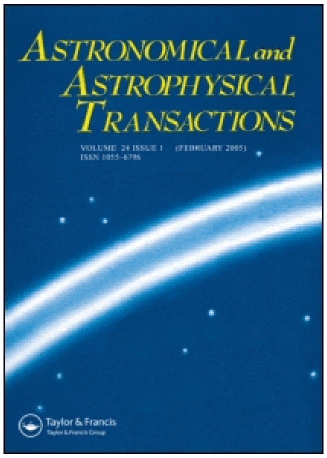

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ON THE STATISTICS OF GALACTIC WARPS

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A complete sample of 120 northern galaxies of angular diameters $a > 2$ arcmin and apparent axial ratio $a/b > 7$ (Karachentsev *et al.*, 1992) is considered. It is found that at least 50–60% of spiral galaxies exhibit warps in outer parts of optical disks with typical amplitude 4°–5°. The observed frequency of warped galaxies does not show significant dependence on morphological type: spirals of all types demonstrate warped disks. Disks of more massive, large and luminous galaxies are, probably, somewhat less warped.

1 INTRODUCTION

In many (if not all) spiral galaxies the outer parts of their disks are warped (Sanchez–Saavedra *et al.*, 1990; Bosma, 1991). This is most often seen in HI though optical disks of many galaxies also show warping. A number of mechanisms have been proposed to explain the observed warps: tidal interactions, cosmic infall, extragalactic magnetic field and gravitational effect of the halo on the disk (see Binney & Tremaine, 1987; Binney, 1992 for a review).

To constrain these models, new statistical data about the frequency and properties of observed warps are needed. We present here the results of the study of a complete sample of 120 northern edge-on galaxies presented by Karachentsev *et al.* (1992).

2 THE SAMPLE

Karachentsev *et al.* (1992) published the results of surface photometry in the Cousins R_c passband for a complete sample of 120 northern ($\delta > 0°$) galaxies with angular diameters $a > 2$ arcmin and apparent axial ratios $a/b > 7$ selected from UGC (Nilson, 1973). Isophotal images of all the galaxies down to surface brightness of $\approx 1\%$ of the night sky level are presented in that paper.

Only 13 of the sample galaxies belong to the sample examined by Sanchez–Saavedra *et al.* (1990) (SSBF) on the basis of the Palomar Observatory Sky Survey.

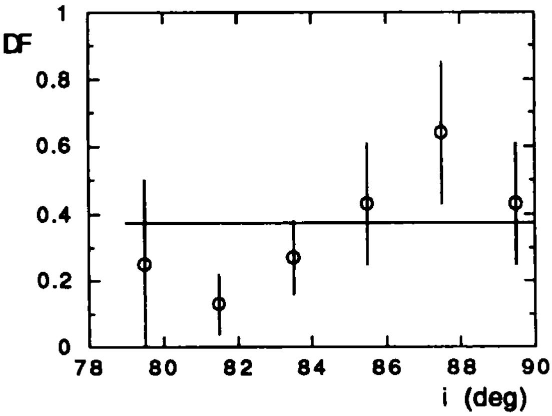

Figure 1 Observed DF of warped galaxies vs inclination. Solid line represents the mean DF for the whole sample.

Therefore, the sample considered represents convenient and almost independent material for the study of the frequency and properties of the optical warps in galaxies.

3 RESULTS

3.1 Frequency of Warped Spiral Galaxies

Out of 120 galaxies in the sample, 45 galaxies demonstrate measurable warps of their optical disks. Most of warps are quite symmetrical, integral-shaped but sometimes warps are not seen on the both sides of a galaxy. (It should be noted that the identification of a weak optical warp is not a quite objective procedure – for example, in some cases we could take for a warp a highly inclined spiral arms. Nevertheless, we identified a warp simply as a large-scale systematic deviation of galactic isophotes from the plane defined by the inner region of a galaxy). Hence, the total observed frequency of warped galaxies is 0.375 ± 0.056. This value is slightly lower than that determined by SSBF (0.488 ± 0.075) but within the limits of poor statistics the difference is insignificant. The agreement is better if one takes into consideration that the SSBF detection fraction (DF) of warped galaxies includes warps detected in red and blue passbands. Thus, according to SSBF data, the observed frequency of red warps is $32/86 = 0.372 \pm 0.066$, which is in excellent agreement with our value.

