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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; interactions; spiral; structure

1. Introduction

The majority of spiral galaxies have a warped plane, as has been revealed in the neutral gas extended component, through HI-21 cm 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 therfore 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[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.

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[1] The Digitized Sky Surveys were produced at the Space Telescope Science Institute under U.S. Government grant NAG W-2166.

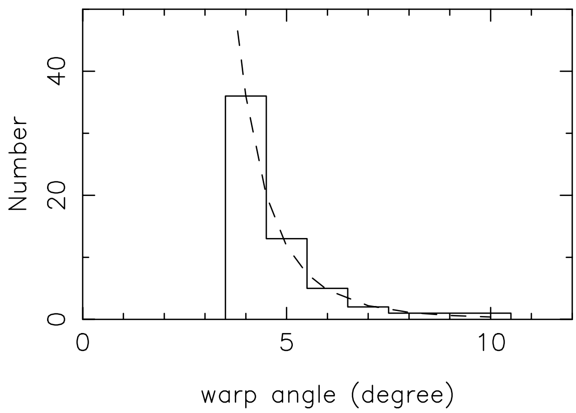

Fig. 1. Distribution of the observed warp angles. Dashed line shows ψ^{-5} law

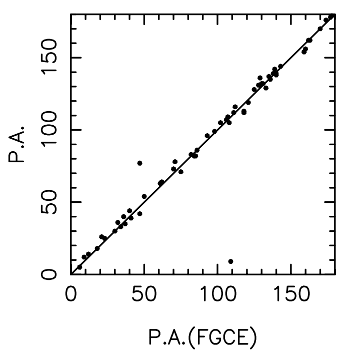

Fig. 2. Comparison between position angles measurements (in degrees) in our work (PA) and FGCE – PA (FGCE). The solid line shows equality

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.

2. The sample and statistics

Table 1 presents extraction from the Southern Extention of FGC (Karachentsev et al. 1993, FGCE) for the galaxies with large S-type warps. The sample is limited by coordinates $0\stackrel{h}{.}0 \leq \alpha(1950) \leq 14\stackrel{h}{.}0$, $\delta(1950) \leq -17\stackrel{\circ}{.}5$. The columns are as follows: galaxy FGCE, PGC and ESO number; right ascension and declination for the epoch 1950.0; B magnitude (NED[2]); heliocentric radial velocity (NED); major and minor diameters measured on blue films (in arcmin); morphological type; warp angle ψ – 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) – PA; direction of warp: clockwise (+) or counter-clockwise (−).

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

[2] NASA/IPAC Extragalactic Database.

Figure 1 presents the distribution of the sample galaxies according to warp angle ψ. 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 ψ is $4\stackrel{\circ}{.}8 \pm 1\stackrel{\circ}{.}3(\sigma)$ that is comparable with the amplitudes of optical warps found by Sanchez-Saavedra et al. (1990); Reshetnikov (1995), and de Grijs (1997). Dashed line in Fig. 1 shows the ψ^{-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 $<$ PA − PA (FGCE) $>$ = $-0\stackrel{\circ}{.}6 \pm 1\stackrel{\circ}{.}8$ (s.e.m.). Excluding two most deviating galaxies (FGCE 333, 981) we have $<$ PA − PA (FGCE) $>$ = $+0\stackrel{\circ}{.}6 \pm 0\stackrel{\circ}{.}4$ (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 undistinguishable. 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 3σ).

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. 4).

