Spiral galaxies with large optical warps

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Abstract. As a result of our statistical study of 540 edge-on galaxies, we present here the images and preliminary statistical analysis of a sub-sample of 60 galaxies, that were selected to be S-type warped spirals. Computing the average volumic density of galaxies from available redshift surveys, a first analysis suggests that warped galaxies are found in denser environments. Only the clearest and strongest warps have been extracted here, and therefore this sample of 60 objects gather the best candidates for future HI or optical works on galaxy warps.

Key words: galaxies: evolution, general, interactions, photometry, peculiar, spiral

1. Introduction

The majority of spiral galaxies have a warped plane, as has been revealed in the neutral gas extended component, through HI-21cm observations (e.g. Bosma 1981, Briggs 1990), and in a lesser extent through optical observations (Sanchez-Saavedra et al. 1990, Reshetnikov & Combes 1998). This dynamical feature raises the problem of its origin and maintenance, and the numerous mechanisms that have been proposed and explored have not yet given a definitive and satisfactory answer (e.g. the review by Binney 1992).

Differential precession should be very quick to wrap up any warp perturbation even in the outer parts of the galaxies (Kahn & Woltjer 1959), unless the potential is nearly spherical (Tubbs & Sanders 1979). But most warps are observed while the disk is still a significant part of the potential, which cannot therefore be spherical. It has been shown that coherent bending modes cannot be sustained, since the oscillations spectrum is continuous, for realistic disks that have no sharp edges (Hunter & Toomre 1969). Models then tried to consider a non-spherical dark halo, misaligned with the inner visible disk of the galaxy (Sparke 1984, Sparke & Casertano 1988, Dubinski & Kuijken 1995). However, these structures can only be transient, since the inner disk is bound to align with the dark halo (New et al. 1998, Binney et al. 1998). Alternatively, the warp could be the consequence of continuous accretion of gas with a slewed angular momentum, due to cosmic infall, as suggested by Ostriker & Binney (1989) and Binney (1992). It is not excluded either that a large part of warps are due to interactions or mergers: the prototypical warped galaxy NGC 5907 (Sancisi 1976) that was long thought isolated, might have experienced a minor merger recently (Lequeux et al. 1998), and is currently interacting with two dwarf companions (Shang et al. 1998).

To progress about the puzzle of the origin of warps, it is important to have a sample of optically strongly warped galaxies, to perform new observations and statistical studies. Recently, we have presented a survey of optical warps in a sample of 540 galaxies, about 5 times larger than the previous samples (Reshetnikov & Combes 1998). The galaxies were selected from the Flat Galaxy Catalogue of Karachentsev et al. (1993) (FGC) and we studied their optical images extracted from the Digitized Sky Surveys\textsuperscript{1}.

We identified three classes of galaxies, those without observable warps (30%), and those with U-shaped (37%) and S-shaped (33%) warps. We have considered the artefacts due to projection effects, that could be severe in nearly edge-on galaxies, when there are spiral arms or $m = 2$ perturbations. Through numerical simulations, it was found that the U-shape are more affected by projection effects, but that no more than 15% of S-shape warps could be geometrical artefacts. On the other hand, intrinsic warps could be missed through projection effects (but no more than 20%).

We therefore select a sample of 60 S-shape warped galaxies, the strongest and clearest among the 174 found. The selection is subjective, based on isophotal maps from the DSS. This sample should be a suitable material for future detailed HI and optical works on galaxy warps.

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**2. The sample and statistics**

Table 1 presents extraction from the Southern Extension of FGC (Karachentsev et al. 1993, FGCE) for the galaxies with large S-type warps. The sample is limited by coordinates $0.3^h \leq \alpha(1950) \leq 14.3^h, \delta(1950) \leq -17.5^\circ$. The columns are as follows: galaxy FGCE, PGC and ESO number; right ascension and declination for the epoch 1950.0; $B$ magnitude (NED); heliocentric radial velocity (NED); major and minor diameters measured on blue films (in arcmin); morphological type; warp angle $\psi$ – angle measured from the galaxy centre, between the plane and average line from centre to tips of outer isophotes (see Reshetnikov & Combes 1998); position angle of average line passing through the tips of outer contour (measured from N to E) – P.A.; direction of warp: clockwise (+) or counterclockwise (−).

In the appendix, we present the DSS images of all galaxies (in the $B_J$ passband), rotated to horizontal.

