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Warps and correlations with intrinsic parameters of galaxies in the visible and radio

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Abstract. From a comparison of the different parameters of warped galaxies in the radio, and especially in the visible, we find that:
a) No large galaxy (large mass or radius) has been found to have high amplitude in the warp, and there is no correlation of size/mass with the degree of asymmetry of the warp.
b) The disc density and the ratio of dark to luminous mass show an opposing trend: smaller values give more asymmetric warps in the inner radii (optical warps) but show no correlation with the amplitude of the warp; however, in the external radii is there no correlation with asymmetry.
c) A third anticorrelation appears in a comparison of the amplitude and degree of asymmetry in the warped galaxies.
Hence, it seems that very massive dark matter haloes have nothing to do with the formation of warps but only with the degree of symmetry in the inner radii, and are unrelated to the warp shape for the outermost radii. Denser discs show the same dependence.

Key words. galaxies: statistics – galaxies: spiral – galaxies: structure – galaxies: kinematics and dynamics

1. Introduction

Many spiral galaxies have warps, disc distortions with an integral-sign shape (S-warp), cup-shape (U-warp), or some form of asymmetry. The Milky Way is an example (Burton 1988, 1992). Indeed, most of the spiral galaxies for which we have relevant information on their structure (because they are edge-on and nearby) show a warp. Sánchez-Saavedra et al. (1990, 2002) and Reshetnikov & Combes (1998) show that nearly half of the spiral galaxies of selected samples are warped, and many of the rest might also be warped since warps in galaxies with low inclination are difficult to detect. For high redshift, it seems that the effect of warping is even stronger (Reshetnikov et al. 2002).

At present, there are several theories in the literature about the causes of warps in galactic discs. Four remarkable examples of theories which explain the formation of warps are:

– Gravitational tidal effects on a given spiral galaxy due to the presence of a satellite. This does not seem to be enough to induce the observed amplitude in the Galactic warp (Hunter & Toomre 1969). Weinberg (1998) proposed a mechanism for amplifying the tidal effects caused by a satellite by means of an intermediate massive halo around the galactic disc, but García-Ruiz et al. (2000) have found that the orientation of the warp is not compatible with the generation of warps by means of this mechanism if the satellites are the Magellanic Clouds, and moreover the magnification of the amplitude is not so high (García Ruiz 2001, Ch. 2). However, this mechanism could operate in galaxies other than the Milky Way.
– The intergalactic magnetic field has been suggested as the cause of galactic warps (Battaner et al. 1990; Battaner et al. 1991; Battaner & Jiménez-Vicente 1998) directly affecting the gas in the Galactic disc and producing warps in it. Stellar warps in the old population could also be possible as a result of interactions between the gaseous and stellar discs. This gives rise to some interesting predictions, such as the alignment of warps of different galaxies (Battaner et al. 1991) and differences between the stellar and gaseous warps.
– Cosmic infall is invoked to explain the reorientation of a massive Galactic halo, which produces a warp in the disc (Ostriker & Binney 1989; Jiang & Binney 1999). This model requires a halo that is much more massive than the disc, an extremely high accretion rate (3 disc masses in 0.9 Gyr; Jiang & Binney 1999) and, in this scenario, after a sufficiently long time, the angular momentum of the Galaxy to become parallel to the direction of the falling matter causing the warp to decay. It is difficult to understand why the warps are so frequent in this scenario but this difficulty might be overcome by including a prolate halo

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(Ideta et al. 2000), which would prolong the warp's existence. Also, it is difficult to understand how a low-density halo can retain the accreted intergalactic matter. A generic misalignment between halo and the disc (Debattista & Sellwood 1999) might answer the question, but then we need to think about the reason for the misalignment.
- The accretion of the intergalactic medium directly on to the disc is another possibility (Revaz & Pfenninger 2001; López-Corredoira et al. 2002). The torque produced in the different rings of the disc by an intergalactic flow of velocity $\sim$100 km s^{-1} and baryon density $\sim 10^{-25}$ kg m^{-3} is enough to generate the observed warps (López-Corredoira et al. 2002) and also predicts the existence of U-warps (cup-shaped), which are less frequent than S- (integral-shaped) warps. Some alignment of the warps in neighbouring galaxies and differences between the gaseous and stellar warps might also be expected. This hypothesis assumes only the existence of a not necessarily homogeneous intergalactic medium with a reasonably low density. Although the idea is plausible and compatible with our observations, there is still no direct proof of the existence of this intergalactic medium.

All these theories make different assumptions about the conditions of the spiral galaxies and their neighbourhood (massive haloes, magnetic fields, intergalactic medium, satellites), so the study of warps becomes interesting as a tool for discriminating among the different scenarios. There are already important works about the observed properties of warps, however we feel that these are inadequate, and that an effort must be made to reduce the number of possible hypotheses. Here, we do not aim to give a final answer to the question but instead present some new correlations that might be useful together with other data to discriminate among the different models.

Some interesting observational results already published are the dependence on the environment (isolated or in clusters) of the warp amplitude asymmetries (differences between the east and west wings of the warp) and frequency (in the visible Reshetnikov & Combes 1998 and also in the radio García-Ruiz 2001; Kuijken & García-Ruiz 2001). Curiously, more isolated galaxies seem to be more frequently warped (García-Ruiz 2001; Kuijken & García-Ruiz 2001) and this would be against the gravitational interaction of satellites, at least in some cases. Halo-disk misalignments without external dependence are also excluded. It seems that intergalactic magnetic fields, or the accretion of intergalactic matter on to either the halo or the disc are better representations. Therefore, there already exists in the literature some papers which have correlated the warp characterictics with the environmental parameters. We are not going to explore these correlations again, but rather focus on the correlations with the intrinsic parameters of galaxies. For instance, one interesting question now is whether there is any correlation between halo properties and warp amplitude/asymmetry.

If the halo were an important element in the formation of warps, we should observe some dependence on it. Some models have a warp amplitude depending on the halo mass. Apart from the hypotheses which talk about a halo as an intermediary between external forces and the disc (Weinberg 1998; Jiang & Binney 1999), works by Nelson & Tremaine (1995) or Debattista & Sellwood (1999) predict that, although in most cases the dynamical friction between the disc and the halo damps the warp, it can also excite the warp. This is the reason why we will try to analyze the optical and radio warps in the present paper through the correlations with the mass/luminosity ratios derived from the rotation curves (provided they are related to the fraction of dark matter in the galaxies). We also produce correlations with other parameters that represent the intrinsic size of the galaxy (radius, mass, or luminosity).

2. Data

This study is based on two samples of galaxies, one of 228 galaxies in optical bands (see Table 1) and the other of 26 galaxies in radio (see Table 2). We have completed the information on the warp amplitudes with some intrinsic parameters of the galaxies.