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

Table 1. General characteristics of the sample galaxies

FGCE	PGC	ESO	α(1950)	δ(1950)	B	V_r km s^{-1}	a ($'$)	b ($'$)	Type	ψ (°)	PA (°)	D
22			00 08 56.5	−32 42 50			1.18	0.11	d	3.5	178	–
28	988	149-G 024	00 12 21.0	−56 09 39	16.53		1.29	0.15	bc	5	116	–
38	1324	150-G 002	00 18 15.0	−56 41 28	16.37		1.12	0.15	bc	4	162	–
44			00 20 36.8	−25 27 30			1.03	0.13	c	4.5	40	–
50		294-IG 011	00 24 59.7	−40 52 56	17.28		1.34	0.19	cd	4	44	–
53	1729	112-G 004	00 25 43.4	−58 22 48	15.86		1.49	0.20	c	4	30	–
63	2167	540-G 004	00 33 43.4	−19 24 21	17.08		1.10	0.10	c	5	131	–
72			00 39 25.8	−33 14 36	15.5	9525	1.05	0.11	bc	4	137	–
80		194-IG 037	00 44 24.4	−51 15 46	17.11		1.14	0.11	c	8.5	5	–
99	3088	474-G 035	00 50 14.9	−26 00 19	16.75		1.12	0.13	bc	4	82	+
108	3369	151-G 008	00 54 27.5	−55 36 26	16.23		1.23	0.13	cd	3.5	86	+
129	4010	113-G 013	01 05 45.6	−58 20 34	16.62	5914	1.25	0.15	cd	6	26	–
170			01 30 31.7	−56 07 38			1.29	0.11	c	4	112	+
187	6349	477-G 001	01 41 17.0	−27 11 59	16.82		1.75	0.11	cd	4	176	–
189	6394	297-G 024	01 42 29.0	−40 49 12	15.91	10171	1.26	0.18	bc	5	36	–
202	6917	354-G 005	01 49 53.7	−33 46 34	15.95	8703	1.70	0.22	bc	3.5	129	+
226	8499	053-G 002	02 12 25.7	−71 08 46	16.21	8000	1.88	0.20	cd	3.5	109	+
238	9125	355-G 014	02 22 18.7	−36 47 21	17.37		1.19	0.11	c	4	82	+
240	9191	115-G 011	02 23 46.2	−57 56 47	16.16		1.68	0.20	c	5	14	–
260			02 39 39.4	−33 10 04			1.01	0.13	dm	4.5	25	–
267	10605	299-G 017	02 46 22.0	−41 51 37	16.74	20082	1.85	0.22	b	6.5	39	+
269	10640	356-G 012	02 46 43.0	−36 43 24	15.82		1.57	0.22	bc	4	35	+
294			03 03 20.5	−41 42 29			1.62	0.11	bc	9	132	–
319	12791	116-G 019	03 24 07.3	−57 40 31	16.1		1.23	0.12	c	5.5	71	+
320			03 24 09.0	−48 08 40			1.12	0.11	c	5	131	–
333		482-G 005	03 30 51.9	−24 18 06	15.40	1915	1.68	0.21	cd	7	77	+
354	13939	359-G 001	03 48 14.8	−34 54 13	16.7		1.74	0.20	c	3.5	128	–
363	14212	249-G 035	03 57 21.8	−45 59 56	16.24	1031	1.90	0.20	c	4	99	–
377			04 06 50.5	−62 10 50	16		1.08	0.13	cd	4	112	–
382	14701	157-G 010	04 12 37.5	−54 11 46	16.21		1.21	0.13	c	4	83	–
412			04 30 10.7	−29 33 28			1.14	0.11	c	4	63	–
416	15621	304-G 003	04 34 35.3	−37 53 20	17.43		1.18	0.12	cd	3	42	+
441	16116	361-G 012	04 48 03.9	−36 11 18	15.14	5303	1.90	0.24	c	4	142	–
539	17581	004-G 021	05 49 10.1	−84 21 07	17.29		1.12	0.12	c	3.5	170	–
541	18052	364-G 010	05 51 46.0	−34 56 36	16.39		1.19	0.17	c	5	156	+
623	19629	207-G 001	06 46 41.1	−48 14 15	16.85		1.01	0.12	cd	3.5	139	–
630	19816	087-G 050	06 53 33.9	−63 09 19	15.77	3538	1.79	0.22	c	4.5	119	–
638	20010	034-G 015	07 03 21.8	−77 24 42	16.86		1.34	0.12	c	5.5	18	–
642			07 09 37.3	−51 17 38		19556	1.23	0.11	c	5	105	+
674	21690	123-G 023	07 43 41.6	−58 01 52	14.92	2920	2.91	0.34	cd	4.5	107	–
690	22797	059-G 026	08 07 25.6	−70 20 47	16.81		1.29	0.17	b	4	179	+
706	24027	562-G 017	08 31 34.0	−18 52 00			1.01	0.10	c	6	154	+
725	25300	496-G 025	08 58 20.3	−25 02 15	16.97	4677	1.85	0.20	c	10	63	–
806	30030	567-G 038	10 14 35.3	−21 02 02	17.09		1.12	0.13	bc	4	139	–
834	31981	437-G 054	10 41 17.5	−28 36 09	14.95	3461	1.90	0.27	b	5	54	–
835	32100	569-G 003	10 42 56.4	−22 23 52	15.81	3731	1.59	0.22	dm	4.5	96	–
840	32162	006-G 008	10 46 54.8	−83 34 52	17.28		1.57	0.15	c	3.5	135	+

