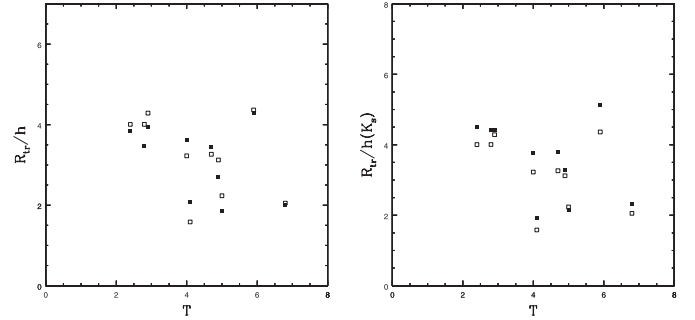


Fig. 1. Ratio of truncation radius to scalelength (R_{tr}/h) versus morphological type T (from the LEDA database, <http://leda.univ-lyon1.fr>). Symbols are: open square for K_s and filled square for J . In the first panel we plot R_{tr}/h when R_{tr} and h are obtained by the same filter. In the second one we plot $R_{tr}/h(K_s)$ using $h(K_s)$ for this ratio with each filter.

the selection of our samples was not based on physical criteria, but rather considering appropriate angular size, large galactic latitude and date of observations. Therefore the possibility that a bias may be responsible cannot be ruled out.

We looked for a relation of $R_{tr}(J)/h(J)$ versus T , where R_{tr} is the truncation radius, h is the radial scale length and T is the galaxy type. J and K_s are the filters used (Fig. 1). The following tendency was observed: the larger the value of parameter T , the smaller that of $R_{tr}(J)/h(J)$ is. This fact is consistent with the above suggestion that truncation is a phenomenon mainly affecting late-type spirals.

For some relationships, if we want to adopt h as a length representative of the size of the galaxy, then $h(K_s)$ better represents the “true” radial scale length, as it is less affected by extinction and better represents the old stellar population. Therefore, we have plotted $R_{tr}(J)/h(K_s)$ and $R_{tr}(K_s)/h(K_s)$. In this case, the relationship seems to be reinforced.

Therefore, truncation could be a phenomenon that mainly affects late type spirals. This relation is also found when the large sample of Schwarzkopf & Dettmar (2000) is used. This suggestion, although attractive, remains to be confirmed.

B) Colour dependency of truncations

Table 1 reveals an evident property: $R_{tr}(J) > R_{tr}(K_s)$. This is so even if the differences are small, because in all galaxies, on all sides, we find $R_{tr}(J) > R_{tr}(K_s)$, with the exception of NGC 6504. Therefore, there is a dependence of R_{tr} with colour. This number of values is not small but we have applied three tests in order to discard an effect of chance: the T test, the Wilcoxon test and the sign test. In all three tests, the null hypothesis of null difference between $R_{tr}(J)$ and $R_{tr}(K_s)$ was rejected. Taking, as usual, a contrast size of $\alpha = 0.05$, in every case the significance level (P -value) was much less than 0.05, being 0.004 for the T test. Therefore, $R_{tr}(J)$ is unambiguously higher than $R_{tr}(K_s)$. This significant difference informs us about a relation with the age of the population.

With respect to relative values, taking the radial scale-length as the unit, we obtain $\langle (R_{tr}/h) \rangle_J = 3.12$ with $\sigma = 0.85$ and $\langle (R_{tr}/h) \rangle_{K_s} = 3.21$ with $\sigma = 0.93$. As mentioned above, $h(K_s)$ better represents the size of the galaxy. Then, we obtain $\langle R_{tr}(J)/h(K_s) \rangle = 3.57$ with $\sigma = 1.06$. Of course $\langle R_{tr}(J)/h(K_s) \rangle$ is significantly higher than $\langle R_{tr}(K_s)/h(K_s) \rangle$.

These values are in reasonable agreement with other values found in the literature (Pohlen et al. 2002; Barteldrees & Dettmar 1994). For comparison, it should be taken into account that some authors give R_{br} or the point where the break takes place and oth-

Table 1. Basic properties of the galaxies.