The observed DF of warped galaxies is only a lower limit of the true frequency. Indeed, our and SSBF samples include galaxies at different inclinations with different conditions of warps appearance and detectability. It is evident that for edge-on galaxies small perturbations of the galactic plane must be easier to detect than for inclined galaxies. To test this "inclination" effect, we combined our DF of warps with the homogeneous estimations of inclinations according to Guthrie (1992) (this

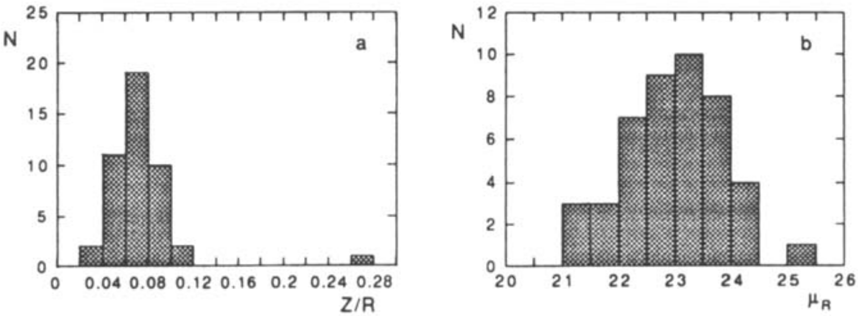

Figure 2 **Distributions of observed relative magnitudes of warps (a) and of surface brightness levels at which optical bending becomes detectable (b).**

work presents inclinations for 83 (69%) of the sample galaxies). Figure 1 shows the dependence of the observed frequency of warped galaxies on their inclination. It is apparent that DF is significantly larger for stronger inclined galaxies. Thus, for the galaxies with $i \geq 87°$ the DF of warped disks is 0.54 ± 0.14 while for the galaxies with $i \leq 84°$ DF is 0.22 ± 0.07 only. The SSBF data confirm this results: for 45 (52%) of SSBF sample galaxies there are inclination in Guthrie (1992) and observed DF of warped galaxies for $i \geq 87°$ is 0.67 ± 0.27. Therefore, the real frequency of optically warped spiral galaxies should be at least (50–60)%.

3.2 Observed Properties of Warps

Amplitudes of warps. Using isophotal maps published by Karachentsev *et al.* (1992), for each warped galaxy we measured the magnitude of the warp as tangent of the maximum observed angle of warp, $Z/R = \tan\psi$. The distribution of the Z/R values for our sample galaxies is shown in Figure 2a. The mean value of the dimensionless amplitude Z/R is $0.074 \pm 0.034(\sigma)$ (or $\psi = 4.^\circ7$). Excluding the most strongly warped galaxy UGC 3697, we have $\langle Z/R \rangle = 0.070 \pm 0.019(\sigma)$ ($\psi = 4.^\circ45$).

One can expect that the amplitude of the detected warps depends on inclination. Indeed, for the galaxies with $i \leq 85°$ the average value of ψ is $5.^\circ2$, while for those with $i > 85°$ $\langle\psi\rangle = 3.^\circ9$. This demonstrates that the observed distribution of warp magnitudes (Figure 2a) is affected by observational selection - small warps are detectable mainly in edge-on galaxies. The real distribution of warp magnitudes is, probably, a function monotonically rising to $Z/R = 0$. Probably, outer parts of all disk galaxies are warped with typical amplitudes of a few degrees.