2.1. Optical data

The optical warp measurements come from Sánchez-Saavedra et al. (1990, 2002), who have analysed images obtained from the Palomar Observatory Sky Survey (POSS) and the DSS. They measured the amplitude of the warp in galaxies mostly from the southern hemisphere (Sánchez-Saavedra et al. 1990, 2002); however, we also took some data from the northern hemisphere (Sánchez-Saavedra et al. 1990). The galaxies were selected according to the following criteria:

- high surface brightness ($B < 14.5$);
- galaxies large enough to detect the warp. The galaxies have a log$R_{25} \geq 24$ arcsec (R_{25} is the radius of the angular size of the isophote $\mu = 25$ mag/arcsec^2);
- morphological type, T, between 0 and 7;
- inclination angle greater than 75 degrees.

We took these data and sought several intrinsic parameters of each galaxy in the literature. The H-band (λ 1.6 μm) magnitude was used because it is a good mass tracer of the stellar population. Moreover, the luminous mass in NIR bands is not much affected by dust and gas extinction as the visible bands are and is less contaminated by the young population of the spiral arms. The total luminosity of a galaxy near 2 μm is thought to be a better tracer of the stellar mass than the visible (which is biased by recent star formation) or the far-infrared (biased again by recent star formation, which creates and heats dust grains that emit thermally in this waveband; Jablonka & Arimoto 1992). We then tried to find some correlations between these intrinsic parameters and the warp amplitudes in our sample. In Table 1 are shown all the galaxies with these parameters. The columns list the following information:

- *Column 1:* PGC and NGC number.
- *Columns 2 and 3:* Warp amplitudes extracted from Sánchez-Saavedra et al. (1990, 2002). The first number is the amplitude on the east side of the galaxy and the second

Table 1. Optical data. Columns in the table represent: name of the galaxy, warp amplitude in the west and east side of the galaxy, redshift, maximum rotation velocity, log(D_{25}), H magnitude and distance.

PGC/NGC	East WA	West WA	cz (km s^{-1})	$V_{\rm rot}$ (km s^{-1})	log D_{25} 0.1 arcmin	$m_{\rm H}$	d (Mpc)
PGC 474	13	12	1542 i)	139 i)	1.53	—	20.6
PGC 627	13	13	1495 a)	77 1)	1.39	—	20.0*
PGC 725	19	17	6004 a)	226 1)	1.34	—	80.0
PGC 1851	20	14	1596 a)	233 1)	1.92	7.6	21.3
PGC 1942	8	13	7110 h)	108 h)	1.41	10.1	94.8
PGC 1952	15	12	2626 a)	205 1)	1.45	—	35.0
PGC 2228	13	12	3043 h)	115 1)	1.31	11.6	40.6
PGC 2482	15	17	3946 h)	291 h)	1.45	9.2	52.6
PGC 2789	12	15	241 g)	204 4)	2.43	4.5	3.4*
PGC 2800	13	13	5765 h)	219 h)	1.24	—	76.9
PGC 2805	25	17	1345 c)	59 s)	1.48	—	17.9
PGC 3743	14	12	2290 a)	172 a)	1.57	—	30.5
PGC 4440	13	20	3552 a)	198 1)	1.41	9.8	47.4
PGC 4912	17	25	5883 a)	234 1)	1.29	10.1	40.6
PGC 5688	9	5	5431 h)	255 h)	1.34	9.8	72.4
PGC 6966	4	12	5005 h)	257 1)	1.48	—	66.7
PGC 7306	13	13	4443 h)	136 h)	1.29	—	59.2
PGC 7427	6	13	5530 a)	178 1)	1.27	—	73.7
PGC 8326	7	8	8133 a)	312 1)	1.40	10.2	108.4
PGC 8673	9	10	1890 h)	96 1)	1.34	—	25.2
PGC 9582	5	11	4773 h)	294 1)	1.33	—	63.6
PGC 10965	7	7	2065 a)	160 1)	1.57	—	27.5
PGC 11198	25	20	4495 h)	211 h)	1.45	—	59.9
PGC 11595	18	18	1391 a)	83 1)	1.47	12.0	18.5
PGC 11659	10	10	5529 a)	255 1)	1.36	9.8	73.7
PGC 11851	9	6	1318 a)	116 1)	1.53	10.2	17.5
PGC 12521	15	10	3949 a)	178 1)	1.34	10.5	52.6
PGC 13171	14	10	1812 h)	109 h)	1.40	10.1	24.1
PGC 13458	9	6	1068 a)	150 1)	1.59	9.2	14.2
PGC 13569	0	0	1638 a)	65 1)	1.36	11.2	21.8
PGC 13646	12	8	2168 C)	168 1)	1.50	—	28.9
PGC 13727	15	14	1179 a)	193 1)	1.88	8.3	15.7
PGC 13809	6	0	1882 a)	131 1)	1.69	9.4	25.0
PGC 13912	9	9	980 a)	120 1)	1.63	—	—
PGC 14071	9	9	1050 a)	84 h)	1.40	—	14.0
PGC 14190	7	16	1279 a)	95 1)	1.56	—	17.0
PGC 14255	13	13	1291 a)	95 1)	1.28	11.3	17.2
PGC 14259	9	13	4111 a)	175 1)	1.43	10.8	54.8
PGC 14337	0	0	5386 a)	182 1)	1.31	10.7	71.8
PGC 14337	0	0	5386 a)	182 1)	1.31	10.7	72.0
PGC 14397	8	8	1094 a)	190 1)	1.72	—	14.6
PGC 14824	7	10	1359 C)	92 1)	1.59	—	18.1
PGC 15455	9	8	1851 a)	120 1)	1.44	—	24.6
PGC 15635	9	17	4852 h)	288 h)	1.52	—	64.6
PGC 15654	10	10	4759 h)	225 h)	1.37	—	63.4
PGC 15674	14	15	3705 h)	202 h)	1.27	10.0	49.4
PGC 15749	20	20	1678 a)	92 1)	1.38	—	22.4
PGC 16144	0	0	2819 h)	155 h)	1.35	10.7	37.6

number is the warp amplitude on the west side. These values divided by 100 give the tangent of the angle. This is the angle between the galactic centre and the end of the warp.

- *Column 4:* Redshift of each galaxy taken from the NED. Each reference is specified in the table.
- *Column 5:* Rotation velocity of the galaxy at R_{25}, which is more or less the maximum rotation velocity. This parameter comes from several sources, mainly from Mathewson et al. (1992) and Persic & Salucci (1995). Each reference is specified in the columns of the table.

Table 1. continued.