Table 1. continued

FGCE	PGC	ESO	α(1950)	δ(1950)	B	$V_{\rm r}$ km s^{-1}	a ($'$)	b ($'$)	Type	ψ (°)	PA (°)	D
871	33906	215-G 029	11 08 07.1	−47 53 40	16.35		1.12	0.16	cd	4.5	12	–
872			11 08 57.1	−42 03 16			1.01	0.10	c	5	162	–
891			11 27 31.4	−35 29 25			1.01	0.09	c	4	64	–
919	37906	505-G 003	11 58 32.9	−24 17 30	14.10	1808	3.00	0.39	m	4.5	132	–
930			12 06 17.6	−35 39 45			1.18	0.11	c	5	78	–
944	39238	321-G 017	12 13 10.2	−42 27 53	15.93	6704	1.70	0.24	b	5.5	136	–
974	42066	442-G 012	12 33 55.0	−27 54 00	16.99		1.01	0.13	c	6	33	+
981		381-G 014	12 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			1.01	0.11	c	4.5	113	+
1082			13 32 28.4	−36 54 31			1.23	0.11	c	4.5	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	17.27		1.03	0.13	c	4	144	–

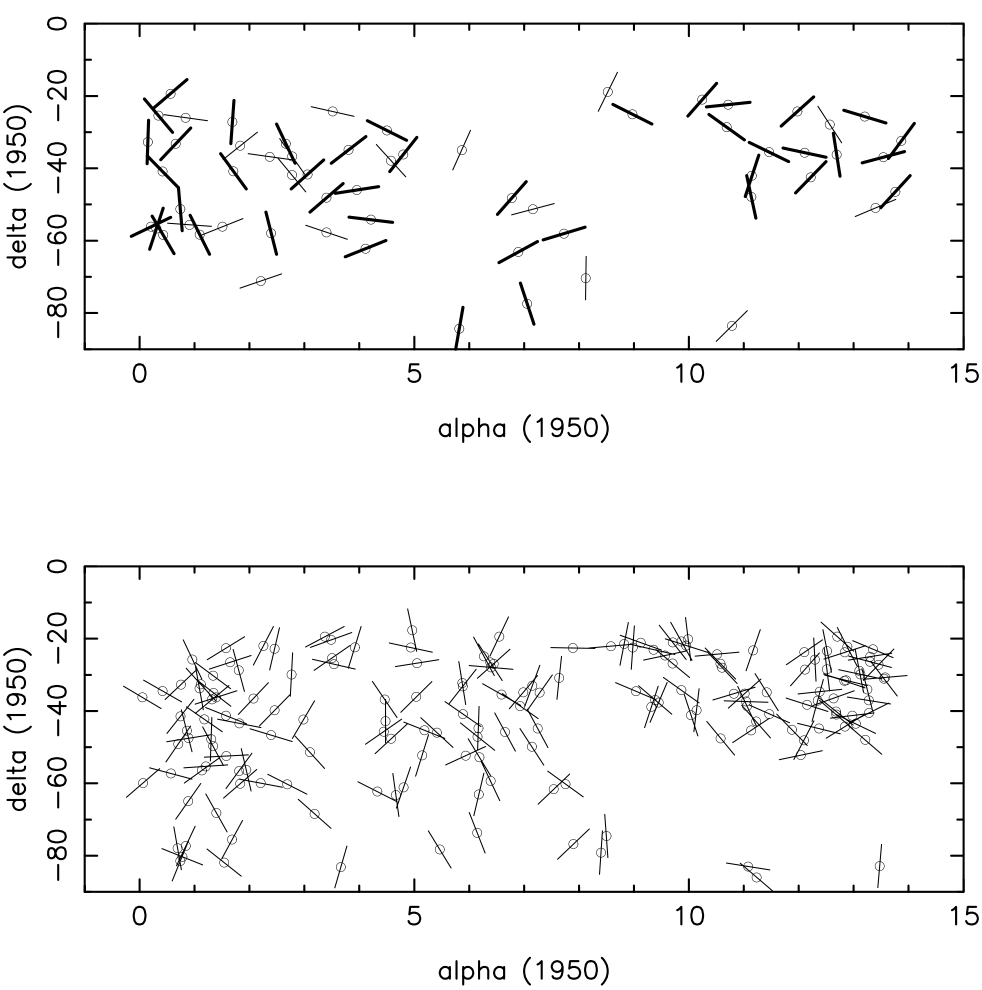

Fig. 3. Distribution of the warped galaxies on the sky: top – S-shaped warps, bottom – U-shaped warps. Plots of declinations (in degrees) versus right ascension (hours). The position angles of the galaxies (PA) are indicated by dashes (the length of each dash is 12°). Thick dashes show galaxies with counter-clockwise warp, thin dashes – clockwise warps (for S-shape warped galaxies)

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

R_s in 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}

density of galaxies around the S-shape warped population, and compare it with a control sample. The control has been selected from the un-warped FGCE galaxies, with the condition that the asymmetry index along the minor axis is lower than 1.05 (cf. Reshetnikov & Combes 1998). We have used the Southern Sky Redshift Survey (SSRS2, da Costa et al. 1998), where redshifts and