Fig. 1 presents the distribution of the sample galaxies according to warp angle $\psi$. The distribution is truncated for $\psi \leq 4^\circ$ since we selected only galaxies with clearest warps to avoid selection effects. The mean value of $\psi$ is $4.8\pm1.3(\sigma)$ that is comparable with the amplitudes of optical warps found by Sanchez-Saaavedra et al. (1990), Reshetnikov (1995), and de Grijs (1997). Dashed line in Fig. 1 shows the $\psi^{-5}$ law proposed by Reshetnikov & Combes (1998) to fit the observed distribution. A naive extrapolation of this law to $\psi=0^\circ$ suggested that outer parts of all disk galaxies are warped with typical amplitudes of a few degrees.

In Fig. 2 we compare our measurements of the position angles of the sample galaxies with the FGCE data. The agreement is quite good. The mean difference is $<\text{P.A. - P.A.(FGCE)}>=+0.6\pm0.4(\text{s.e.m.})$. Excluding two most deviating galaxies (FGCE 333, 981) we have $<\text{P.A. - P.A.(FGCE)}>=+0.6\pm0.4(\text{s.e.m.})$.

It is evident in Figs. 3 that the projected spatial distribution of strongly warped galaxies and the distribution of their position angles are quite homogeneous (at least in the first order approximation). The large “void” in Figs. 3 is due to absorption in the plane of Milky Way. Comparison of the distributions for the galaxies with S-shaped and U-shaped warps shows that both distributions are statistically indistinguishable. There is no evidence of any significant large-scale alignment effect.

The number of galaxies with clockwise warps (18) is smaller than counter-clockwise galaxies (42). But, within our relatively poor statistics, the difference is not significant (both numbers are consistent within $3\sigma$).
Reshetnikov (1995) found that disks of more massive and luminous galaxies are somewhat less warped. Our present data do not show any significant correlation (see Fig. 3).

3. The environment

Among the warped objects, 10 galaxies are members of interacting systems. The relative fraction of interacting galaxies – 17% – is higher than the analogous fraction – 6% – for our complete sample of 540 galaxies (Reshetnikov & Combes 1998). The fraction of isolated galaxies (9 objects – 15%) is smaller in the warped sample than in the control sample (25%) while the relative number of galaxies with companions (68%) is the same in both samples. This supports our conclusion that S-shaped warps are connected with galaxy environment (Reshetnikov & Combes 1998). But this connection is not perfectly tight since there are warped galaxies among relatively isolated objects (an interpretation could be in terms of recent accretion).

To get more insight on the large-scale environment of warped galaxies, we have tried to compute the average density of galaxies around the S-shape warped population,
Table 1. General characteristics of the sample galaxies