PGC/NGC	East WA	West WA	cz (km s^{-1})	V_{rot} (km s^{-1})	log D_{25} 0.1 arcmin	m_H	d (Mpc)
PGC 16168	7	7	4577 h)	170 h)	1.22	—	61.0
PGC 16199	12	12	1169 a)	87 1)	1.44	—	15.6
PGC 16636	0	0	4329 h)	199 h)	1.49	—	57.7
PGC 17056	10	10	2828 a)	172 1)	1.24	—	37.7
PGC 17174	0	0	1755 a)	158 h)	1.51	—	23.4
PGC 17969	10	10	2382 h)	145 1)	1.34	10.5	31.8
PGC 18437	6	5	1228 a)	137 1)	1.60	9.6	16.4
PGC 18765	0	0	1696 i)	143 a)	1.52	9.8	22.6
PGC 19996	5	5	2681 h)	166 f)	1.35	10.1	35.7
PGC 21815	6	6	1131 b)	98 b)	1.67	8.4	15.1
PGC 21822	17	7	3237 h)	245 h)	1.48	9.3	43.1
PGC 22272	0	0	1558 h)	130 h)	1.45	11.1	20.8
PGC 22338	8	9	1119 ii)	148 m)	1.80	—	14.9*
PGC 22910	13	12	5954 a)	223 1)	1.41	—	79.4
PGC 23558	20	20	1776 h)	91 h)	1.27	—	23.7
PGC 23992	15	17	4533 a)	190 1)	1.15	—	60.4
PGC 24685	6	8	4570 a)	308 1)	1.48	9.4	60.9
PGC 25886	9	9	1838 h)	256 h)	1.63	—	24.5
PGC 25926	3	3	2178 a)	158 a)	1.65	—	29.0
PGC 26561	10	10	1640 a)	245 1)	1.75	—	21.8
PGC 27135	0	0	929 i)	100 1)	1.86	—	6.40*
PGC 27735	13	13	4449 a)	171 1)	1.28	—	59.3
PGC 28117	17	27	4315 a)	170 1)	1.41	—	57.5
PGC 28246	17	20	2893 a)	183 1)	1.50	—	38.5
PGC 28283	0	0	2868 h)	220 h)	1.59	—	38.2
PGC 28778	8	8	2697 a)	154 i)	1.40	—	36.0
PGC 28840	7	8	2802 a)	123 1)	1.53	—	37.3
PGC 28909	0	0	2520 a)	208 1)	1.83	—	33.6
PGC 29691	0	0	2840 h)	142 1)	1.35	—	37.9
PGC 29716	0	0	2526 v)	161 k)	1.59	—	33.7
PGC 29743	9	9	2603 j)	164 1)	1.50	—	34.7
PGC 29841	0	0	3603 h)	185 1)	1.32	10.5	48.0
PGC 30716	0	0	3138 a)	160 1)	1.30	—	41.8
PGC 31154	0	0	3608 a)	254 1)	1.35	—	48.1
PGC 31426	10	6	5042 C)	290 u)	1.41	—	67.2
PGC 31677	10	0	3756 h)	204 1)	1.50	—	50.1
PGC 31723	11	0	4152 h)	169 1)	1.32	—	55.4
PGC 31919	0	0	1032 a)	60 1)	1.46	11.8	13.8
PGC 31995	8	8	2932 a)	185 1)	1.45	—	39.1
PGC 32271	6	7	3047 h)	218 h)	1.54	—	40.6
PGC 32328	0	0	5704 a)	245 1)	1.30	—	76.0
PGC 32550	6	0	3108 j)	114 a)	1.54	—	41.4
PGC 35861	25	25	2702 h)	241 h)	1.53	—	36.0
PGC 36315	10	6	3701 a)	136 1)	1.21	—	49.3
PGC 37178	0	0	2013 a)	141 1)	1.60	9.7	26.8
PGC 37243	5	4	2944 a)	176 1)	1.42	—	39.2
PGC 37271	7	6	1702 a)	123 a)	1.64	—	22.7
PGC 37304	9	9	5715 a)	254 1)	1.36	—	76.2
PGC 37334	0	0	2889 b)	162 b)	1.42	—	38.5
PGC 38426	12	11	4476 C)	198 1)	1.31	—	59.7
PGC 38464	5	9	1728 a)	121 1)	1.38	—	23.0
PGC 38841	0	0	3133 a)	150 h)	1.31	—	41.8
PGC 40023	0	0	2940 a)	237 j)	1.50	—	39.2
PGC 40284	17	19	2002 a)	176 1)	1.49	9.3	26.7
PGC 42684	0	0	5502 a)	221 1)	1.32	—	73.4
PGC 42747	13	20	3210 a)	145 1)	1.42	11.2	42.8
PGC 43021	0	0	5260 a)	278 1)	1.41	10.0	70.1
PGC 43224	10	10	3211 h)	162 h)	1.25	10.3	42.8
PGC 43313	0	0	3693 C)	209 u)	1.40	10.	49.2
PGC 43330	14	16	1408 c)	60 2)	1.47	10.3	18.8

Table 1. continued.