Galaxy	$R_{\text{tr}}(J)$ (Kpc)	$R_{\text{tr}}(K_s)$ (Kpc)	M_B	$\log V_m$	T	$\mu_0(J)$ (mag/arcsec ²)	$\mu_0(K_s)$ (mag/arcsec ²)	$h(J)$ (Kpc)	$h(K_s)$ (Kpc)
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
NGC 522	13.7	11.2	-20.53	2.252	4.1	20.6	21.0	6.6	7.1
MGC-01-05-047	29.3	27.9	-21.77	2.410	4.9	20.9	19.6	10.8	8.9
NGC 781	11.0	9.8	-20.87		2.4	19.6	18.1	2.9	2.4
NGC 2862	21.7	18.6	-21.44	2.464	4.0	19.5	18.5	6.0	5.8
NGC 3279	7.8	6.9	-19.27	2.208	6.8	19.8	18.4	3.9	3.4
NGC 3501	8.2	7.0	-19.05	2.147	5.9	20.0	18.1	1.9	1.6
NGC 4013	8.5	7.8	-19.50	2.276	2.9	18.6	17.6	2.2	1.8
NGC 4217	11.1	10.0	-19.97	2.298	2.8	18.8	17.4	3.2	2.5
NGC 5981	14.6	12.6	-20.61	2.424	4.7	19.3	18.0	4.2	3.9
NGC 6504	22.2	23.0	-22.53		5.0	19.5	18.7	11.9	10.3

Columns: (1) Galaxy name; (2) truncation radius in J ; (3) truncation radius in K_s ; (4) absolute B -magnitude; (5) Log of maximum velocity rotation (in km s^{-1}) from radio observations; (6) morphological type code; (7) central surface brightness in J ; (8) central surface brightness in K_s ; (9) and (10) radial scale-lengths in J and K_s . Columns 4–6 are obtained from the LEDA database (<http://leda.univ-lyon1.fr>). The values of $R_{\text{tr}}(J)$, $R_{\text{tr}}(K_s)$, $h(J)$ and $h(K_s)$ were independently obtained for both sides of each galaxy. The figure given in this table is the mean value.

ers where it ends. Furthermore, our data in the NIR do not have to coincide with optical data, the differences being important.

C) Truncation and rotation and luminosity

Figure 2 clearly shows a relation between R_{tr} and V_m , the asymptotic rotation velocity (taken from LEDA). R_{tr} (measured in kpc) is an increasing function of V_m , which is emphasized in the log-log plot, showing a relation of the type $R_{\text{tr}} \propto V_m^c$. A relationship between R_{tr} and V_m was first obtained observationally by Pohlen et al. (2004). This is clearly supported by our present findings, in another wavelength range, with less scattering and with the mathematical function being determined quantitatively. This fact can be used to restrict the number of theoretical models, as we will see in the discussion.

As different truncation values were detected for J and for K_s , we have analyzed this relation ($\log R_{\text{tr}}$, $\log V_m$) for the two filters independently (Fig. 2). Standard Pearson correlations are used because the relation appears to be fairly linear in log space with classical significance tests. For $[\log R_{\text{tr}}(J), \log V_m]$ the correlation coefficient is 0.83, the slope is 1.54 with error 0.28 and the $\log R_{\text{tr}}$ at the origin is -2.45 . The P -value is 0.001, much less than 0.05, and therefore the null hypothesis of the absence of a linear relation between both quantities is clearly rejected. For $[\log R_{\text{tr}}(K_s), \log V_m]$ the correlation coefficient is again 0.83, the slope is 1.58 with a typical error of 0.29 and the value of R_{tr} at the origin is -2.61 . The P -value is 0.002, again much lower than 0.05. For both filters, the slope of the regression line (1.54 ± 0.28 and 1.58 ± 0.29) can be approximated to the value 1.5, which is more useful when looking for simple low-power relations.

A relationship physically connected to this one (R_{tr} , V_m) is the relation (R_{tr} , L) with L the luminosity of the galaxy. This is shown in Fig. 3, where we plot $\log R_{\text{tr}}$ versus the absolute B -magnitude, showing a clear relation, with R_{tr} being larger for brighter galaxies. A statistical analysis is unnecessary as this relation is a consequence of the previous one, taking into account the Tully-Fisher relation.

D) Other relationships

Figure 4 plots R_{tr} versus h and shows a clear correlation between the two parameters. Thus, more extended galaxies have larger truncation radii, in agreement with Kregel (2003). Larger galaxies have lower truncation radii when measured with the radial scale length as the unit. This relation seems to be non-linear.