magnitudes are reported for 5369 galaxies. Unfortunately, the redshifts are not known for all of the FGCE catalog, and we have only extracted from NED 15 redshifts for the warped sample, and 17 for the control (non-warped) galaxies. Some of them are plotted in Fig. 5 superposed on the SSRS2 points.

Around each object of our sample, we compute the average distance of the SSRS2 galaxies, given a search radius R_s. This average distance d_m is computed taking the luminosity of galaxies as weight. The mean density is then estimated as

$$\rho_m = \frac{3N_{gal}}{4\pi d_m^3}$$

where N_{gal} is the total number of objects within R_s. Taking a common weight for all galaxies only changes d_m by 10% at most. The results obtained for the warped and control samples are displayed in Table 2. The average density appears $3 - 4$ times higher for the warped objects. This result has to be confirmed by more statistics, when the redshifts for the whole FGCE catalog are known.

4. Appendix

We present here a condensed summary of the 60 warped galaxies photographs; each galaxy has been rotated by the position angle given in Table 1 and can be retrieved by its FGCE number.

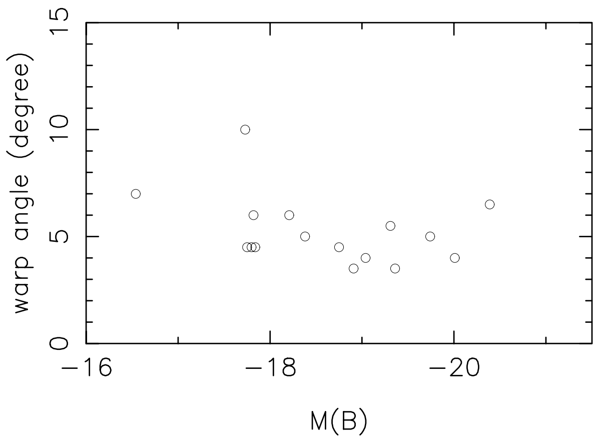

Fig. 4. Warp angle versus blue absolute magnitude for the S-shape warped galaxies ($H_0 = 75$ km s^{-1}/Mpc)

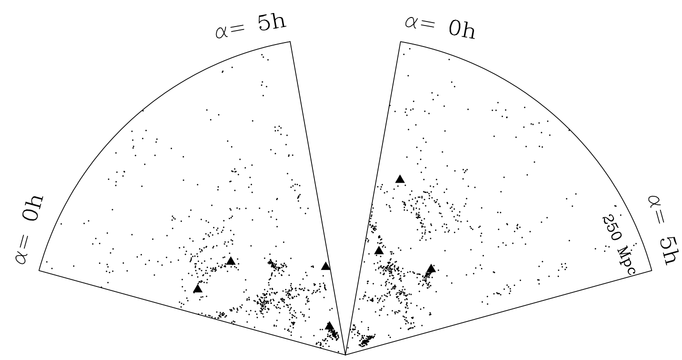

Fig. 5. Location of some of the FGCE galaxies (filled triangles) among the SSRS2 survey objects (dots). The left sector corresponds to warped galaxies and right to un-warped ones, between declinations −24 and −37°. Right ascensions run from 0 to 5 h, and the maximum distance is 250 Mpc ($H_0 = 75$ km s^{-1}/Mpc)