PGC/NGC	East WA	West WA	cz (km s^{-1})	V_{rot} (km s^{-1})	logD_{25} 0.1 arcmin	m_H	d (Mpc)
PGC 43342	0	0	4459 $_{h)}$	254 $_{h)}$	1.39	—	59.4
PGC 43679	0	0	2258 $_{i)}$	106 $_{j)}$	1.39	—	30.1
PGC 44254	0	0	2839 $_{c)}$	142 $_{u)}$	1.28	10.7	37.8
PGC 44271	0	0	3376 $_{a)}$	172 $_{1)}$	1.43	—	45.0
PGC 44358	0	0	1487 $_{c)}$	114 $_{i)}$	1.51	—	19.8
PGC 44409	0	0	2173 $_{a)}$	184 $_{1)}$	1.67	—	29.0
PGC 44931	8	7	3812 $_{c)}$	201 $_{1)}$	1.45	—	50.8
PGC 44966	0	0	4995 $_{a)}$	231 $_{1)}$	1.19	—	66.6
PGC 45006	9	13	4527 $_{c)}$	206 $_{1)}$	1.42	—	60.4
PGC 45098	12	9	2896 $_{a)}$	169 $_{1)}$	1.46	—	38.6
PGC 45127	10	10	4007 $_{h)}$	180 $_{1)}$	1.27	10.7	53.4
PGC 45279	14	14	560 $_{a)}$	180 $_{a)}$	2.31	7.5	6.7*
PGC 45487	0	0	2621 $_{a)}$	114 $_{1)}$	1.48	—	34.9
PGC 45911	0	0	2754 $_{a)}$	143 $_{1)}$	1.47	—	36.7
PGC 45952	0	0	3006 $_{a)}$	170 $_{1)}$	1.38	—	40.1
PGC 46441	10	10	2744 $_{d)}$	191 $_{2)}$	1.54	—	36.6
PGC 46650	4	15	2566 $_{e)}$	131 $_{a)}$	1.46	—	34.2
PGC 46768	0	0	2256 $_{a)}$	112 $_{1)}$	1.25	—	30.1
PGC 47345	7	14	3604 $_{h)}$	207 $_{h)}$	1.52	—	48.0
PGC 47394	0	0	1503 $_{a)}$	251 $_{a)}$	1.91	8.6	20.0
PGC 47948	8	9	2577 $_{a)}$	158 $_{1)}$	1.40	—	34.4
PGC 48359	0	0	3631 $_{v)}$	229 $_{1)}$	1.31	—	48.4
PGC 49129	9	15	141 $_{a)}$	47 $_{a)}$	1.41	—	—
PGC 49190	17	15	3931 $_{h)}$	93 $_{h)}$	1.23	—	52.4
PGC 49586	8	8	2760 $_{a)}$	196 $_{b)}$	1.45	—	36.8
PGC 49676	11	13	2663 $_{a)}$	241 $_{a)}$	1.76	8.7	35.5
PGC 49836	4	10	2907 $_{a)}$	153 $_{1)}$	1.37	—	38.8
PGC 50676	14	15	1541 $_{a)}$	112 $_{1)}$	1.64	10.9	20.5
PGC 50798	0	0	3017 $_{a)}$	164 $_{1)}$	1.41	—	40.2
PGC 51613	0	0	2245 $_{a)}$	123 $_{1)}$	1.48	—	29.9
PGC 52410	0	0	2869 $_{a)}$	174 $_{1)}$	1.35	—	38.2
PGC 52411	9	9	3420 $_{a)}$	215 $_{1)}$	1.45	9.5	45.6
PGC 52991	0	0	2945 $_{a)}$	99 $_{1)}$	1.30	11.3	39.3
PGC 53361	0	0	4510 $_{a)}$	152 $_{1)}$	1.36	—	60.1
PGC 54392	0	0	522 $_{m)}$	79 $_{5)}$	2.05	—	7.0*
PGC 54637	9	12	4655 $_{a)}$	212 $_{1)}$	1.40	—	62.0
PGC 56077	0	0	2692 $_{a)}$	115 $_{1)}$	1.30	—	35.9
PGC 57582	0	0	2044 $_{f)}$	169 $_{i)}$	1.78	—	27.2
PGC 57876	0	0	3410 $_{a)}$	222 $_{1)}$	1.59	—	45.5
PGC 59635	0	0	1508 $_{a)}$	101 $_{1)}$	1.57	—	20.1
PGC 60216	15	15	2859 $_{a)}$	109 $_{1)}$	1.30	—	38.1
PGC 60595	0	0	4698 $_{a)}$	190 $_{1)}$	1.39	—	62.6
PGC 62024	0	0	3183 $_{a)}$	201 $_{1)}$	1.22	—	42.4
PGC 62706	0	0	3182 $_{a)}$	133 $_{1)}$	1.57	—	42.4
PGC 62782	8	4	1841 $_{a)}$	83 $_{1)}$	1.47	—	24.5
PGC 62816	10	10	5024 $_{a)}$	233 $_{1)}$	1.25	—	66.9
PGC 62922	7	0	4404 $_{a)}$	280 $_{1)}$	1.57	—	58.7
PGC 62964	13	13	2847 $_{a)}$	241 $_{4)}$	1.62	—	38.0
PGC 63395	3	6	1928 $_{a)}$	117 $_{a)}$	1.51	—	25.7
PGC 63577	12	12	4231 $_{a)}$	138 $_{1)}$	1.29	—	56.4
PGC 64597	5	5	4196 $_{a)}$	120 $_{a)}$	1.34	—	55.9
PGC 65794	9	3	9150 $_{a)}$	323 $_{1)}$	1.42	—	122.0
PGC 65915	11	8	3122 $_{a)}$	177 $_{1)}$	1.53	—	41.6
PGC 66530	14	7	3144 $_{a)}$	266 $_{1)}$	1.50	—	41.9
PGC 66617	0	0	2715 $_{r)}$	101 $_{1)}$	1.25	—	36.2
PGC 66836	0	0	797 $_{d)}$	73 $_{1)}$	1.52	—	16.2*
PGC 67045	0	0	857 $_{d)}$	96 $_{3)}$	1.89	9.3	16.0*
PGC 67078	0	0	2479 $_{a)}$	85 $_{1)}$	1.30	—	33.0
PGC 67158	0	7	3400 $_{a)}$	175 $_{1)}$	1.44	10.3	45.3
PGC 67904	6	5	2635 $_{a)}$	264 $_{1)}$	1.78	8.5	35.1

Table 1. continued.

PGC/NGC	East WA	West WA	cz (km s^{-1})	V_{rot} (km s^{-1})	logD_{25} 0.1 arcmin	m_H	d (Mpc)
PGC 68223	11	11	2847 [r)]	169 [r)]	1.38	10.1	38.0
PGC 68389	6	5	1746 [a)]	174 [1)]	1.64	—	23.3
PGC 69161	19	18	2091 [k)]	117 [1)]	1.55	10.9	27.9
PGC 69539	9	8	1240 [a)]	102 [1)]	1.60	10.7	16.5
PGC 69661	16	11	2360 [a)]	175 [1)]	1.48	9.8	31.5
PGC 69707	0	0	2364 [a)]	100 [1)]	1.59	—	31.5
PGC 69967	0	0	3001 [a)]	148 [1)]	1.41	10.5	40.0
PGC 70025	7	7	2857 [n)]	167 [f)]	1.50	—	38.1
PGC 70070	0	0	1681 [a)]	109 [1)]	1.58	—	22.4
PGC 70081	9	9	1940 [a)]	240 [1)]	1.49	—	25.9
PGC 70084	13	7	5041 [a)]	308 [a)]	1.31	—	67.2
PGC 70324	0	0	1059 [a)]	85 [a)]	1.62	10.1	14.1
PGC 71800	7	0	2008 [a)]	101 [a)]	1.24	—	26.7
PGC 71948	0	0	2876 [a)]	253 [1)]	1.74	—	38.3
PGC 72178	4	8	1489 [a)]	110 [1)]	1.43	—	19.8
NGC 4013	5	5	834 [f)]	193 [1)]	1.72	8.7	12.0*
NGC 1560	5	5	−36 [d)]	76 [1)]	1.99	9.4	3.0*
NGC 2654	8	8	1347 [f)]	197 [1)]	1.63	—	22.4
NGC 2683	7	7	411 [f)]	275 [1)]	1.97	6.8	5.1*
NGC 2820	12	16	3811 [o)]	210 [1)]	1.46	9.5	50.8
NGC 2820	12	16	3811 [o)]	210 [1)]	1.46	9.5	50.8
NGC 3510	10	10	705 [ll)]	83 [1)]	1.58	11.2	9.0*
NGC 3628	16	16	843 [s)]	223 [1)]	2.17	6.9	6.7*
NGC 4010	6	6	907 [i)]	118 [1)]	1.62	10.2	11.0*
NGC 4565	2	2	1282 [t)]	259 [1)]	2.21	6.7	10.0
NGC 6045	11	11	9986 [a)]	258 [1)]	1.12	10.9	133.1
NGC 6161	14	12	5904 [a)]	256 [1)]	1.29	10.2	78.7
NGC 6242	13	13	4620 [a)]	172 [1)]	1.28	—	61.6
NGC 7640	7	7	369 [f)]	110 [1)]	2.03	9.3	9.2*