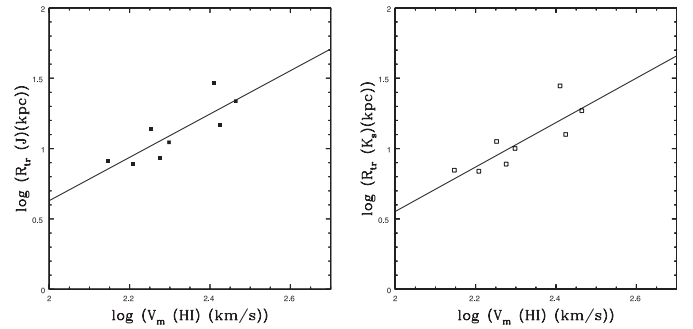


Fig. 2. Log of truncation radius versus log of maximum velocity rotation. Symbols as in Fig. 1.

Figure 5 shows R_{tr}/h versus μ_0 (deprojected central surface brightness). This relation has been studied by Kregel & van der Kruit (2004), as mentioned above. Although the scatter of the points is much higher, we see that R_{tr}/h seems to be a decreasing function of μ_0 . The correlation coefficient for $[R_{\text{tr}}(J), \mu_0]$ is only 0.39 and is the same for $[R_{\text{tr}}(K_s), \mu_0]$. Therefore, the non existence of this relation cannot be statistically rejected, as the P -value is (in both cases) 0.091, larger than the usual value of 0.05. The correlation coefficient for $[R_{\text{tr}}/h(K_s), \mu_0]$ is again very poor for J (-0.41) and the P -value very large, 0.071 (>0.05). However, for K_s the P -value is less than 0.04 and the correlation coefficient -0.73 . Therefore, for the K_s filter there is a more significant relation: the larger the μ_0 value, the lower the truncation radius when measured with $h(K_s)$ as the unit.

4. Discussion

Despite the relatively small size of our sample (10 galaxies), some clear relationships between the truncation radius and structural parameters of galaxies have been found. These relations are obtained in the near infrared and therefore some caution must be taken when comparing with optical data, as they could differ. For example, star formation can take place beyond the truncation; optical measurements would be sensitive to newborn stars but not NIR measurements. The difference could be very large when comparing data in the U -filter and our NIR data and less so when using the R -band and the I -band. It should also be taken into account that young stars are visible in the NIR, especially red

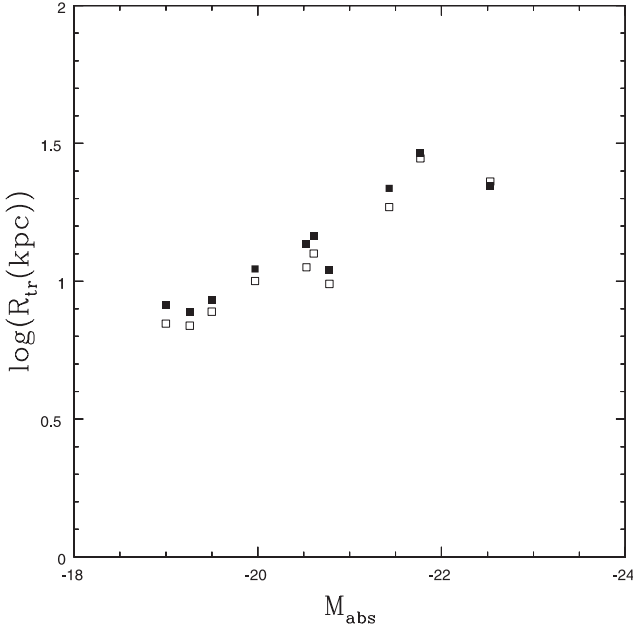


Fig. 3. Truncation radius versus absolute B -magnitude. Symbols as in Fig. 1.

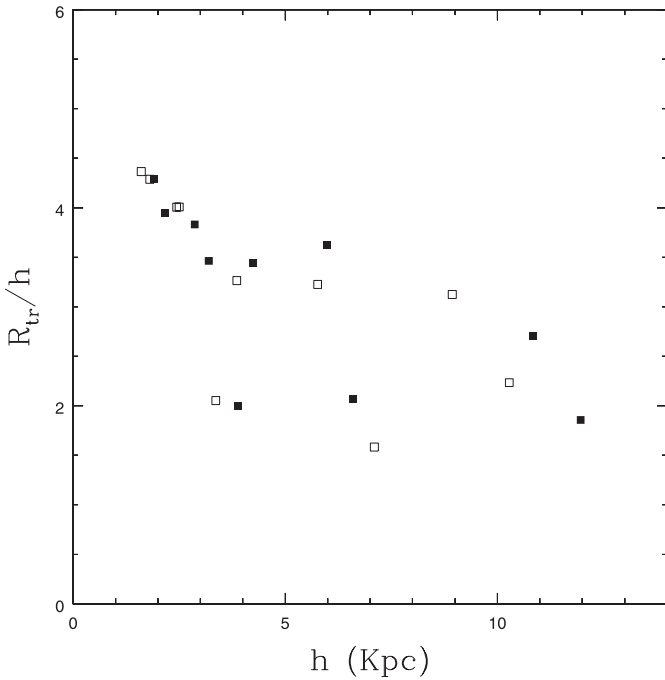


Fig. 4. Ratio of truncated radius to scalelength. Symbols as in Fig. 1.