Location of warps. Figure 2b represents the distribution of the surface brightness levels at which optical warping becomes detectable. The average value of μ_R is 23.0 mag arcsec^{-2} with $\sigma = 0.8$ (we did not correct the observed surface brightnesses for the Galactic absorption since the mean value of this correction is < 0.1 mag). The corresponding average distance from the centers of galaxies is $0.75a_{24}$, where a_{24} is the major semiaxis measured at surface brightness level $\mu(R_c) = 24$ (Karachentsev *et al.*, 1992). The maximum observed deviation of the

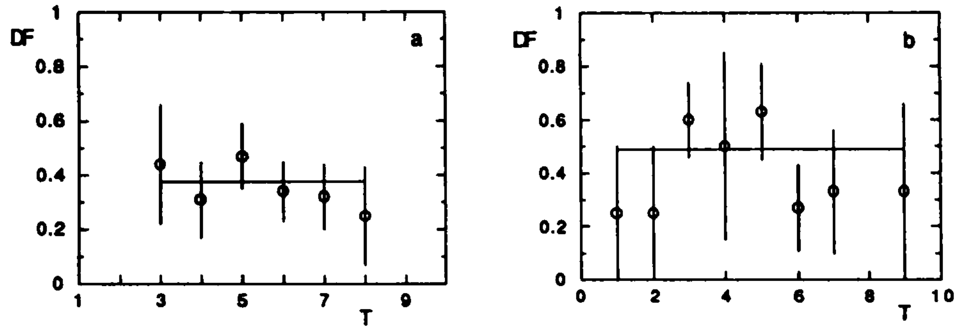

Figure 3 Dependence of the observed DF of warps on numerical morphological type in our (a) and SSBF (b) samples. Solid lines show the mean DF for the samples.

galactic plane (Z) for the sample galaxies was detected, on average, at the surface brightness level $24.3 \pm 0.8(\sigma)$ (or at mean distance $R = 1.07a_{24}$). Assuming a simple photometric model of exponential disk that is transparent in the outer region having central surface brightness $\mu_0 = 21.7$ in the B passband and $\mu_0 = 20.7$ in the R_c band, we find that for face-on galaxy these surface brightness levels correspond to 25.0 and 26.4 in the B band. Thus, our results are in a good agreement with those of Briggs (1990), who found that HI warps typically develop between $\mu_B = 25.0$ and $\mu_B = 26.5$.

Dependence on the galactic morphology. In Figure 3a, b we plot the dependence of the DF of warped galaxies in our and SSBF samples on their morphological type. For the SSBF sample we used the types presented in that work, for our sample galaxies we used data from Karachentsev *et al.* (1993) and *RC*3 (de Vaucouleurs *et al.*, 1991). It is evident from this figure that the present data do not show noticeable correlation between the frequency of warps and morphological type.

Warps and general characteristics of galaxies. Figures 4a–d show the relations between the warp magnitude (Z/R) and global characteristics of galaxies: maximum of rotational velocity (a), total blue luminosity in solar units (b), linear diameter (c), and total mass of the galaxy in solar units (d) (these characteristics were taken from Karachentsev, 1991a, b and Karachentsev & Zhou Xu, 1991). As one can see, there are trends of the warp magnitude with the properties of host galaxies: more massive, large, and luminous galaxies demonstrate, on average, smaller warps (we excluded from the consideration the most warped galaxy UGC 3697). For the most significant correlation ($Z/R - V_{\rm max}$) the linear correlation coefficient is -0.375, indicating a weak correlation significant at the 99% confidence level.

DISCUSSION

From the study of a complete sample of 120 nearby edge-on spiral galaxies we found the following main results:

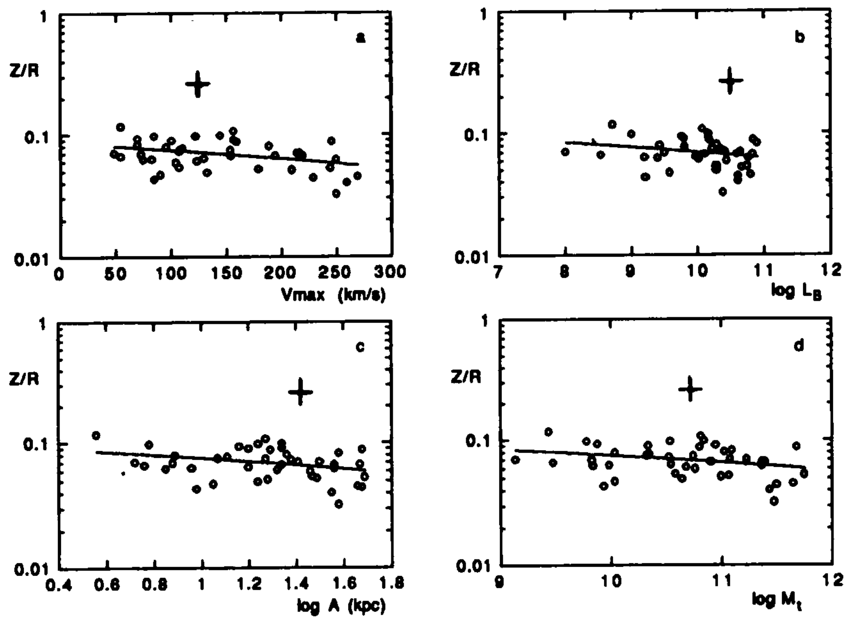

Figure 4 Dependence of the warp magnitude on the general characteristics of a galaxy. Solid lines represent the best fit of the data. UGC 3697 data are shown as crosses.

(i) at least (50-60)% of spiral galaxies demonstrate warps in outer parts ($\mu_B \gtrsim 25$) of their optical disks with typical amplitude 4°–5°;

(ii) the observed frequency of warps does not show strong dependence on the galactic morphology – spirals of all types demonstrate wrapped disks;

(iii) disks of more massive, large and luminous galaxies are, probably, somewhat less warped.

Let us compare these empirical findings with predictions of some models. One of the most elaborated and popular ideas is that observed galactic warps are discrete models of bending in a self-gravitating disk embedded in an oblate dark halo (Sparke & Casertano, 1988). This model predicts that galaxies with concentrated halos and large disks should not have warps. A direct comparison of the frequency of warped disks with the ratio of the halo core radius to the optical radius of a galaxy shows that warps indeed occur rarely if this ratio is small (Bosma, 1991). Our conclusion that large disks are, on average, less warped probably also supports this model. However, Athanassoula *et al.* (1987) found that the halos of early type spiral galaxies are more concentrated than those of later types. Hence, one can expect the dependence of the DF of warps on morphological type – warps should be less frequent in earlier type disk galaxies. Our data do not demonstrate such a trend though such a correlation can be entirely masked by poor statistics (see Figure 3). We stress also that there are good examples of warped stellar and gaseous disks in some early type galaxies: NGC 4762 (Wakamatsu & Hamabe, 1984), NGC 3718 (Schwarz, 1985), NGC 4452 (Hamabe & Wakamatsu, 1989), UGC 7576 (Reshetnikov *et al.*, 1994), etc.

Binney (1992) argues that it is unlikely that real galaxies have discrete warping models. He notes that existing normal mode calculations, which treat the halo as a rigid object, must be considered doubtful. Binney (1992) supposes that a realistic picture of warp exciting and maintenance should include environmental effects – actually galaxies must be subject to a variety of disturbances, and warps may be connected with these. For example, warp might represent a response of the disk to a tidal field of a companion or intruder. Indeed, in some cases warps are generated by tidal interactions (e.g. Reshetnikov, 1989; Kollatschny & Dietrich, 1990), but very often warps occur in apparently isolated galaxies.

Another manifestation of the environmental influence is a continuing building of galactic disks by the acquisition of external mass and angular momentum (Ostriker & Binney, 1989; Ostriker, 1991; Binney, 1992). Due to gradual infall of matter with skewed angular momentum, a flattened galactic halo should be reoriented. Following this skewing external potential, the embedded galactic disk warps. In this scenario, a warp requires ongoing accretion of gas with a skewed angular momentum in so far as it persists only while the potential slews. This model has two potential problems: the required accretion rate and the nature of accreting material. But, probably, it can explain the absence of a visible dependence of the DF of warps on galactic morphology and less warps in more massive galaxies. The data about environment of our sample galaxies testify that cosmic infall and tidal interactions are the most promising interpretations of warps: according to the UGC Notes (Nilson, 1973), the portion of galaxies with close companions (or suspected companions) for the subsample of unwarped galaxies is 0.36, while for warped galaxies this value is 0.51.

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