The references of each value are: * Huchtmeier et al. (1989); [a)] Mathewson et al. (1996); [b)] Di Nella et al. (1996); [c)] Da Costa et al. (1998); [d)] Saunders et al. (2000); [e)] Longmore et al. (1982); [f)] Haynes et al. (1998); [g)] Huchtmeier et al. (1985); [h)] Theureau et al. (1998); [i)] Fisher et al. (1981); [ii)] Tully (1988); [j)] Richter et al. (1987); [k)] Davies et al. (1989); [l)] de Vaucouleurs et al. (1991), [ll)] Thuan et al. (1981); [m)] Strauss et al. (1992); [n)] Fairall et al. (1988); [o)] Staveley-Smith et al. (1987); [p)] Dressler et al. (1991); [q)] Fairall et al. (1991); [r)] Chengalur et al. (1993); [s)] Tifft et al. (1988); [t)] Giovanelli et al. (1997); [u)] Fairall et al. (1992); [v)] Bottinelli et al. (1993); [w)] Loveday et al. (1996); [1)] Mathewson et al. (1992); [2)] Staveley-Smith et al. (1988); [3)] Reif et al. (1982); [4)] Corradi et al. (1991); [5)] Banks et al. (1999).

– *Column 6:* The values of $\log D_{25}$ extracted from the LEDA database, where D_{25} is the diameter of the isophote with 25 mag/arcsec^2 in units of 0.1 arcmin.
– *Column 7:* Magnitude in H from 2MASS (Jarret et al. 2000 and de Vaucouleurs & Longo 1988).
– *Column 8:* Distance to the galaxy, obtained using the redshift value and the Tully–Fisher relation with a Hubble constant of 75 km s^{-1} Mpc^{-1}. This method is not very accurate for very close galaxies; therefore, when the redshift is less than 1000 km s^{-1}, we used distances from Huchtmeier & Richter (1989).

With this information, we sought any correlation between the amplitude of the warp or the difference between the east side and west side, and mass/luminosity, dimensions, infrared luminosity or total mass of the galaxies derived from the rotation curves. The results are commented on in Sect. 3.

2.2. Radio data

Radio data are from García-Ruiz (2001). There are only 26 galaxies with measurements of warps at these wavelengths. All the information is given in Table 2; the meaning of each column is the same as for the optical data. There are no other important works on radio warp amplitudes in the literature. In most cases, the warp is more prominent in radio observations than in optical images because the former extends to greater galactocentric distances. The galaxies were selected according the following criteria:

– listed in the *Upsala General Catalogue of Galaxies* (Nilson 1973);
– galaxies from the norther hemisphere with declinations higher than 20 degrees;
– blue diameters greater than 1.5′;
– optic inclination angles greater than 75 degrees;
– flux density higher than 100 mJy in the radio.

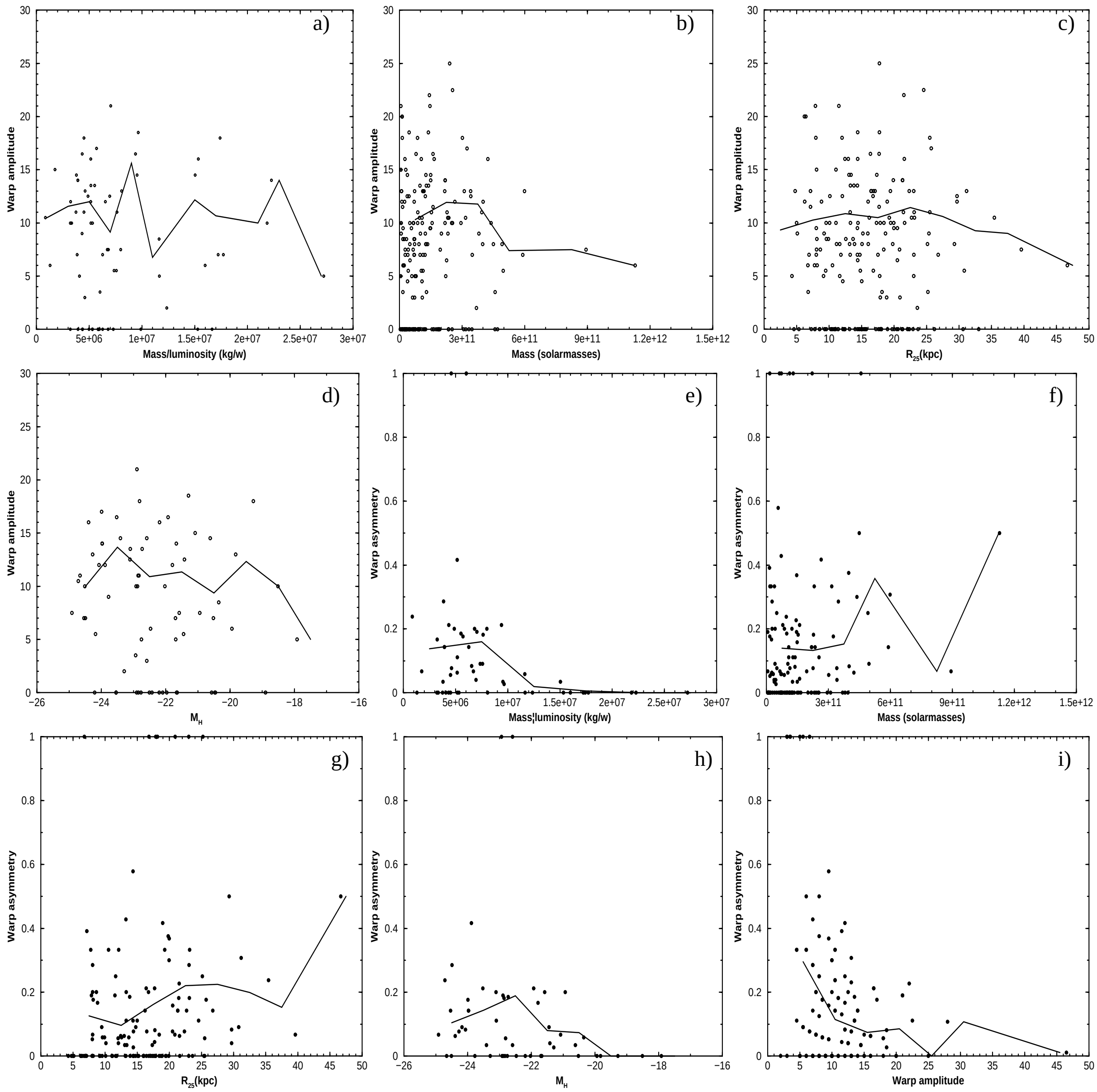

Fig. 1. Optical data from Sánchez-Saavedra et al. (2002). The panels represent from top to bottom: mass/luminosity versus warp amplitude, total mass in solar masses versus warp amplitude, R_{25} versus warp amplitude, absolute magnitude versus warp amplitude, Mass/luminosity versus warp asymmetry, total mass in solar masses versus warp asymmetry, R_{25} versus warp asymmetry for optical sample, absolute magnitude versus warp asymmetry and amplitude versus warp asymmetry. The points represent each galaxy in the sample and the line is the average of the galaxies with amplitude >3, taking a given width of the bin in the x axis.