supergiants. Nevertheless, optical and NIR data provide different information. This difference would be larger if stars moved from their birthplace. The results obtained are summarized here:

- Late-type galaxies seem to be more affected by the mechanism of truncations.
- Bright galaxies have larger R_{tr} .
- $R_{\text{tr}} = \text{const.} \times V_m^c$ ($c \cong 1.5$).
- Larger galaxies (higher h) have larger R_{tr} .
- $\langle R_{\text{tr}}(J)/h(K_s) \rangle = \alpha(J) \approx 3.57$; $\langle R_{\text{tr}}(K_s)/h(K_s) \rangle = \alpha(K_s) \approx 3.21$; hence, we find lower values for K_s . The difference is small but $R_{\text{tr}}(J) > R_{\text{tr}}(K_s)$ for all galaxies with only

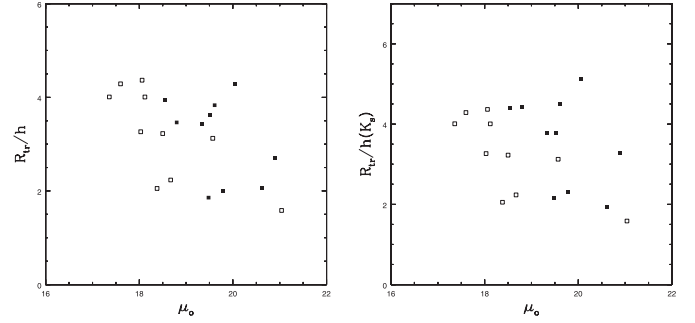


Fig. 5. *Left panel:* ratio of truncated radius to scalelength versus deprojected central surface brightness. *Right panel:* always considering the scalelength in K_s . Symbols as in Fig. 1.

one exception. Statistical tests show that this difference is significant.

- R_{tr}/h is an increasing function of the central surface brightness, I_0 , even if the correlation seems to be very weak.

All these properties can be used to put restrictions on the different theoretical models. Other groups should confirm these results with larger samples of galaxies, with independent NIR observations. Clearly, taking into account the fact that some galaxies lie behind many Milky Way stars and/or that the observations were noisy, the number of galaxies in our sample is low and should be enlarged.

The above results agree very well with the magnetic model of Battaner et al. (2002). In this model an inward magnetic force is added to gravity to explain the high rotation velocity and flat rotation curve of the gas.

From the observational point of view, it is now evident that large magnetic centripetal forces exist, as can be directly deduced from observational magnetic field strengths and energy densities in the Milky Way, NGC 6946 and M 31 (Beck 2004; Battaner & Florido 2005). These measurements show large values of the magnetic field strength and, what is more important, such low gradients of the field, i.e. such a low decline of the field for increasing radii, that an important centripetal magnetic force does exist; this is now empirically demonstrated. These magnetic forces act on the gas and are in equilibrium with gravitational and centrifugal forces. When stars are formed this equilibrium is destroyed and stars escape, thus producing the truncation.

In the simplest version of the magnetic model, Battaner et al. (2002) obtained a formula for the truncation radius

$$R_{\text{tr}} \approx \frac{2GM}{V_m^2} \quad (1)$$

where M is the visible galactic mass and θ_0 is the constant value of the rotation velocity at large radii.

As $M \propto L$ and the Tully-Fisher relation establishes that $L \propto V_m^c$ (where c lies between 3 and 4), it is concluded that

$$R_{\text{tr}} \propto V_m^{(c-2)} \quad (2)$$

with the exponent $(c - 2)$ being between 1 and 2. This fact matches Fig. 2 very well, showing $R_{\text{tr}} \propto V_m^x$, where $x = 1.54 \pm 0.28$ (approximately 1.5 within the estimated error) and the constant of proportionality is $0.004 \text{ kpc km}^{-1/2} \text{ s}^{1/2}$ for J . If we fit the data in K_s the values obtained are: $x = 1.58 \pm 0.29$ and the constant of proportionality is $0.002 \text{ kpc km}^{-1/2} \text{ s}^{1/2}$. On the other hand, this would imply that more massive (or more luminous) galaxies would have larger R_{tr} , so that the truncation might become undetectable if R_{tr} is larger than the last observable point.