| FGCE | PGC  | ESO  | $\alpha$ (1950) | $\delta$ (1950) | $B$ | $V_r$ (km/s) | $a$ ('') | $b$ ('') | Type | $\psi$ (') | P.A. (') | D |
|------|------|------|----------------|----------------|-----|-------------|--------|--------|------|----------|--------|---|
| 22   | 00   | 08   | 56.5           | -32 42 50      | 1.18| 0.11       | d      | 3.5    | 178  | –        |        |   |
| 28   | 149  | 024  |                |                |     |             |        |        |      |          |        |   |
| 38   | 150-G| 002  |                |                |     |             |        |        |      |          |        |   |
| 44   |      |      |                |                |     |             |        |        |      |          |        |   |
| 50   | 294-IG| 011  |                |                |     |             |        |        |      |          |        |   |
| 53   | 112-G| 004  |                |                |     |             |        |        |      |          |        |   |
| 63   | 540-G| 004  |                |                |     |             |        |        |      |          |        |   |
| 72   | 112-G| 002  |                |                |     |             |        |        |      |          |        |   |
| 80   | 194-IG| 037  |                |                |     |             |        |        |      |          |        |   |
| 99   | 474-G| 035  |                |                |     |             |        |        |      |          |        |   |
| 108  | 151-G| 008  |                |                |     |             |        |        |      |          |        |   |
| 129  | 113-G| 013  |                |                |     |             |        |        |      |          |        |   |
| 170  |      |      |                |                |     |             |        |        |      |          |        |   |
| 187  | 477-G| 001  |                |                |     |             |        |        |      |          |        |   |
| 189  | 297-G| 024  |                |                |     |             |        |        |      |          |        |   |
| 202  | 354-G| 005  |                |                |     |             |        |        |      |          |        |   |
| 226  | 053-G| 002  |                |                |     |             |        |        |      |          |        |   |
| 238  | 355-G| 014  |                |                |     |             |        |        |      |          |        |   |
| 240  | 115-G| 011  |                |                |     |             |        |        |      |          |        |   |
| 260  |      |      |                |                |     |             |        |        |      |          |        |   |
| 267  | 290-G| 017  |                |                |     |             |        |        |      |          |        |   |
| 269  | 356-G| 012  |                |                |     |             |        |        |      |          |        |   |
| 294  |      |      |                |                |     |             |        |        |      |          |        |   |
| 319  | 116-G| 019  |                |                |     |             |        |        |      |          |        |   |
| 320  |      |      |                |                |     |             |        |        |      |          |        |   |
| 333  | 482-G| 005  |                |                |     |             |        |        |      |          |        |   |
| 354  | 359-G| 001  |                |                |     |             |        |        |      |          |        |   |
| 363  | 249-G| 035  |                |                |     |             |        |        |      |          |        |   |
| 377  |      |      |                |                |     |             |        |        |      |          |        |   |
| 382  | 157-G| 010  |                |                |     |             |        |        |      |          |        |   |
| 412  |      |      |                |                |     |             |        |        |      |          |        |   |
| 416  | 304-G| 003  |                |                |     |             |        |        |      |          |        |   |
| 441  | 361-G| 012  |                |                |     |             |        |        |      |          |        |   |
| 539  | 504-G| 021  |                |                |     |             |        |        |      |          |        |   |
| 541  | 364-G| 010  |                |                |     |             |        |        |      |          |        |   |
| 623  | 207-G| 001  |                |                |     |             |        |        |      |          |        |   |
| 630  | 087-G| 050  |                |                |     |             |        |        |      |          |        |   |
| 638  | 034-G| 015  |                |                |     |             |        |        |      |          |        |   |
| 642  |      |      |                |                |     |             |        |        |      |          |        |   |
| 674  | 123-G| 023  |                |                |     |             |        |        |      |          |        |   |
| 690  | 059-G| 026  |                |                |     |             |        |        |      |          |        |   |
| 706  | 562-G| 017  |                |                |     |             |        |        |      |          |        |   |
| 725  | 496-G| 025  |                |                |     |             |        |        |      |          |        |   |
| 806  | 567-G| 038  |                |                |     |             |        |        |      |          |        |   |
| 834  | 437-G| 054  |                |                |     |             |        |        |      |          |        |   |
| 835  | 569-G| 003  |                |                |     |             |        |        |      |          |        |   |
| 840  | 006-G| 008  |                |                |     |             |        |        |      |          |        |   |
| 871  | 215-G| 029  |                |                |     |             |        |        |      |          |        |   |
| 872  |      |      |                |                |     |             |        |        |      |          |        |   |
| 891  |      |      |                |                |     |             |        |        |      |          |        |   |
FGCE  PGC  ESO  α(1950)  δ(1950)  B  V_r  a  b  Type  ψ  P.A.  D
919    37906  505-G 003  11 58 32.9  -24 17 30  14.10  1808  3.00  0.39  m  4.5  132  -
930    35238  321-G 017  12 06 17.6  -35 39 45  15.93  1906  1.18  0.11  c  5  78  -
944    42066  442-G 012  12 53 55.0  -27 54 00  16.99  1906  1.01  0.13  c  6  33  +
981    381-G 014  13 41 26.9  -36 14 12  15.15  3305  1.34  0.18  c  6  9  -
1035   13 12 15.4  -25 41 19  13760  1.57  0.11  c  7  73  -
1063   13 23 55.3  -50 57 26  1.10  0.13  c  4  138  -
1082   13 32 28.4  -36 54 31  1.23  0.11  c  4  105  -
1102   13 45 37.9  -46 26 26  1.10  0.13  c  4  138  -
1112   49478  445-G 077  13 52 12.6  -32 26 47  -

Table 2. Average density around warped and non-warped galaxies

| Rs (Mpc) | 10  | 15  | 20  | 25  | 30  |
|----------|-----|-----|-----|-----|-----|
| Warped galaxies | 7.4E-2 | 4.2E-2 | 3.0E-2 | 1.6E-2 | 1.0E-2 |
| Un-warped sample  | 1.2E-2 | 8.8E-3 | 7.3E-3 | 5.5E-3 | 4.4E-3 |

R_s is the search radius, and the average densities are in gal Mpc^{-3}

4. Conclusion

In the present note we describe a new sample of southern spiral galaxies demonstrating strong S-shape optical warps. The galaxies were selected on the basis of their optical images from the DSS. First statistics indicate that warped morphologies are found preferentially in rich environment, although this result must be confirmed from larger redshift surveys. The sample gives the largest available material for future works (optical and HI) on galaxy warps.

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5. Appendix

We present here a condensed summary of the 60 warped galax-
ies photographs; each galaxy has been rotated by the position
angle given in Table 4 and can be retrieved by its FGCE num-
ber.
**Fig. 6.** Digital Sky Survey images of the S-shape warped galaxies. The size of each image is 1’×3’. The images have been rotated, by -PA given in Table 1.