Again, we have performed the same analysis as in the previous section for optical data, as described in the following section.

3. Analysis of the correlations

With the information available in the tables we can determine R_{25} (kpc) from the angular size and the distance, and the mass $M = R_{25}v^2/G$. The luminosity (or absolute magnitude) is also immediately derived once we know the apparent magnitude and the distance. We define the amplitude as the $\frac{1}{2}$(East WA + West WA) and the asymmetry as |East WA − West WA|/(East WA + West WA). In this section, we analyse the correlations among the different quantities.

Our results are represented in Figs. 1 and 2 for optical and radio warps respectively. For each one, we have two different sets of plots, graphs of warp amplitudes and graphs of the warp asymmetries against intrinsic parameters of the galaxies. The following parameters are represented:

– warp amplitude against the mass–luminosity relation. The total mass in kilograms that was calculated with the maximum of the rotational velocity curve, the radius of the isophote with 25 mag/arcsec^2 in kpc and the absolute magnitude in H for the reasons given in Sect. 2;

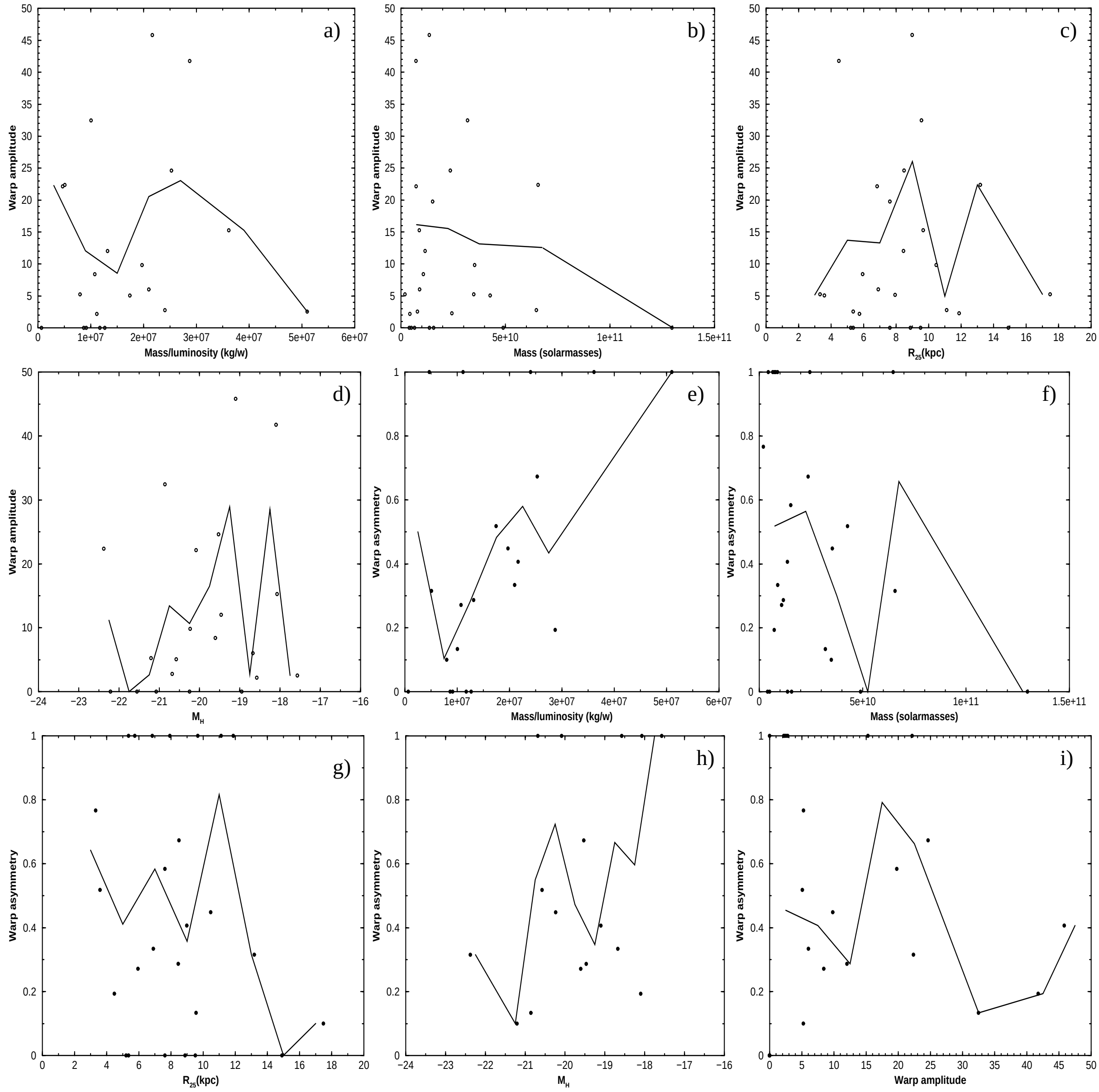

Fig. 2. Radio data from García-Ruiz (2001). The panels represent from top to bottom: mass/luminosity versus warp amplitude, total mass in solar masses versus warp amplitude, R_{25} versus warp amplitude, absolute magnitude versus warp amplitude, mass/luminosity versus warp asymmetry, total mass in solar masses versus warp asymmetry, R_{25} versus warp asymmetry for optical sample, absolute magnitude versus warp asymmetry and amplitude versus warp asymmetry. The points represent each galaxy in the sample and the line is the average of the galaxies, taking a given width of the bin in the *x* axis.

- warp asymmetry against the same quantities;
- the relation between the warp amplitude and the asymmetry of the warps comparing their east and west wings.