Using the Tully-Fisher relation again, we find $R_{\text{tr}} \propto L^{1-\frac{2}{c}}$, the exponent $(1 - \frac{2}{c})$ being between 1/3 and 1/2, which also explains Fig. 3.

The magnetic model can also explain the relation between R_{tr}/h and μ_0 , the surface brightness at the centre. From Eq. (2) and $M \propto L \propto I_0 h^2$ (where L is the luminosity and I_0 the intensity, in physical units, at the centre) and the Tully-Fisher relation, taking now for simplicity $L \propto V_m^4$

$$\frac{R_{\text{tr}}}{h} \propto \frac{L}{V_m^2 h} \propto \frac{L^{1/2}}{h} \propto \frac{I_0^{1/2} h}{h} = I_0^{1/2}. \quad (3)$$

As $\mu \propto -\log I$, the magnetic model predicts a relation between R_{tr} (when measured in radial scale units) and μ_0 , the central surface brightness. Any other characteristic galactic magnitude (such as h itself) cancels out.

The magnetic model also predicts $R_{\text{tr}}/h \propto M^{1/2}/h$, and hence it explains an observational fact mentioned above: extended galaxies, with large values of h , have smaller truncation radii (measured with the radial scale length, h , as the unit). In this case, the presence of $M^{1/2}$ in the formula would make the relation $[R_{\text{tr}}/h, h]$ be affected by a high degree of scatter, and the relation is certainly more complex than that.

The fact that the magnetic model satisfactorily explains the relations found here does not necessarily imply that all other models should be excluded. For instance, on qualitative grounds, the threshold model (e.g. Schaye 2004) could predict a relationship between absolute magnitude and truncation if the threshold gas surface density were located further out in a bright galaxy. Some development of this model to explain the findings of this paper is necessary. The magnetic model remains an interesting alternative, as it predicts not only a qualitative relation, but also the mathematical function.

5. Conclusions

The magnetic model satisfactorily explains all the statistical properties reported in this paper. We thus propose this scenario as responsible for producing truncations. The agreement is particularly noticeable concerning the relation between truncation radius and the power 3/2 of the asymptotic rotation velocity.

Magnetic forces are important in the rotation dynamics of the gas, as deduced from observed magnetic field strengths. These forces no longer act when gas is converted into stars, which must have a large influence on the stability of the orbits of young stars, even leading to massive escape.

Large galaxies of type Sa and Sb have less need for dark matter, hence, in the magnetic interpretation, they require lower magnetic fields, i.e. the truncation would be a less important effect in large (massive and luminous) galaxies, especially those with a prominent bulge. The fact that late-type galaxies, which are bulge-poor, could be more affected by truncations is in agreement with the magnetic scenario.

Pohlen et al. (2004) found several examples of truncations in edge-on SO galaxies. Even if these galaxies are at present

gas-poor, they had both gas and star formation in the past. Thus, the mechanisms suggested by the magnetic hypothesis would have been operating in the past, and they would have inherited truncations.

The fact that the truncation in the optical could be better described by a two-exponential profile could be compatible with a smooth, complete truncation in the near infrared. The newly formed stars would be, under the magnetic interpretation, in the process of escaping. If the escape speed is roughly equal to V_m , i.e. of the order of 100 km s⁻¹, and if the length of the escape path is of the order of ~10 kpc, the escape time would be of the order of 10⁸ years, a time that differentiates clearly between new-born and old stars. The fact that $R_{\text{tr}}(K_s) < R_{\text{tr}}(J)$ also fits this interpretation.

In the magnetic interpretation, the truncation corresponds to a true decrease in the total mass (stars + gas) and a connection with a decrease in the rotation velocity should be expected. This decrease has been observed (Casertano 1983; van der Kruit 2001; Bottema 1995) although this fact requires more observational support and may be explained by other means.

Acknowledgements. This paper has been supported by the ‘‘Plan Andaluz de Investigaci3n’’ (FQM-108) and by the ‘‘Secretar3a de Estado de Pol3tica Cient3fica y Tecnol3gica’’ (AYA2004-08251-C02-02, ESP2004-06870-C02-02). We are indebted to Andr3s Gonz3lez-Carmona who helped us with the statistical analysis. We also acknowledge the LEDA data base organisation, which was highly useful for this research. Thanks to the anonymous referee for valuable comments and suggestions that have contributed to improve the final version of the paper.

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