5. 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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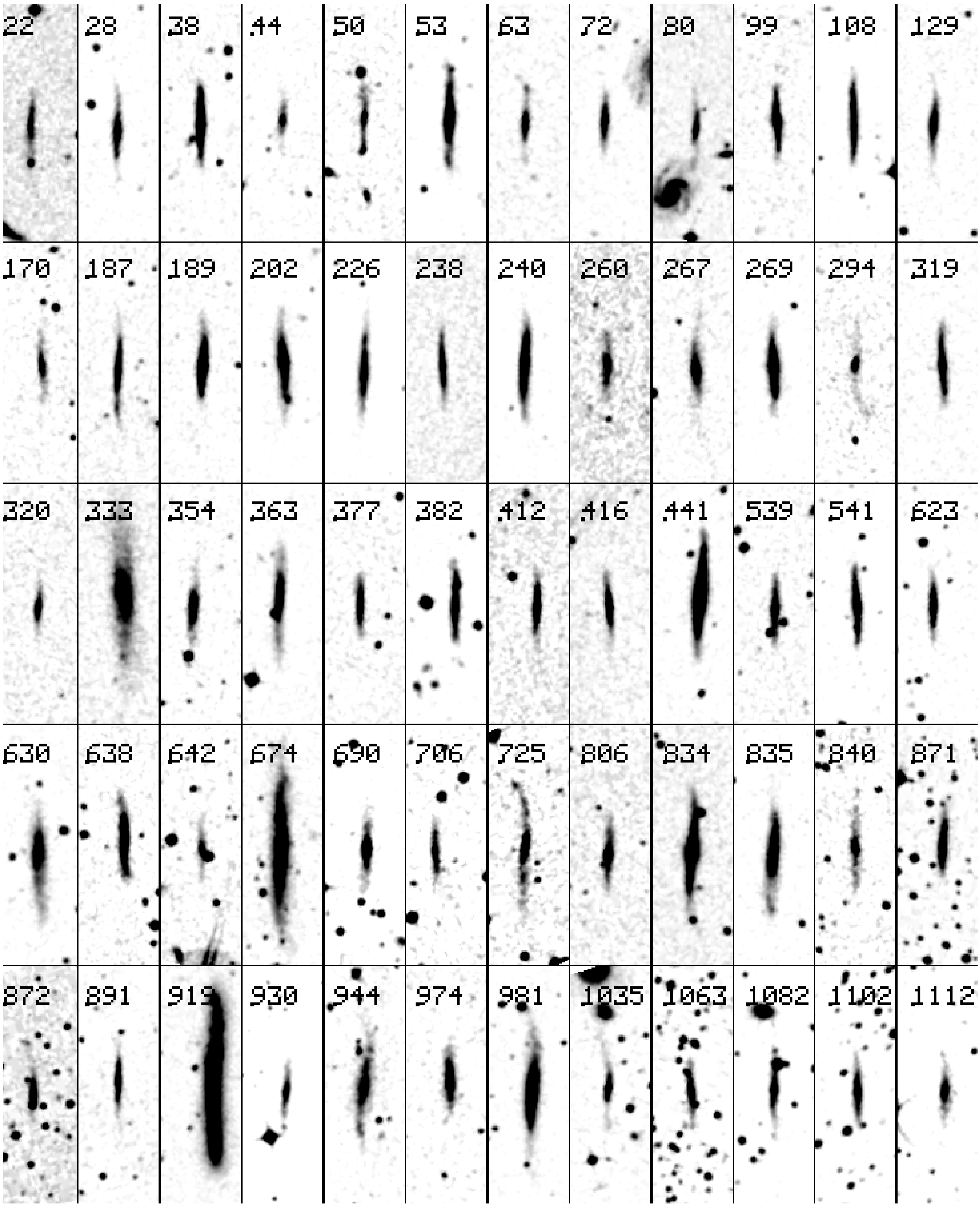

Fig. 6. Digital Sky Survey images of the S-shape warped galaxies. The size of each image is $1' \times 3'$. The images have been rotated, by -PA given in Table 1

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