In Figs. 1 and 2 are represented the relations between the parameters of the warp (amplitude and asymmetry) against: mass-luminosity relation (Figs. 1a and 1e for its relation with the warp amplitude and the warp asymmetry respectively; and 2a and 2e), the total mass (Figs. 1b and 1f; and 2b and 2f), R_{25} (Figs. 1c and 1g; and 2c and g2), the absolute magnitude in *H* (Figs. 1d and 1h; and 2d and h2). Finally, Figs. 1i and 2i represent the relation between the warp amplitude and the warp asymmetry. The points represent each galaxy of the sample of Sánchez-Saavedra et al. (1990, 2002) and García-Ruiz (2001). The number of points in each plot depends on the number of available galaxies with information on the two variables represented. The solid line represents the average of the warp amplitude and warp asymmetry respectively along the *x* axis and was determined with data for the warp amplitude between 3 and 30 for optical data. We try to avoid galaxies with a small warp that might introduce errors in the measurements. In the case of the radio data all the measurements are presented in the average representation. Here, we have calculated the average value (solid line) with warp amplitudes between 0 and 50 for two reasons: there are fewer galaxies at this wavelength and we cannot discard any of them; it is easier to measure the warp in the radio than in the optical bands. In the case of the warp asymmetry graphs, the average value is between 0 and 1. In all cases, ten points along the x axis have been used to fit this value. The total number of galaxies is 228 for the optical data and 26 for the radio data, but sometimes there is no parameter (in H band because 2MASS is not yet complete, the rotational velocity, etc.) for all galaxies (see Tables 1 and 2). In these cases, the figures show a lower number of galaxies. The data displayed in the figures show the following behaviour:

- In the relation between mean warp angle and mass–luminosity relation, we have not found any correlation in either the visible or the radio. Points are distributed in all ranges of M/L. Large oscillations in the average value (solid line) reinforce this conclusion. In Fig. 2a there is a fall but is due to only one point with $M/L \sim 5 \times 10^7$.
- However, in the representations of the amplitude versus total mass, R_{25} (both parameters are related since larger galaxies are more massive) there is a slight anticorrelation, more pronounced in the visible and more conspicuous in the plot of amplitude vs. mass. Higher values of mass and R_{25} have on average a smaller warp angle. There is an absence of galaxies in all the figures for high-mass/radius galaxies and high-amplitude warps. For instance, we can see that all the galaxies with mass greater than 4–5 $\times 10^{11}$ $M_\odot$ tend to have smaller warps. This anticorrelation is clearer in Fig. 1b, where the solid line falls for large masses. This behaviour is not so clear in Fig. 1c because we have a large concentration of points for small x values and tends to smooth the fall of the solid line. There are small values of x and a low number of galaxies in the radio data (Figs. 2b, 2c), so no correlation can be seen in this region. In general, galaxies from the García-Ruiz (2001) sample are nearer and smaller.
- In asymmetry representations, we see almost the opposite behaviour. There are no apparent correlations with mass or radius (see Figs. 1f and 1g). There are many oscillations in the average value for Figs. 1f, 1g, 2f and 2g, and there is no clear tendency for either the mass or the radio to grow in either sample. But there is a clear anticorrelation in the mass–luminosity relation and in the absolute magnitude representation for visible warps. For Figs. 1e and 1h there is a slight drop around 10^7 kg W^{-1} and -21 mag, respectively. For larger M/L ratios, the galaxies have less asymmetry in their warps (see Fig. 1e). For low M/L values, the galaxies have a high dispersion in asymmetry of between 0 and 0.4. The solid line represents this behaviour. In Figs. 2e and 2h we cannot see this anticorrelation, or, if there is one, it would be opposite to the trend in the visible warps. If we consider the last points with warp asymmetry equal to 1 and a large M/L ratio (see Fig. 2e), the solid line tends to rise. There are not many points in this region and the total sample is very poor. The optical data are more complete. The same behaviour is seen in Fig. 2h.
- In Figs. 1i and 2i, the asymmetry of the warp amplitude in the east and west side against warp amplitude has been represented. For larger warp amplitudes we have less asymmetry. An analogous result is shown in García-Ruiz (2001), who used only radio data and found that warp amplitudes are more prominent than in optical images. We must bear in mind that the errors in the measurements are proportional to $\sqrt{2}S_{\rm a}/A$, where $S_{\rm a}$ is the error in the measurements and A is the average value. This means that for lower amplitudes the error will be larger, and this could introduce scatter in the results. In any case, the average value of the asymmetry should not be affected by this scatter, so we can tentatively talk about the detection of an anticorrelation between both variables.

All these relations are subject to the authenticity of the warp characteristics measured by Sánchez-Saavedra et al. (1990, 2002) and García-Ruiz (2001), especially for the visible warps, since these are more likely to be confused with other features (spiral arms, for instance). Nonetheless, the possible contamination, if reasonably small (no more than 20% of the sample), would only introduce some noise in the correlations. Unless most of the data are wrong, it cannot be expected that the present features are caused by this contamination.

4. Discussion and conclusions

In our analysis of the correlations between warp characteristics and other parameters of the galaxies we find some trends of correlation or anticorrelation in some cases and nothing in other cases. The number of galaxies is not very large, so possible minor systematic errors in the parameters are not totally discarded, and the dispersion of values is large, so the correlations among the different parameters is not perfect (we have no correlation factor close to 1). In any case, we think that these relations reveal some real characteristics which can be tentatively examined as follows:

- There is a slight anticorrelation between the amplitude of the warp in both directions (average between the east and west amplitudes) and parameters such as the total mass, luminosity and radius. We believe that this is to be expected for any mechanism that produces a warp as a reaction to an external torque, whatever it its origin (gravitational torque, magnetic torque, accretion torque; see López-Corredoira et al. 2002). More massive (i.e. generally larger and more luminous) galaxies have a more massive disc which forces the warped rings of the disc to collapse towards the flat disc. The more massive the disc is, the larger are the internal countertorques of the disc and the smaller the amplitude (López-Corredoira et al. 2002).
- There is no correlation between the amplitude of the warp and the mass–luminosity relation. This negative result is indeed very informative. If the halo were the predominant effect in the dynamics responsible of the formation of the warp, we would expect a larger amplitude for higher mass/luminosity ratios (a larger fraction of dark matter embedded in the halo). Either the rotation curve velocity is not related to the total mass of the galaxy or the warp amplitude is independent of the relative proportion of halo mass. Bosma (1991) found that galaxies with small dark halo core

Table 2. Radio data. Columns in the table represent: name of the galaxy, warp amplitude in the west and east side of the galaxy, redshift, maximum rotation velocity, log(D_{25}), H magnitude and distance.

UGC	EAST WA	WEST WA	cz km/sg	$V_{\rm rot}$ km/sg	$\log D_{25}$ 0.1 arcmin	$m_{\rm H}$	d Mpc
1281	1.22	9.27	157	50	1.65	—	5.1
2549	2.44	7.69	10355	226	.83	12.2	36.3
3137	5.76	4.71	992	93	1.55	*11.4	33.8
3909	15.48	8.57	945	77	1.37	12.5	24.5
4278	5.06	0.00	560	79	1.66	11.9	8.1
4806	0.00	5.59	1947	158	1.56	*10.9	21.1
5452	31.33	8.22	1342	93	1.38	—	21.7
5459	5.41	14.23	1112	120	1.66	*10.8	15.9
5986	41.21	8.04	615	109	1.84	10.1	8.5
6126	49.85	33.65	704	83	1.54	11.6	8.8
6283	6.11	10.68	719	88	1.56	10.7	11.3
6964	28.10	36.79	905	120	1.59	10.3	16.9
7089	0.00	0.00	774	57	1.50	8.8	11.6
7090	0.00	0.00	560	149	1.81	*8.9	10.2
7125	10.33	0.00	1071	59	1.64	—	12.6
7151	0.00	0.00	267	64	1.78	9.9	6.0
7321	4.54	0.00	409	94	1.74	—	14.9
7483	0.00	0.00	1248	94	1.47	10.9	17.6
7774	64.44	27.16	526	80	1.48	12.5	20.6
8246	30.57	0.00	794	63	1.53	13.4	19.4
8286	8.04	4.01	407	75	1.77	*10.8	8.0
8396	44.31	0.00	945	68	1.23	12.1	27.5
8550	0.00	4.36	364	57	1.48	12.0	13.2
8709	0.00	0.00	2402	194	1.71	9.3	19.8
8711	15.30	29.43	1531	146	1.60	9.4	22.5
9242	0.00	0.00	1436	81	1.68	—	12.6

The references of each value are: Cols. 1–3 from García-Ruiz (2001), the warp amplitudes are in the same units than optical amplitudes; Cols. 4–6 from García-Ruiz (2001) and LEDA database; Col. 7 from 2MASS and galaxies with (*) Tormen et al. (1995); Col. 8 from García-Ruiz (2001).

radii (as determined from rotation curve decomposition) are less likely to be warped, but this could be due to an indirect dependence on the scales. The fact here is that larger fraction of dark mass in the galaxy do not relate to the amplitude of the warps.

- There is no correlation between the asymmetry of the warp (differences between the east and west amplitudes) and the total mass and radius. This means that the reasons for the asymmetry are mainly external (satellites, accretion, intergalactic magnetic fields) and are independent of the size of the galaxy.
- There is an anticorrelation between the asymmetry of the warp and the mass–luminosity relation and perhaps also with the luminosity of the stellar population in the disc, but only for optical warps in both cases. In the radio there is no clear correlation, or, if there is one, it is opposite to the behaviour in the visible. This result is somewhat puzzling. It seems to indicate that the halo is responsible in some degree for the symmetry of the warp in the inner part, which is visible in the optical. The luminosity density or mass density in the disc would also be related with the degree of asymmetry (since there is no correlation with the radius and there is an anticorrelation with the total luminosity, it seems that the luminosity density is the factor to be related with the symmetry). The more massive the halo is with respect the rest of the galaxy and the more luminous the disc is (within a constant radius), the more symmetric it is in its inner parts. However, in its outer parts, visible in the radio, the symmetry seems to be independent of these factors. It seems that the forces which produce the asymmetry in the warp (interaction with other satellites, combination of U- and S-warps, etc.) are predominant in the most external radii with respect the halo forces, which tend to produce the symmetry; that is, the asymmetry due to external forces is effected at larger radii for smaller dark mass fractions. As a matter of fact, we have a clear example of this behaviour in our own Galaxy: the gas warp observed in the radio (Burton 1988) is clearly symmetric for $R < 1.6\ R_{\odot}$ but asymmetric for $R > 1.6\ R_{\odot}$ ($R_{\odot} \approx 8$ kpc; López-Corredoira et al. 2000). In our Galaxy, this radius of transition is equal to 13 kpc, which is precisely the value of R_{25} (Goodwin et al. 1998). A tentative explanation for this would be that the halo mass distribution, reflected in the rotation curves, plays a major role for $R < R_{25}$; outer rotation curves are not caused by the presence of a massive halo but have another explanation (magnetic fields, MOND, etc.; see Battaner & Florido 2000). In any case, if a very massive halo existed well beyond R_{25} it is clear that the asymmetry could not be reduced

as for $R < R_{25}$ so its dynamical effects must be negligible with respect to the forces that produce the asymmetries.

- Galaxies with larger amplitudes are more symmetric. This is another observational fact that must be accounted for by any theory which tries to explain asymmetric warps. If we interpret the asymmetries as a superposition of S- and U-warps, we regard the relative contribution of the U-warp as lower for larger absolute values of S-warps. For instance, in the theory of the accretion of intergalactic matter on to the disc (López-Corredoira et al. 2002) this would mean that large warps were produced only when the direction of the infalling flow is far from the galactic pole, and this provides also small asymmetries. If the asymmetries were produced by the presence of a companion galaxy, that would mean that the typical gravitational forces are comparable to the forces that produce S-warps with small amplitudes, and that they become unimportant for large S-warps.

Summing up, we think that the correlations analysed here can give us some clues about the predominant mechanism for the formation of warps in spiral galaxies. At present, the data seem to indicate that the role of the halo is important only in making S-warps at $R < R_{25}$ more symmetric, and that asymmetries are more important in less warped galaxies. This favours scenarios in which the halo is not very important in the formation of S-warps, especially radio S-warps and is in agreement with theories that identify the origin of the warps as directly related to external (intergalactic) factors without the mediation of the halo. The origin of the asymmetries in the warps might be different from the mechanism of S-warps, and in such a case the halo could play a role, only in the inner region.

In the introduction, we have described four different theories to explain the formation of warps. The present results cannot give a definitive answer about which is the correct one. Our goal in the present paper is just to present observational results, not to defend or deny a particular theory. As a consequence of these results, a few words can be added to the comparisons between theories and observations:

- Gravitational interaction with a satellite: this can be the mechanism, but only if there are nearby satellites massive enough to produce the observed warps without any amplification of the halo as an intermediary, which seems not to be the case in many warped galaxies (for instance, Milky Way and many apparently isolated galaxies).
- Intergalactic magnetic field: this is in general consistent with the present results. A slight anticorrelation between asymmetry and mass/luminous relation is seen in Fig. 1e in $R < R_{25}$. Under this hypothesis, the asymmetry could be due to inhomogeneous intergalactic fields or to other perturbative effects, even of a non-magnetic nature. If the asymmetries are really driven by a magnetic field mechanism, the anticorrelation found would suggest that this mechanism would also have an influence on rotation curves.
- Misalignment of the halo: this should produce some correlations of the warp amplitude with the mass-luminosity ratio, which are not observed. Hence, unless an explanation can be found for this non-correlation, it seems that this theory should be discarded.
- Direct accretion of intergalactic medium onto the disc: this explains the present results, but need either to have a dark matter halo within $R < R_{25}$ which has some effect on the amplitude of U-warps, or flat rotation curves are produced by the same matter accretion onto the disc which is responsible of the U-warps.

These are just attempted interpretations in the light of the present results. It is also possible that several mechanisms can be present in the warp formation at the same time. With further data for more galaxies, at higher resolution, and with a more detailed theoretical analysis of the different hypotheses to fit the observations, these results and interpretations can be corroborated and/or improved. New work with optical, infrared and radio data could be very useful for confirming the present trend and to reduce the dispersion of values.

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